FURNITURE DESIGN WITH COMPOSITE MATERIALS

A thesis submitted for the degree of Doctor of Philosophy

by

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This thesis examined the feasibility of fibre composite reinforcement in the furniture industry. The development of post war furniture design was reviewed, with particular emphasis on the main design movements and the use of new materials and technologies. The use of fibre composite materials in contemporary furniture was discussed in terms of technical development, environmental effects and psychological acceptance. Fibre reinforcements and adhesives were compared, as were fabrication techniques applicable to the existing British furniture industry. Particular emphasis has been placed on the fibre reinforcement of laminated timber sections as a method of overcoming many of the manufacturing problems of composites. Methods of analysing the behaviour under load of fibre reinforced laminated wood were reviewed. Resistance among the furniture buying public to modern, non-traditional furniture design was discussed, along with ways of making composite materials more aesthetically acceptable. Experimentation to determine the mechanical properties of fibre composite reinforced wood against wood control samples was undertaken, along with methods used to analyse the results for flat and curved samples. Modulus of elasticity, modulus of rupture and impact strength were measured, as was the level of distortion of the samples before and after testing. A full size chair form was produced to demonstrate the behaviour of the material on a larger scale. The development of the design was discussed in terms of ergonomic requirements, aesthetics, practicality and environmental concerns. The problem of predicting the behaviour of complex shapes was discussed and a finite element analysis of the form is carried out to gain an accurate picture of the composite's performance. Production of fibre reinforced materials was discussed, along with the furniture industry's reluctance to invest in new materials and technologies. The feasibility of adapting traditional furniture making skills and equipment to the production of fibre composite reinforced wood has been assessed.

APPENDICES PAGE

A	medium strength glass fibre, or amp, depending on context
AC	alternating current
ARP	aramid reinforced plastic
b	width of a beam
BRE	Building Research Establishment
BS	British Standard
c	subscript to denote composite, or depth of core, depending on context
C	medium strength glass fibre, or Centigrade, depending on context
CFRP	carbon fibre reinforced plastic
CoV	coefficient of variation
CSM	chopped strand matting
d	depth of beam
e	extension at peak load
E	Young's modulus (modulus of elasticity, MOE), or medium strength glass fibre
ECR	medium strength glass fibre with good chemical resistance
ELVE	European Laminated Veneer Engineering
f	subscript for facing material
F	peak load
FEA	finite element analysis
g	gram
G	modulus of rigidity (shear modulus)
GRP/GFRP	glass fibre reinforced plastic
h	depth of a composite beam
I	moment of inertia
J	Joule
k	stiffness
KFRP	Kevlar fibre reinforced plastic
l	length of a beam
L	span/depth ratio
LVL	laminated veneer lumber
m	metre
mc	moisture content
M	bending moment
MOE	modulus of elasticity (see E)
MOR	modulus of rupture (see ∂)
n	number of samples
N	Newton
P	load applied to a beam within the elastic region

P	load applied to a beam within the elastic region
Pa	Pascal (N/m^2)
PAN	polyacrylonitrile
PEEK	polyetheretherketone
PF	phenol formaldehyde
PPTA	poly(p-phenylene terephthalamide)
PRF	phenol resorcinol formaldehyde
psi	pounds per square inch
PVC	polyvinyl chloride
R	high strength glass fibre, or radius of curvature, depending on context
RCA	Royal College of Art
RF	radio frequency
RIBA	Royal Institute of British Architects
S2	high strength glass fibre
S.D.	standard deviation
S.G.	specific gravity
t	value from Student's t test
UF	urea formaldehyde
V	volt
v/o	volume fraction
W	force
y	deflection of a beam
∂	stress, or modulus of rupture, depending on context

'A chair is a very difficult object to design. A skyscraper is almost easier, that is why Chippendale is so famous' (Mies van der Rohe, 1957)

Reference
van der ROHE, M. *Time Magazine* (18 February 1957)

1.1 Introduction

'Designers should now use materials to create objects which up to now they could only see in their dreams. Personally, I'd like to design chairs which exhaust all the technical possibilities of the present' (Panton, 1960). The enormous progress in the development of materials in the last 50 years has been one of the most influential factors in furniture design and manufacture. The designer now has to come to terms with a wide range of furniture material attributes, namely:

(a) *Visual (Aesthetic),* colour, texture, opacity, creation of new forms;
(b) *Physical (Practical),* especially size, weight, ease of cleaning;
(c) *Tactile,* is the material warm or cold, soft or hard to the touch?;
(d) *Structural,* will it withstand abnormal loading and fatigue, does it fail safely and predictably?;
(e) *Traditional,* especially the connotations of wood to the furniture-buying public;
(f) *Economic (Cost),* of material, processing, specialist equipment and assembly;
(g) *Environmental,* are the materials recyclable or biodegradable, are woods readily replacable?

Gloag (1952) suggested that in the second half of the twentieth century, designers would have a *'limitless control of material'*, furnished by plastics, light metals, and plywood. By the 1960s the use of new materials was commonplace in the United States, with one commentator saying *'Most of the furniture manufacturers seem to feel that utilisation of new materials is of the greatest importance. Plastics have become popular wood substitutes with wood textures and finishes. I have seen dressers and chests, 80% plastic, which are incredibly accomplished wood imitations; I have seen aluminium supplanting bentwood, with a perfect wood finish'*. (Baermann, 1967). In contrast to the American example, Trippe (1962) reports: *'There is no doubt that the production engineer would have his problems greatly simplified if only the general (British) buying public could be persuaded that it was good, respectable mid-twentieth century taste to buy furniture made of mid-twentieth materials instead of an unstable material like timber'*. Modern technology, as well as economic competition from other materials, requires designs of structural composites of wood with metals or reinforced plastics. *'It is surely an anachronism in this day and age to slice up wood into thin strips, pay expert craftsmen to inspect each piece by eye, and then glue it together, just to make it look like a natural piece of wood'* (Trippe, 1962).

1.1.1 The 1940s

As the twentieth century draws to a close, the design achievements of the postwar period can be seen in perspective. The first half of the century was a testing ground for ideas that could only become reality in succeeding generations, benefiting from the huge technological advances made during the Second World War. The years between the two World Wars were characterised by the search for new uses of materials and by the desire to use as few components as possible in any one design; minimising the number of components would not only encourage aesthetic purity but would also, it was hoped, facilitate mechanised production. The war dramatically

Figure 1. Children's chair, Charles Eames (1945)

increased the need for better, faster and more cost effective methods of industrial production. After 1945 the American furniture industry in particular benefited from this surge of research. New materials and techniques created previously unimaginable possibilities, exploited to the full by innovative furniture designers. The highly sculptural moulded plywood chairs by Charles and Ray Eames for Herman Miller were among the first (1940) to use organic shapes derived from the natural world. Eames' state of the art plywood shells were also the first to use three dimensional compound curves in furniture design. The use of compound curves in the moulding of the plywood gave the chairs an inherent flexibility and meant they were comfortable, even though they were not upholstered. The chair shown is made in two sections from birch plywood.

1.1.2 The 1950s

The 1950s, the decade of *'good design'*, saw much new low cost housing built, and a demand for affordable furniture that would fit into small spaces, and the modernist ideal of simple, flush surfaces and basic forms with minimal decoration was gradually to enter the public consciousness. The spatial qualities of furniture were emphasised through the use of plywood, perspex and aluminium. Fewer pieces of 'case' furniture were produced, living space was maximised and, as a result, free-standing furniture and in particular the chair was to achieve a greater status. Arguably the seminal chair of the 50s, Eames' DAR (Dining Arm Rod) of 1950, was initially produced with a stamped aluminium shell, although when it was later produced by Herman Miller, a shell of thermoset polyester resin reinforced with fibreglass was used instead. The shell was connected to the metal rod base with rubber shock mounts 'cycle welded' to the polyester, a technique patented in 1941 by Chrysler. It allowed wood and plastics to be joined to glass, metal and rubber. Using the shock mounts it was possible to mount the shells dyed in different colours on different bases without having to alter the mountings. This enabled the hydraulically controlled positive/negative metal moulds to be produced efficiently while retaining the greatest variation among the models. Early models had a 'Zenith' shell of very fine fibreglass which was left unpainted and translucent, a technique later used for the roof of the 1955 Citroën DS.

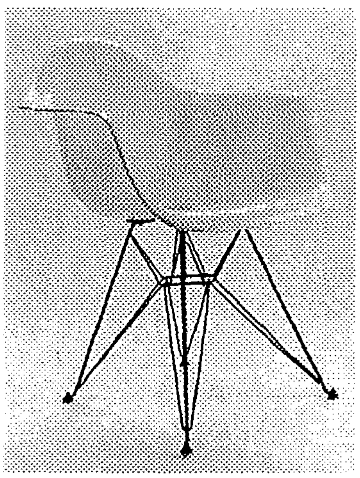


Figure 2. DAR, Charles Eames (1950-53)

1.1.3 The 1960s

The popular culture of the 1960s was based on an *'enjoy it today, sling it tomorrow'* philosophy, finally replacing the *'use it up, wear it out, make it do'* slogan which had maintained the war effort and subsequent economic recovery. As often happens, the *'Pop'* scene in the 60s was fuelled by a rejection of the sensible, economic and carefully designed furniture of the previous decade. The spirit of optimism that produced a quest for new designs prevailed until the end of the decade, when it was succeeded by a general awareness of the potential ecological effects of mass consumerism. This shift in conscience brought a marked change in public taste, with most consumers preferring craft-based design to the more avant garde designs like the 1967 inflatable PVC Blow chair by D'Urbino, Lomazzi and De Pas. The first single-form plastic chair was put into production in 1968 (Figure 3). Originally prototyped in glass reinforced polyester, early production models were produced in moulded 'Baydur' HR (High Resistance) Polyurethane hardfoam, and then lacquered. Each piece took thirty minutes to mould. In 1970 the material was changed to 'Luran-S', an injection moulded non-reinforced thermoplastic.The edge profiles had to be reinforced and reinforcing ribs placed under the seat, thus destroying the purity of the original form. In the long run, the material did not withstand dynamic stress and many chairs failed. Production ceased in 1979, resuming in 1983 using HR foam. The 1972 oil crisis and the subsequent world recession reduced furniture production, and petroleum by-products such as plastics dramatically increased in price and were no longer seen as viable materials for furniture production.

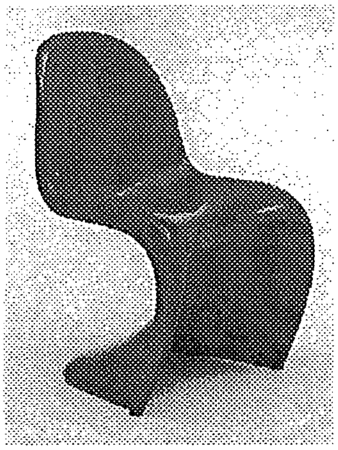


Figure 3. Stacking chair, Verner Panton (1959-67)

1.1.4 The 1970s

Figure 4. Easy Edges, Frank Gehry (1972)

Worldwide recession in the 1970s compelled manufacturers to rationalise production in order to remain competitive. Mainstream designers distanced themselves from the excess of the 1960s and created rational, simple furniture. Frank Gehry produced his Easy Edges Group in 1972, seventeen pieces constructed from laminated, corrugated cardboard. The fluting inside each sheet was placed at 90° from the sheet directly above and below it, giving it great strength and resilience, as shown in the picture (left), taken from the 1972 brochure. Easy Edges used simple technology and cheap paper products to create strong, well designed, low cost furniture. Nevertheless, Gehry's Edge Board, as he called

1.1.4 Continued

it, could not at the time compete with plastics, which were just as light. The mid 70s backlash against plastics caused Gehry's work to be reevaluated, and four pieces were reissued in 1986. Due to their surface quality, the pieces had a noise reducing effect in the room. The design theorist Victor Papanek, one of the first to address the ecological responsibility of designers, praised Edge Board as a useful application of a packing material to furniture. The pieces were made for $7 and sold for $55 in 1973.

1.1.5 The 1980s

The 1980s were years of political change and economic prosperity, with *'high-tech'* contract furniture becoming much more profitable, and therefore important for large manufacturers. This move left many designers manufacturing their own designs in limited quantities, using simple, labour intensive techniques. *'I think we can anticipate a return to a more primitive form of craftsmanship - not in the sense of going back to the techniques of the past, but a return to smaller scales of operation, making use of all the potential offered by present and future technology. There may still be a need for manufacturers on a large scale to meet some needs, but more and more will be produced by individuals. The impact on creativity could be enormous'* (Perriand, 1984). Because limited edition furniture is not subject to the constraints of mass production, designers working in this field are able to express themselves more freely through designs that employ a wide variety of forms and materials. Richard Rogers, one of the originators of architectural 'high-tech', has described this type of anti-design furniture as *'usable artwork'*, identifying its aesthetic intentions. Tom Dixon's work has always been consciously distanced from mass-produced furniture, and while he has not transposed furniture into art, he aims to create three dimensional design which possesses aesthetic characteristics similar to those of paintings and sculpture. Dixon works from his own studio with a staff of a few assistants producing highly individual furniture like the 'S' chair of 1988. This is available in various tactile coverings such as latex rubber, rush and wickr over a bent steel frame. Aggressive curves define the narrow waist and full hips of the chair, while its bent cantilevered shape allows a comfortable, springy action while sitting in it. The chair was only ever intended for limited 'batch' production.

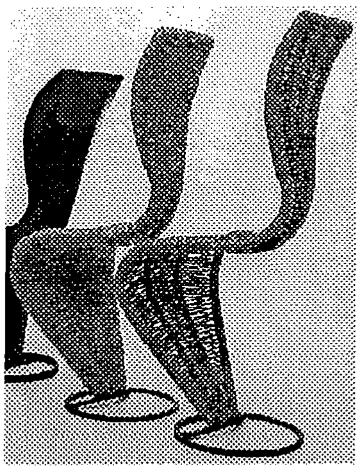


Figure 5. S Chairs, Tom Dixon (1988)

1.1.6 The 1990s

At a seminar entitled 'Synthetic Visions' at the Royal College of Art in 1990, architect and designer Michele De Lucchi concluded that new technology and synthetic materials must be exploited for the manufacture of durable products. Modelmaker John Greed's 1991 Mocean chair gains it strength from carbon fibre and weighs just 1990g. Greed wrapped the fibre around a polyurethane foam base before applying a coating of epoxy resin. He was attracted not only by the material's physical characteristics, but by the fish scale effect of the fabric beneath the resin. Composite materials have many unique properties which could influence furniture design more than any other, yet the Mocean chair, along with Alberto Meda's LightLight chair of 1987 (Figure 14), are the only notable examples of composite materials used for their own sake in furniture. Glass fibre has for many years been used to make shells for chairs that were subsequently upholstered, such as Arne Jacobsen's 1957 Egg (see Figure 72), but apart from the work of Charles and Ray Eames, glass fibre has rarely been celebrated in furniture.

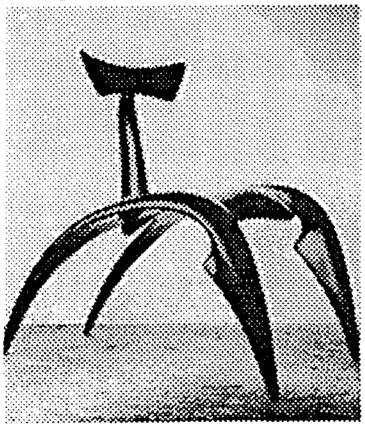


Figure 6. Mocean chair, John Greed (1991)

1.1.7 The next decade

Since the Second World War, the cycles of rational design and anti-rational 'Pop' design have coincided with the decline and growth of the western economy. The rational use of plastics in the furniture industry, although a fundamentally non-disposable material, can be justified by producing ecologically efficient products. Plastics still have many negative connotations, namely that they are cheap, fragile, damaging to the environment and cold to the touch. Designers are now addressing these problems - the 1995 Museum of Modern Art, New York show 'Mutant Materials in Contemporary Design' presented 200 products that provide examples of material modification or technological process. Even so, Janet Abrams reported *'the predominant feeling is of coldness to the touch.'* The chair is an intensely personal object, and natural organic materials provide a very tactile surface. Future furniture designs will undoubtedly mix modern composite materials for strength with natural materials like wood, leather, rattan and natural fibres for a sensual feel.

1.2 Future furniture design

Charles Eames interpreted design as *'a plan for arranging elements in such a way as to best accomplish a particular purpose'*. Eames (1907-78), like Alvar Aalto (1988-1976), and Frank Gehry (1929-), shaped the world of furniture design through their training as architects. Unlike many designers, they approach the design process as a technical rather than a visual challenge,

1.2 Continued

approach which is more likely to succeed as truly definitive or absolute design cannot be created since solutions only apply to specific purposes and periods in time. Furniture 'classics' are more forward looking and better designed than their contemporaries, and they express the spirit of the time in which they were created. *'The designer is responsible less for the technology and more for the construction'* (Schwartz-Clauss, 1996). The architect, and the furniture designer of the future, need to understand the potential of modern materials and manufacturing processes. They must produce designs that are technologically superior to succeed, yet are psychologically sound to comfort the stressed individual of the new millennium. The tradition of using timber for furniture is coming under threat from rising costs, dwindling availability and falling quality. Combining modern composite materials into timber using existing technology such as laminating would allow reinforcement to be introduced into glued laminated timber, increasing quality and allowing thinner sections and exciting new forms, whilst preserving the look and feel of wood.

1.3 Composite Beams

The per capita usage of glulam (glued laminated timber, see 1.3.8 and 1.14.1) in the UK is far below that of any other European country (Pellicane *et al.*, 1986) (Table 1). *'The difference between American and European furniture is that they in America they are making things of the past with methods of the future; in Europe we are making things of the future with the methods of the past'* (Covell, 1971).

Country	*Annual Volume* (m^3)	*Population* (x 10^6)	*Annual Volume/Population* (m^3 x 10^{-6})
Finland	40,200	5	8,040
Denmark	40,000	5	8,000
Norway	19,400	4	4,850
West Germany	260,000	55	4,730
Sweden	29,000	8	3,625
USA	500,000	250	2,000
France	80,000	55	1,450
Holland	20,000	14	1,430
UK	10,000	55	180

Table 1. Glulam use in selected countries by volume and population (Pellicane et al., 1986)

Further optimisation of laminated timber is necessary to improve its viability against other structural materials. The method of manufacture of laminated timber allows the use of low grade wood laminations in areas of low stress (usually the core) and high grade materials like fibre composites where higher stresses occur (usually the outer surfaces) hence improving structural efficiency. As a result, the strength to weight and stiffness to weight ratios may be increased substantially, and lighter members can perform the essential load bearing function without undue

1.3 Continued

deflection. Variability is also reduced, as natural defects in the timber are dispersed through the laminates. From an economic point of view, by using lighter and less strong cores, which in the case of wood are less expensive than the facing material, the composite can be more economical, assuming the manufacturing cost does not exceed the difference in cost of the two materials.

1.3.1 Wood and Glass composites

Creating a composite with wood and a fibre reinforcement is not a new idea. The use of synthetic materials to reinforce wood has been discussed in numerous research papers dating from the early 1960s. Wangaard (1964) published *The Elastic Deflection of Wood-Fibreglass Composite Beams* in which he proposes methods of analysis for these beams. Fibreglass was chosen for its high tensile strength and stiffness. It was also one of the first readily available fibre composites. The fibre reinforcement used was Scotchply 1002, an early unidirectional glass fibre impregnated with epoxy resin, a layer of which was bonded on top and bottom faces of different wooden cores with Armstrong A6 epoxy resin. 30 beams were tested to failure, which took the form of compression failures in the uppermost fibres of the wood core. In no case was the ultimate load limited by the facing material or by the adhesive bond between the facing material and the wood core.

1.3.2 Wangaard

Wangaard computed modulus of elasticity for his composites using the relationship: $E = \frac{Pl^3}{48Iy}$

where P = load within the elastic range, l = span of the composite beam, I = moment of inertia of the composite (considered to be homogeneous), and y = corresponding deflection within the elastic range. This is the standard flexure formula for a simply supported centrally loaded beam, using the method of equivalent (transformed) sections to modify the composite beam's moment of inertia. A more accurate method for predicting the stiffness of the beams was proposed which takes into account the span/depth ratio of the beams. Values of E will include a component of shear deformation that contributes to the deflection of wood beams at this span and depth. A ratio was employed that was originally proposed by Timoshenko (1955) which involves the hyperbolic relationship: $E' = \frac{E}{1 + 0.3(^2/_L)^2\, ^E/_G}$

where E' is the experimental modulus of elasticity at a specified span/depth ratio (L), E and G are pure modulus of elasticity and modulus of rigidity, respectively. Following a precedent that has been used in wood design, an assumption was made that the ratio of modulus of rigidity to modulus of elasticity is a species constant. Two further methods of analysis are employed.

Method 1: $E = \frac{E_f I_f + E_c I_c}{I}$

1.3.2 Continued

where E and I are modulus of elasticity and moment of inertia of the c respectively, is essentially the equivalent sections method. E_f and I_f are the corresponding values for the facing and E_c and I_c are corresponding values for the core. This method neglects shear deformation in the core wood, or rather assumes that the core wood behaves in the composite beam exactly as it behaves when loaded by itself as a simple beam over the same span/depth ratio. All predicted values using this method were too high differing from a few per cent to 50 per cent. Similar results were obtained by Mark (1961) who used the same method of analysis in predicting modulus of elasticity values for wood-aluminium composite beams. The second method yields more accurate results as it involves separating the individual contributions to deflection of the composite beam from: (i) axial strain as a result of the compressive and tensile stresses set up under load, and (ii) deformation of the core in shear. This method is only applicable, as is the work of Kuenzi (1959), for structural sandwich with two thin facings bonded to a thick core.

1.3.3 Biblis

Biblis (1965 a) continued the work of his Yale University colleague Wangaard in the *'Analysis of Wood-Fibreglass Composite Beams Within and Beyond the Elastic Region'*, perhaps the best known work in this field. Biblis points out that from the viewpoint of the forest products industries (the work was published in Forest Products Journal), composite structures using wood cores have the advantage of *using* a high percentage of wood. Otherwise, wood may not be used at all, because for certain designs, solid wood structures would be impractical and undesirable. The purpose of Biblis' work was to make it possible to predict the stiffness and bending moment of composite beams. Literature cited by Biblis includes (1) March and Smith (1955), who developed a mathematical analysis for the flexural analysis of sandwich beams which takes into account the shear effect of the core in terms of its MOR; (2) Norris, Ericksen and Kommers (1957) who further developed the above analysis for certain extreme sandwich constructions; (3) Ethington (1960) who accepts the general assumption that the effects of shear become important only in beams of very low span-depth ratios. Biblis points out, however, that as far as shear deformation is concerned, the effective span-depth ratio of a composite beam may be much lower than the actual span-depth ratio. This depends on both the ratio of the MOE of the face to that of the core and the ratio of their respective depths. Wangaard was the only analysis cited by Biblis which took into consideration the effect of shear deformation of the core in predicting the MOE of the composite.

1.3.4 Span-Depth Ratio

It is known that the effective modulus of elasticity of wood varies according to the span-depth ratio as indicated in Figure 7 for hickory. As mentioned previously, the effective span-depth

1.3.4 Continued

ratio corresponds to the span-depth ratio of a beam having the same span, but a 'transformed depth'. This transformed depth will be the depth of a hypothetical beam having the same width, but in which the faces have been replaced with equivalent core material (see Figure 7).

Span-Depth Ratio	*Young's Modulus* (GPa)
8	12.035 - 14.105
11	20.010 - 21.875
14	22.205 - 24.775
18	25.275 - 26.375
21	25.675 - 27.035

Table 2. Effect of the span-depth ratio on the Young's Modulus of hickory (Biblis, 1965 a).

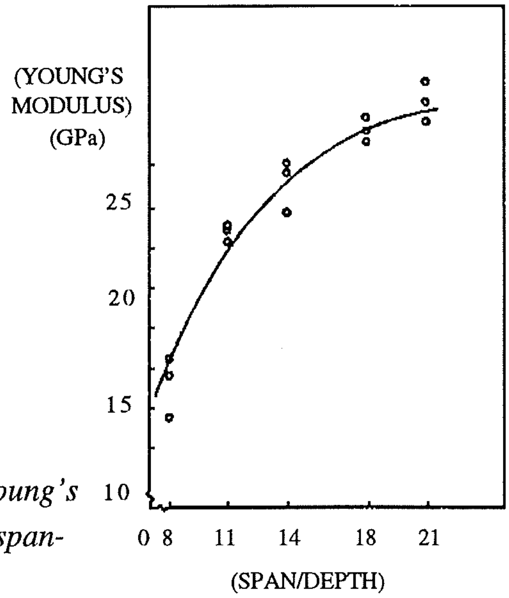


Figure 7. Hyperbolic relationship between Young's modulus in static bending of hickory and the span-depth ratio (Biblis, 1965 a).

1.3.5 Wood and Aluminium Beams

Sliker (1962) laminated a series of wooden beams with aluminium sheet stock inserted between selected layers. Two problems concerning shear appeared in the reinforcement of the beams. One of these was the increase in shear deflection as a percent of total deflection over that for solid wood beams. This increase would be most significant for beams with small span-depth ratios since shear deflection varies directly as the span-depth ratio. In addition, reinforcement of beams with small span-depth ratios to increase their bending strength would prove less valuable since they are most prone to be limited in design by their shear strength. Sliker restricted the use of metal reinforcement to the most highly stressed areas such as the mid-span portion of beams with an evenly distributed load, making the reinforcement much more economic. Delamination with dimensional changes in metal-wood combinations was a problem, and overcoming this might involve a combination of mechanical fastening (not used here) and bonding.

1.3.6 Kuenzi

The deflection (y) consists of a portion due to pure bending which is equal to:

$$y_1 = \frac{Pl^3}{48EI}$$

and a part due to shear deformation which, according to Kuenzi (1959) is equal to:

1.3.6 Continued

$$y_2 = \frac{PL}{4N}.$$

So the total deflection is equal to:

$$y = y_1 + y_2 = \frac{PL^3}{48EI} + \frac{PL}{4N}$$

where P = load within elastic range, L = span, $EI = E_cI_c + E_fI_f$ where: E_c = pure tangent MOE of the core, I_c = moment of inertia of the core, E_f = pure MOE of the face (in tension or compression), I_f = moment of inertia of the faces, and

$$N = \frac{(h + c)^b}{2} \times G_c$$

where h = total depth of the composite, c = depth of core, b = width of the composite, G_c = modulus of rigidity of the core. Kuenzi's equation is a simplified form of:

$$\frac{KPl}{AG}$$

in which shear stress is considered to be uniformly distributed throughout the depth of the core. This will not be true for cores that contribute substantially to the EI of the beam cross section, but Biblis considers this a reasonable approximation. His results are shown in Table 3.

The woods used by Biblis were tropical American Balsa (*Ochroma pyramidale*), Douglas fir (*Pseudotsuga menziesii*), Ceiba (*Ceiba pentandra*), of the same *baobab* family as Balsa, and Cedro (*Cedrela,* from the genus *Cedrus*, or cedar, known as Spanish Cedar). All these timbers were used widely in the 1960s American furniture industry, and it should be pointed out that Biblis chose timbers which would effectively support the U.S. department of forestry.

Core	*Specific Gravity of wood*	*E (Core)*	*E (Reinforced Core)*	*% Gains*	*Predicted E*
Balsa	0.09	1.53 MPa	7.55 MPa	492%	5.17 MPa
Douglas fir	0.57	16.88 MPa	19.87 MPa	19.6%	20.30 MPa
Ceiba	0.27	2.85 MPa	10.54 MPa	370%	9.53 MPa
Cedro	0.46	9.86 MPa	14.62 MPa	148%	14.60 MPa

Table 3. Actual and predicted elastic modulus (E) of composites (Biblis, 1965 a).

1.3.7 Accuracy of theory

Biblis abraded the glass fibres prior to gluing to remove the glossy finish, and then sealed all radial surfaces of the wooden cores with a light coat of epoxy sealer. The bonding of all his 30 samples was assumed to be successful, since no delamination of the glue line occurred during the testing of the composites. Predicted values for MOE using the theoretical analysis were in good agreement with the test results except when the cores are from low density species such as balsa, when they are 10-30% lower than the actual values (Table 3). The method of analysis

1.3.7 Continued

proposed by Biblis predicted values of MOE, bending moment at proportional limit, and bending moment at 90% of ultimate, with significantly smaller percentage error than a method which ignores shear.

1.3.8 Glue line effects

As part of the research on laminated timber at the Structural Timber Research Unit, Brighton Polytechnic (Whale *et al.*, 1988), a glue sensitivity study was carried out to assess the strength contribution of glue joints. Materials tested included laminated timber involving 3mm thick laminations ('microlam' or 'laminated veneer lumber') as well as traditional glulam, with 30-45mm thick laminations. Laminated Veneer Lumber (LVL) differs from plywood, which is also a glued veneer product. In plywood, the grain direction of each ply is at some angle, usually 90°, to that of adjacent plies. In LVL, the grain direction of all plies is essentially parallel to the length of the lumber. From the study it was concluded that the effect of glue line properties on the behaviour of glulam is negligible. For microlam however, in which the proportion of glue to timber is higher, it was found that the effect of glue line stiffness could be much greater, and that for example, reinforced glue lines could bring about substantial benefits depending on the value of Young's modulus of the adhesive used.

1.3.9 Moulin

Moulin *et al* ., (1990) produced a composite made from poplar wood bonded together with a phenol-resorcinol adhesive and fibreglass layers introduced into the first and last glue joints. Poplar was chosen as this species is abundant in France, where the study was carried out, but rarely used by industry due to its low mechanical characteristics. Tests showed up the following results with respect to normal gluelam: (i) Elastic modulus is higher (9000MPa against 7500MPa); (ii) Maximum stress is nearly the same (60MPa against 61MPa); (iii) Mode of fracture is very different: the first cracks appear only in the outer lamella in tension and stress decreases. Then, because the fibreglass located in the last joint in tension can easily support the present stress, the load can increase again to 70-90% of its maximum value and final fracture occurs with a large strain (20%). Experimental results were analysed using a general relationship for layered systems:

$$E_c = \frac{1}{I_c} \sum_i E^i \cdot I^i$$

($_c$ being subscript for composite). This is valid for longitudinal elastic modulus with the following assumptions: (i) The stress state is plane stress and the uniform strain theory is used; (ii) Each lamella is considered as an homogeneous material; (iii) A plane cross section before loading remains plane after loading; (iv) Each joint is considered as a single lamella (in spite of its very small thickness).This equation becomes:

1.3.9 Continued

$$E_c = \frac{1}{I_c}\left[\sum_i E^i_b \cdot I^i_b + \sum_j E_f \cdot I^j_f + \sum_k E_c \cdot I^k_c\right].$$

Good agreement was found between experimental and theoretical results derived from the layered systems theory. This analysis requires individual mechanical properties of each material: wood of each lamella, solid glue and fibres alone. Moulin concludes that introduction of fibreglass in a laminated beam increases its rigidity and its loading capacity, allowing the use of low grade species for structural members, and that such a reinforced beam can sustain very large strains after rupture of the outer lamella without noticeable decrease of the supported load.

1.3.10 Rowlands

Rowlands *et al*., (1986) were among the first to reinforce wood with uncured pre-impregnated materials and internally with graphite or aramid fibres. Several different forms of glass-, aramid- and graphite-reinforced materials and adhesives were evaluated. The following generalisations were made regarding the adhesive-reinforcement systems: (i) Strengths obtained with fibres preimpregnated (prepreg) with phenol formaldehyde are vastly superior to those obtained using phenol formaldehyde separately (3822lb/in^2 (26.2MPa) against 3265 lb/in^2 (22.4MPa) for glass reinforced maple; (ii) The prepregs outperformed the bidirectional materials (glass or aramid) bonded with resorcinol formaldehyde, phenol resorcinol formaldehyde, epoxy or isocyanate; (iii) The woven glass prepreg material produced a shear strength approaching the best demonstrated by the unidirectional reinforcements; (iv) Glass prepreg, and unidirectional glass, aramid or graphite cured with epoxy adhesives all produced an interface shear strength as great as that of maple, and greater than that of Douglas fir; (v) Preimpregnated fibre reinforcements are exceedingly easy to use. However, their cure times are longer than those for resorcinol formaldehyde, phenol resorcinol formaldehyde, or epoxy adhesives. Failed specimens that had been reinforced by prepreg materials suggested insufficient resin for optimum performance. Rowlands, like Biblis and Wangaard, computed the elastic stiffness from:

$$EI = \frac{Pl^3}{48\partial}\left[1 + 1.2\frac{h^2E}{l^2G}\right]$$

and E/G = 16 (Anon., 1974) where G = shear modulus (modulus of rigidity), P = load, ∂ = stress, l = span, h = depth, I = area moment of inertia, E = elastic modulus. Glass reinforcement increased beam stiffness by 20% and strength by as much as 50%. Under normal dry conditions, the epoxies that Rowlands used performed very well with all three fibre materials. Resorcinol formaldehyde and phenol resorcinol formaldehyde worked well with graphite and glass but performance was marginal with aramid fibres. Of all the reinforcements considered, Rowlands concludes: (i) Glass is technically and economically superior for wood; (ii) Glass fibre reinforced Douglas fir (18% glass by volume) produced a 40% stiffness enhancement and

1.3.10 Continued

doubled the strength over similar unreinforced wood; (iii) Preimpregnated cloth of high strength synthetic fibre works well with wood substrates; (iv) The fabrication process and economics could be improved by preheating the wood and prepreg reinforcement to minimise cure time. Reinforced veneer products could then be manufactured on a production basis using simple equipment and unskilled personnel.

1.3.11 Laufenberg

Laufenberg *et al* ., (1984) studied the economics of fibre reinforced wood composites, starting with the premise that the changing market, whilst driving up the price of structural lumbar, is also characterised by a decline in the price of synthetic fibre reinforcements due to rapidly expanding markets. Specific strength costs were found to be lowest for an E glass/phenol formaldehyde (PF) composite, which is a significantly cheaper material than wood for providing tensile load capacity. Douglas fir was shown to be nearly three times more expensive in providing the same tensile strength capacity as the glass reinforced wood. Little correlation was shown between specific strength and specific stiffness costs, with E glass/PF proving to be an expensive material for providing stiffness. Placement of the stiffer glass on the outer plies of the laminate will decrease the cost of adding bending stiffness. Tensile strength enhancement by the glass fibre composite is the attribute which could be exploited in laminates made of low quality veneer. Graphite and aramid (in this case Kevlar®) systems were found to be too expensive for commodity items, with their use being confined to specialised items.

1.3.12 Spaun

Spaun (1981) points out that the presence of growth related defects pose a challenge to the efficient use of wood as a structural material. Knots, and the associated cross grain, serve as trigger mechanisms, initiating failure long before the clear wood has reached its ultimate strength. One example of how trigger mechanisms can limit design loads is with large glue-laminated beams. The ultimate strength of these beams is usually controlled by the strength of the bottom tension lamination, with failures characteristically initiating near a knot on the tension side of the beam. If the compressive side of laminated beams can be forced to fail first by strengthening the tensile side, beam strength will be optimised. Braun *et al.,* (1977) reported that increases in bending strength of up to 20% can be achieved by replacing the outer tension lamination of laminated beams with high strength laminated veneer lumbar. It was thought that a fibrous material had advantages over bulk material like metal because of the fibre's ability to bond intimately with the wood. This would reduce problems of delamination due to stress concentrations and changes in temperature and moisture content. Glass fibre was chosen as the most suitable material due to it's low density, high proportional limit, low thermal conductivity,

1.3.12 Continued

availability in different forms and superior machinability. Unidirectional, non woven roving was chosen for the wood reinforcement in bending and tension for the following reasons: (i) Roving offers the highest strength at the lowest cost; (ii) Strength is only needed in one direction. (In a 50/50 bidirectional weave, 50% of the fibre is unstressed); (iii) The fibres in woven mats are crimped as the glass strands bend over and under one another and thus have lower strength (due to mechanical handling) and stiffness (due to the straightening out of crimped fibres under tensile load) (See Table 4).

Reinforced Plastic	*Tensile Strength* (psi and MPa)		*Tensile E* (10^6psi and GPa)	
Unidirectional non woven	149000psi	1020MPa	6.0×10^6psi	41.1GPa
Bidirectional woven	55000psi	375MPa	3.2×10^6psi	21.9 GPa
Chopped strands	20000psi	135MPa	1.3×10^6psi	8.9GPa

Table 4. Typical tensile properties of E-glass reinforced plastics (Broutman, 1969)

1.3.13 Spaun's Results

Spaun performed a series of tests comparing Douglas fir laminates with laminates containing 3.5% and 7% glass fibre. The overall beam stiffness of 1.4 GPa was increased by 12% and 21.5% respectively due to the presence of 3.5% and 7% fibreglass. Doubling the amount of fibreglass did not double the increase in E. This was due to the manner in which the composites were made. The core of the 7% fibreglass composite was thinner than the core of the 3.5% composite. Therefore, the moment of inertia of the core and the moment arm of the fibreglass lamina of the former were less than that of the latter. Predicted E of the composite beams agreed reasonably well with measured values. Predicted E was calculated using the standard flexure formula for a simply supported centrally loaded beam, using the method of transformed (equivalent) sections to modify the composite beam's moment of inertia (I). Shear strain was ignored because of the large span/depth ratio of the beams. Spaun concludes: (i) Conventional phenol based adhesives provide a more than adequate bond between amino-silane treated wood and fibreglass. (The fibreglass used was already treated with an amino-silane coupling agent which makes it compatible with phenolic resins); (ii) The fibreglass did not delaminate from the wood substrate when subjected to severe moisture conditions or cyclic dimension changes; (iii) Stiffness of bending members was increased significantly with the use of relatively small volumes of fibreglass; (iv) The fibreglass significantly increased the tensile strength of the wooden cores. The combination of increased strength and decreased variability resulted in greatly improved 5% exclusion values (up 50% for 3.5% fibreglass, up 65% for 7% fibreglass).

1.3.14 Slack

Slack (1974) followed the work of Biblis using 3-point bending tests with carbon fibre as the

1.3.14 Continued

reinforcement. His initial results were very variable, but by pre coating the wood with the adhesive (in this case epoxy resin), he produced a set of very consistent results, shown in Table 5 below. Before pre coating, the reinforced samples tended to delaminate, probably as a result of poor glue lines due to glue starvation.

Testpiece Configuration: Position of CF Reinforcement in sample	*Modulus of Elasticity (E)* (GN/m^2)	*Modulus of Rupture (MOR)* (MN/m^2)	*% gain over control sample*
Control (Plain timber)	13.37	107.2	0%
Horizontal band at top	20.26	226.4	67%
Horizontal band at bottom	18.95	179.9	78%
Vertical band at right edge	23.21	191.4	122%
Vertical band through middle	22.22	237.8	35%
Horizontal band through middle	11.03	144.9	35%
Vertical bands on left and right	34.47	277.6	159%
Horizontal bands top and bottom	46.7	392.9	265%

Table 5. The effect of positioning of carbon fibre reinforcement (Slack, 1974)

Slack concluded that there was an increase in Modulus of Elasticity, except for those samples reinforced along the neutral axis. There is an increase in the Modulus of Rupture in all cases. He reported strength (Modulus of Elasticity and Modulus of Rupture, hence stiffness and strength) increases of 250% have been reported in similar tests when reinforced with carbon fibres.

1.3.15 Neil

Neil (1989) studied the enhanced performance of glued laminated structures reinforced with carbon fibre. After extensive consultation, he concludes that his target would be a stiffness gain of 20% using carbon fibres over the equivalent all timber beam. This could then save between 10 and 18% of the timber in a beam 300-450mm deep, thereby paying for the reinforcement. The resulting structure would also look more slender, and be physically lighter. His final results show a 30% stiffness increase using carbon fibres and a 16% stiffness increase using glass fibres. Strength gains were 34.3% and 11.7% respectively. Neil also noted that the carbon fibres on failure has assumed a slew of 15° from the direction of load. If timber loses up to 50% of its tensile strength with a slope of grain of 10°, he argues that this is probably the case for all types of fibre reinforcement.

1.3.16 Doran

Doran (1973) studied the effect of carbon fibre reinforcement of beech in bending. He concludes that carbon fibres do not enhance the Young's modulus of the sample, this may be due to what he describes as 'the cheese wire effect', with the stiff carbon fibres exerting a shear force on the

1.3.16 Continued

laminate. His samples were beech with a single 1mm x 1mm carbon fibre strip, later expanded to include samples with 2 and 3 strips.

No. of Carbon strips	*Load* (N)	*MOR* (N/mm^2)	*MOE* (N/mm^2)	*Specific Gravity*
1	2140	112	4650	0.710
1	1990	104	8140	0.680
2	2540	133	11370	0.706
2	2980	156	11875	0.744
3	2420	127	9650	0.723
3	2340	123	9040	0.692
Control (0)	2000	105	8960	0.722
Control (0)	2360	124	11300	0.668
Control (0)	2245	118	11300	0.782

Table 6. The Effect of Carbon Fibre reinforcement of Beech (Doran, 1973)

Doran showed that carbon fibre lowers the modulus of elasticity, but raises the modulus of rupture. He noted a greater beam deflection and 30% more load at failure when reinforced with the carbon fibres. The beech that was used had a Young's Modulus of 10,375 N/mm^2 and for the carbon fibre E was 110,000 N/mm^2 (ie more than ten times that of beech). The mean MOR for the reinforced samples was 136 N/mm^2 with a standard deviation of 18. The mean MOR for the beech control samples was 118 N/mm^2 with a standard deviation of 11. The working stress (mean - 2.33 x standard deviation) is the same for both types of sample at 92 N/mm^2.

1.3.17 Ng

Ng (1986) produced a thesis on long term loading performance of glued laminated beams with reinforced glue lines. He hoped to show that reinforced beams loaded to 50% of their Modulus of Rupture would suffer reduced creep when their glue lines were physically restrained. His results suggest short term gains of 2% could be achieved with glass fibres and carbon fibres, while kevlar showed a 3% decrease. This was put down to poor wetting of the kevlar fibre. Any improvement in the performance of the glue line is likely to be offset by the fact that thicker glue lines are more likely to contain defects, and any shear force on the glue line will surely produce a crack down the glue line. Whale, Hilson and Rodd (*The elastic stiffness of PRF resins and their influence on stiffness of laminated timber beams*, 1988) suggest that glue lines play a negligible role in overall stiffness.

1.3.18 Claxton

Claxton (1983) studied laminating with a view to producing new shapes and forms in furniture. By citing examples of cantilever chairs which are too flexible in laminated wood, Claxton

1.3.18 Continued

tried to produce new geometries and ways of altering the section thickness of laminates along their length. By introducing jute, hessian, canvas, and heavy duty cotton into the timber cores of his samples, he attempted to stabilise his shapes and eliminate twist. His results show little improvement in either strength or stability.

Thickness	*Material*	*No. of Plies*	*Peak Load* (N)	*Deflection* (mm)	*Stiffness* (N/mm²)
5.5mm	Mahogany	3	200	50.6	0.81
8.0mm	Mahogany	7	855	42	4.76
9.0mm	Beech	6	1020	28.5	7.02
10mm	Beech	7	1105	15	13.33
6.0mm	Canvas/Mahogany	5	415	82	1.12
7.0mm	Jute/Mahogany	5	420	62	1.52
13mm	Mahogany	11	900	9	22.22
13mm	Glass Fibre/Beech	9	2015	150	6.85

Table 7. Deflection and distortion of laminates (Claxton, 1983)

1.3.19 Variability

Claxton's variability was predicted from the work of Goitas (1991), whose work on the strength of laminated beams showed the prospect of very high strength laminations, with high variability.

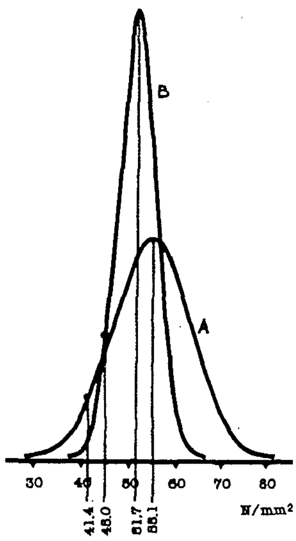


Figure 8. Effect of variability on characteristic values (Pellicane et al., 1986)

Due to the high percentage of juvenile wood and the multitude of knots and associated cross-grain in this material, the quality of available timber used in the furniture industry is in decline, and the general increase in worldwide demand for timber has amplified the problem. It is becoming increasingly clear that the greatest load carrying capacity per fibre will have to be achieved, if wood is to remain competitive with other materials. In order to achieve this high level of material efficiency, forest products will need to be developed which reconstitute solid wood into products which disperse the inherent defects as effectively as possible (Pellicane *et al.*, 1986). The great advantage of defect dispersion is that the resulting product will have a lower variability. This produces higher characteristic values in design. This is illustrated in Figure 8: product A has a mean bending strength of 55.1N/mm² and a standard deviation of 8.3, product B has a mean of 51.7 N/mm² and a standard deviation of 4.1. *Characteristic value = mean - 1.645 x S.D.* This reveals characteristic strengths of 41.4 and 45.0 N/mm² for A and B respectively, therefore B is the more efficient product.

1.3.20 Whale

According to Whale *et al.,* (1988), the glue lines play a negligible role in the overall stiffness, yet this assumes that the laminate is acting as a whole and that the glue lines are at least as strong as the timber. It is apparent that using fibre reinforcement produces a new problem - glues such as urea formaldehyde are produced for wood bonding and will not adhere to the fibres. They will only produce a glue line if the weave is open enough to allow some glue to soak through the fibre mat, this in effect bonds the wood laminates together with a glass reinforced glueline.

1.3.21 Bullen

When properly designed and constructed, glued joints are an excellent form of connection between the components of structural elements. The area at the intersection of such components is often quite large and unit stresses can therefore be of a low magnitude. It is assumed that in joints between reasonably thick materials stresses are uniformly distributed and the creep can be disregarded (Bullen *et al.*, 1986). The basic concept in glued joint design is that loads should be carried in pure shear, and under these conditions, failure will always occur in the timber and not in the adhesive layer between the components. The limit to joint design is thus the appropriate value for shear parallel to the grain given in BS 5268: part 2. The often repeated *'The glue is stronger than the wood itself'* certainly applies to softwoods and medium density hardwoods, but extremely high density hardwoods have sufficient shear strength parallel to the grain to exceed the cohesive strength of the glue line. It is broadly true that as density increases, the proportion of wood failure, in joints loaded in pure shear, decreases and is almost absent in species with densities above about 850-900 kg/m^3, such as greenheart *Octote roddeii* (1009 kg/m^3) and ironbark *Eucalyptus paniculata* (1137 kg/m^3).

1.3.22 Quality of Bonding

Bullen *et al.,* (1986) states that the accuracy taken in surface preparation is reflected in the bond quality. In order to develop maximum bond strengths timber should be cleanly machined or planed not more than 48 hours prior to gluing. Where timber is to be laminated, machining to give a flat parallel faced stock is of prime importance to ensure an accurate fit. Although adhesives specified to BS 1204: part 2 are gap filling and in theory capable of performing satisfactorily in films up to 1.3mm in thickness, this should be regarded as a safety measure.

1.3.23 Fibre Directionality

By using composites in the form of woven fabrics, fibre directionality is lost, therefore the fibre reinforcement is not being efficiently. The gains in stability that woven fabrics offer may offset any perceived loss in performance over unidirectional reinforcement - timber loses up to 50% of its tensile strength with a slope of grain of 10° (see 1.3.15, Neil). Woven fabric composites

1.3.23 Continued

offer a combination of light weight, flexibility, strength and toughness. Two dimensional fabrics exhibit good stability in the warp and fill directions, and the bidirectional reinforcement enhances impact resistance and damage tolerance. Triaxially woven fabrics, made from three sets of yarns at 60°, offer improved isotropy and in-plane shear rigidity. Improving stability is especially important when laminating wood, where the natural resilience of the material tries to open up bends after leaving the mould, leading to distortion of the finished laminate.

1.3.24 Design with Fibres

Composites are mainly used for shell structures in layered form and each layer is a large piece of cloth. As a consequence, the fibres through the whole structure tend to end up in a few standard directions (commonly 0°, 90°, +45°, -45°), producing properties which cause it to be thought of as an homogeneous material, able to carry stresses in any direction. This enables the important issue of 'fibre directionality' to be avoided. If it is assumed that the material can carry reasonable loads in any direction, then it is not necessary to know which direction the load is actually acting in within the structure. However at any point in the component, because the fibres have been put in the right directions or in the right quantities to carry the load efficiently. The fundamental design opportunity offered by the fibrous nature of the material to produce high strength and low weight components has been lost. In fact it has been worse than lost, because it has generated a cost penalty caused by having to use larger component proportions (having sufficient fibre reinforcing) in order to make it strong enough. *'Furthermore, establishing the strength of these components requires extensive mathematical analysis, because failure usually occurs at such weak points, where the directions and strengths of the fibrous content of the material are mismatched to the directions and strengths of the stresses that are being carried'* (Platts, 1995).

1.4 Design Using Composites

Although much of the work in this field has been carried out with a wood technology bias, the designer can play a role in the development of its use. *'Current research in the field of design history has begun to benefit from interdisciplinary scholarship, which has put brought fresh ways of looking at furniture and greater emphasis on its production and consumption'* (Edwards, 1994). Properties of the fibre reinforced component can benefit greatly from the shape awareness skills of the designer. *'Designers with a good sense of shape can achieve in no time what a computer can only laboriously mimic'* (Platts, 1995). Composites are an area in which high performance products depend on design and production skills in equal measure, and quality is achieved by the careful development, practising and verifying (ultimately by test) of these twin skills. Glass reinforced wooden laminates can be produced without any fundamental changes in equipment or lay-up procedures so existing production skills can be utilised.

1.4.1 Technology versus Construction

Technology and construction are closely related domains that reciprocally influence each other. Forms and connecting elements in furniture are frequently based on available materials and manufacturing processes. Likewise, certain constructions may call for specific manufacturing technologies. *'The designer is, however, responsible less for the technology and more for the construction'* (Schwartz-Clauss *et al.*, 1996). The latter is one of the central challenges for designers, for it decisively determines how the furniture can be used and how comfortable it is. New species like swivel chairs, folding chairs, or chairs with cantilever bases were the product of developments in construction. *'New materials bring new designs, the four legged chair looks the way it does because the raw materials dictate, in part, what it would do, and tradition fills in as a guide; a chair made of plastic, however, could have many more legs or none. It could be a ball, cube, cone, hard or soft'* (Newman, 1972).

1.4.2 Edwards

Edwards points out that the furniture industry has an apparent conservatism towards economic, technical and product design matters, and the industry has a rather selective adaption of new developments to suit themselves. Technology and the manipulation of materials in the twentieth century has clearly brought about some far reaching changes in the furniture industry. However, the enduring nature of the trade resulted in indirect progress, which arose from the use of spin-offs from other fields of endeavour, especially wars, transport, and architecture. This has resulted in an industry that remains a compromise between mechanisation, standardisation, and individual craft. *'A chair is the essential structure. Designing a chair can't be a stylistic interpretation. It has to be an integral and essential event. It can't just hang another coat on four legs and a seat.'* (Frank Gehry, 1992)

1.4.3 'One Piece' Designs

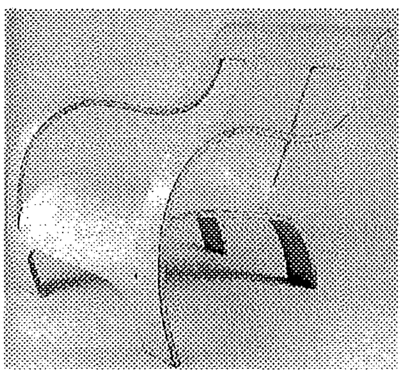
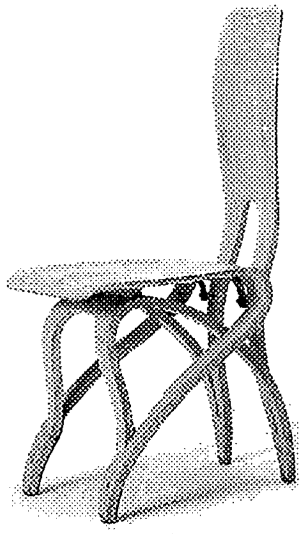


Figure 9. Plywood Armchair, Gerald Summers (1933-4),

In the history of industrial design there have been many attempts to shape everyday objects in only one piece of semifinished industrial material like rod, tube, wire or sheet. The armchair by Gerald Summers (Figure 9) illustrates the ideal unity of material, production and form. This simple construction dispenses with connectors and almost with off-cuts, using a single sheet of plywood. Following a simple pattern, Summers separated the back legs from the back and armrests and bent the segments thus created in different directions. The result was an organically shaped armchair involving low material and labour inputs. Possibly the chair was conceived for use in the tropics.

1.4.3 Continued

With its smooth surface and lack of metal connectors, it is hygienic and deteriorates only slowly. In his own company, Makers of Simple Furniture Ltd, founded in 1929, Summers produced only 120 units of the chair. The economy of production, requiring only four basic steps, and a cold moulding process made this single-sheet bent plywood chair an exciting proposition. Despite the constructive advantages, the production costs of the chair and thus the sales price of the chair were higher than the designs of the popular Scandinavian designer Alvar Aalto, whose similar chair 'Paimio' (see Figure 11) was first shown in London in 1933. It was certainly also a disadvantage that the back legs of Summer's chair could not withstand great dynamic stress and the back legs snapped easily. The retail price of the current 1996 reissue is £1200.



Carlo Mollino designed a chair duo, 'male' and 'female' where the seat, back and legs are all made from laminated wood. The back legs are a continuous extension of the backrest, and via a bow lead to the front legs, which in turn become the seat. The chair looks as (see Figure 10) as though it is built from a slit and bent rectangular plate (like Gerald Summer's plywood armchair, Figure 9), but in processing the chair, parts of the seat, base, and backrest would normally overlap. This requires costly individual production involving craftsmanship. Mollino apparently found the resulting fascination with how the structure managed to stand to be well worth the effort. The chair was only manufactured for a short period in 1953, due to the high production costs imposed by this construction.

Figure 10. Sedia per la Casa Cattaneo, Agra 'feminine', Carlo Mollino (1953)

1.4.4 Aalto

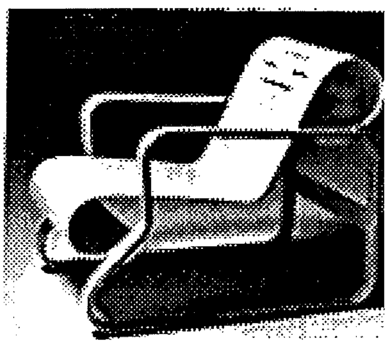


Figure 11. Chair 41 'Paimio' Alvar Aalto (1930-33)

Architect Alvar Aalto's Chair 41 was designed for use in his Paimio Sanatorium. His aim was to make wood elastic and, to this end, he developed a chair which had a unified plywood seat back curved in two dimensions to match the shape of the body, with arms of laminated birch glued on to the sides. He was, in essence, interpreting the principles of tubular steel furniture in wood and thereby producing pieces which blended as easily into private house as into a public space or institution. The design shows the emphasis on the silhouette which encouraged Aalto's many experiments with materials and form. Lightness, elegance and transparency became priorities in his new architecture.

1.4.5 Alternative 'One-Piece' Design

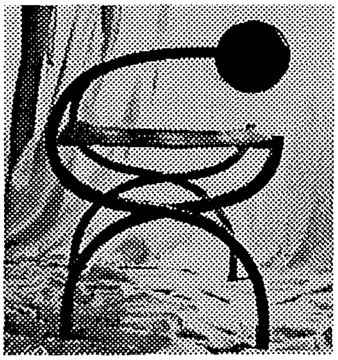


Figure 12. Ash chair, Lyndon Buck (1988)

Figure 12 shows an alternative 'one-piece' design, with the structure made from two sections, moulded using one former. This greatly simplifies stress calculations and subsequent construction, as well as producing a shape which has a graceful geometry. The section of the laminate is thin enough to appear graceful, and to allow a small amount of 'give' in the backrest, which aids comfort. As only two examples were produced, the long term performance of the chair is difficult to assess. The main stress points will coincide with the holes in the laminate to take steel rod, on which the seat pads are fixed. If the laminate was reinforced with a fibre composite, the stress raising effect of the holes could be counteracted with extra reinforcing around the affected areas.

1.4.6 Jacobsen

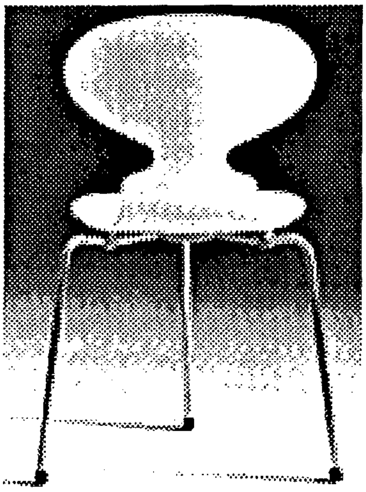


Figure 13. 3100 (Ant), Arne Jacobsen (1952)

In the early 1950s, the Danish Furniture Industry adopted plywood moulding, significantly reducing the need for complex structures. The 'Ant' is an outstanding example of this newfound simplicity. It consists of only a few parts, can be produced at low cost, and is extremely lightweight. The arrangement of the three steel tube legs attached to the underside of the plywood seat in the centre enable it to be stacked. Charles Eames and Erno Saarinen had already produced a three dimensional chair shell in the few prototypes of their 'Organic Armchair' in 1940-41. They tried to prevent breakage between seat and backrest - where dimensional distortion is greatest - by leaving a gap in the material, whereas Jacobsen approached the problem from the outside. He narrowed and reinforced the conjunction of the differently arched surfaces of seat and back by means of additional veneers. This guaranteed that the backrest was both stable and flexible, and its characteristic curved waistline and thin legs earned the 3100 the popular epithet 'Ant'.

1.4.7 Mutant Materials

A recent show *'Mutant Materials in Contemporary Design'* at The Museum of Modern Art, New York presented 200 products that provide examples of material modification or technological process. The show concentrated on industrial production and specifically the technical, formal and manufacturing developments in materials that are shaping the form and function of products today. The aim of the show seems to be to prepare us for a new age where these materials will

1.4.7 Continued

transform our lives - The Composite Age. The development of composites has come on in leaps and bounds towards the end of the 20th century. Alberto Meda's LightLight chair - made of Nomex honeycomb sheathed in epoxy, embedded with carbon fibres for strength - weighs less than 2 pounds. Marco Ferreri's Less chair uses fabric and softwood layers thermally bonded together and moulded. The result is a seat with a softness and flexibility which belies the austerity of the form. *'Where once the designers options were limited by the physical constraints of the material, now it seems the only constraints are imposed by the limitations of their imagination'* (Rashid, 1995). Experiences of the show are reported to be both exciting and disconcerting. Exciting in that it reveals the new possibilities that materials may soon offer the designer, disconcerting in the sense that materials are no longer what they appear to be and their changing character may soon transform the physical landscape we have long taken for granted. With new technologies and materials, objects can be produced more rapidly, in far fewer numbers and with more variety that allows for increasing consumer choice and personalisation. Design is an activity that involves the complete understanding of behavioural and social needs and changes - products must go beyond materials, beyond science, beyond technology. Janet Abrams visited the MoMA show, and says *'as one wanders around one realises that, paradoxically, many of these encounters deflect rather than deepen ones understanding of the substance at hand; the predominant experience is of coldness to the touch.'* These materials are after all not 'natural' but inert and inorganic, and incapable of feeling warm to the touch. A composite may appear too clinical for many tastes. *'Designers and manufacturers lack knowledge and sensitivity concerning human needs and capabilities, and are out of touch with the way things really work.'* (Norman, 1990). A combination of wood and composite in the form of a laminate could give the best of both worlds - the look and feel of wood with the enhanced mechanical properties of a composite.

Figure 14. LightLight, Alberto Meda (1987)

1.4.8 The Composite Age

Meda's LightLight chair (Figure 14) uses vertically aligned carbon fibre in the unfeasibly thin legs, thus increasing the stability in vulnerable areas. The fibres here enable a reduction to rudimentary, fragile-looking shapes without construction details being visible. Meda (1987) described the development process: *'During the first phase the structural problems were discussed without any consideration of economic factors. In the current second phase, a study is*

1.4.8 Continued

underway to explore the ins and outs of the industrial production of the product. At the moment production is still by hand, even though at a high tech standard'. This study resulted in fifty examples of the chair being produced in 1987-8 and sold at a price of about DM 2,200 (approximately £1000). With regard to cutting the carbon fibre and its further mechanical processing, replacing work by hand involves very expensive machinery. Since this did not allow any reduction in production costs, the manufacture of the chair was discontinued in 1988 (von Vegesack *et al.*, 1996). As Rashid says, a suitable name for the current epoch might be the Composite Age. Since 1979, the worldwide volume production of plastic has been greater than that of steel, heralding the Plastics Age. The development of composites has come on in leaps and bounds towards the end of the twentieth century. Advanced and sophisticated materials are emerging from laboratories around the world, whilst established composites are becoming cheaper as quality and usability is improving.

1.4.9 Gehry

Technological changes have made new uses of familiar techniques and materials. Frank Gehry's Cross Check chair for Knoll in bent-white maple wood strips, is a complex innovative use of a furniture standard like plywood. Gehry's technique used the concept of basket work to weave thin laminates into chair shapes which had the seat and support integral with each other: *'Now structure and material have freed furniture from its former heaviness and rigidity, it really is possible to make furniture that is pliable, springy and light'*. With his Knoll collection, Gehry aimed to create furniture whose unified seat and structure would require no extra supporting frame. He created 115 prototypes before settling on seven final pieces. *'I started by thinking about the chairs I knew that had the qualities of integrity and flexibility. Certainly there was the Thonet chair, but as far as I was concerned, it had the problem of being an innovative structure compromised by a separate attached seat. Then there was Aalto, but his pieces were a little harder and also separated their elements - a heavy support structure and a light seating structure. Eames got flexibility with steel and rubber joints, which at the time was a breakthrough, but still didn't fit my definition of a complete, one-piece chair with structure and surface completely integrated'*. (Gehry, 1992). Three years after the production run, Gehry said he wanted to take the concept, which started as intuition and then worked out through trial and error in the workshop, and maximise the efficiency of the forms from an engineering standpoint.

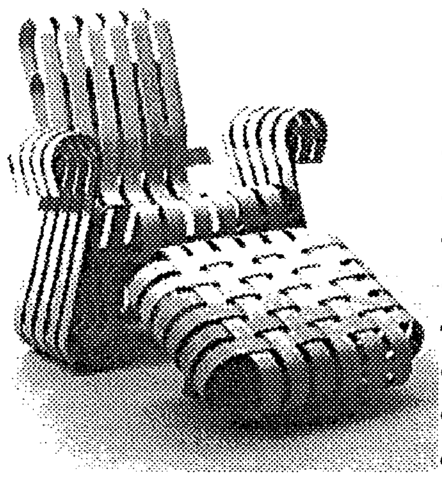


Figure 15. Power Play and Ottoman, Frank Gehry (1991)

1.4.10 Platts

Fibre reinforced composites raise interesting design and manufacturing issues because they present their strengths (and stiffness) as patterns of fibres (Platts, 1995). Put another way, the fibres within a component formed from a composite have directional and linear attributes which give the component its particular properties, unlike a component formed from an homogeneous material which has the universal properties of the material used. This fundamental difference raises questions about the desirable directions of fibres within a component, and how fibres might best be oriented in complex shapes and forms. Fibrous materials like glass and carbon fibre, cloth and paper, take similar cloth and paper like forms. It is therefore assumed that any component made in composites will be essentially two dimensional in nature - generating a skin structure made up of layers of cloth, to which the resin is added, layer by layer. This assumption is so strong that, to designate special multi-layer thick weaves, the words 'three dimensional' are used to indicate the inclusion of some fibrous structure in the 'thickness' direction. By asking a simple 'shape' question, a new approach to the design process requires radically different steps in thought and leads to a fundamentally more efficient component. The question which gives the guidance is simply, *'What is the component actually trying to do?'* In general, in a material strength sense, components carry loads from load points and deliver those loads to support points. If we can visualise how the loads are trying to 'flow' through the component then we can put the fibres in the right directions to act act as 'ducts' for those loads to 'flow' through.

1.4.11 Design Conclusion

'Galloping furniturisation may be diagnosed as an intolerable tension between culture and technology. Pure technology would probably bring furniture to an end, or at least render it invisible' (Banham, 1970). Up until the 1960s, the major furniture breakthroughs of this century have all depended in one way or another on technological advances, yet the mass taste for furniture in this century has been conservative rather than innovatory. Having gone technology mad in the 1950s and 60s, the furniture industry in Britain and much of Europe has regressed and is facing the future through the past. Few real advances in modern furniture have come out of direct experimentation within the area itself, but rather as spin offs from other fields. *'The dualism between innovation and the conservative tendencies of the mass market has been mirrored in the twentieth century furniture industry'* (Sparke, 1986). While the industry has mainly developed into a system which has a high degree of divided labour, mechanisation and standardisation, it has also retained a craft-oriented approach.Those countries which have

Figure 16. Mocean chair, John Greed (1991)

1.4.11 Continued

established strong international reputations for modern furniture (for example Scandinavia and Italy) have been able to retain a craft basis for their furniture production and to cater for fairly affluent markets. From the Arts and Crafts Movement, to the Bauhaus, to the Pop Designers and the High Tech Movement, a furniture avant-garde has existed in this century experimenting with new ideas, new materials and new forms in order to bring furniture into line with cultural change. Most of it's statements have been *'unashamedly artistic, radical, high minded and, above all, exclusive. It is, after all, the essence of the avant garde to be one step ahead of the rest of society'* (Sparke, 1986). Furniture, and in particular the chair, has been the subject of countless efforts at visual innovation, yet many of these owe more to the whims of fashion than to advances in technology. The impact of plywood dramatically altered the appearance of much modern furniture, yet composites, which have been embraced in the worlds of aerospace, transport and sporting goods, have been sadly neglected by the avant-garde furniture designers. Chairs like the Mocean (Figure 16) show that composite materials, with their light weight, high strength and stiffness, can create forms which would be have been unthinkable a generation ago. There is more to design than form however - the psychological role of furniture as a sustainer of conventional values expresses itself in the continued use of wood and other traditional materials, and this must be taken into account before using composites. *'No amount of structural integrity can compensate for the loss of loveliness'* (Harvey Probber, 1959).

1.4.12 Composite Beam Design Theory Summary

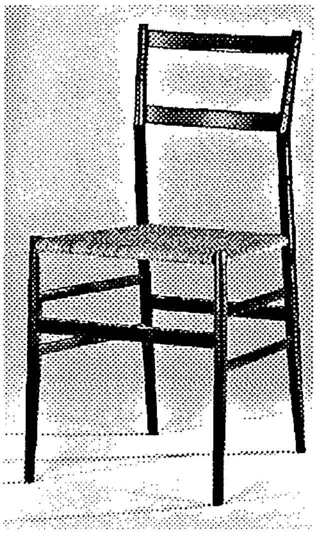


Figure 17. Superleggera Gio Ponti (1951-7)

Gio Ponti described his Superleggera (Super lightweight) chair as *'the normal, true chair, the chair-chair devoid of adjectives.'* The ash frame is made from pieces with a triangular cross section with edges only 18 mm long. A system of slot-in connectors creates a chair which weighs 1.7kg yet which can withstand a fall from four storeys. Meda's Light-Light is less than half the weight of the Superleggera, yet maintains its structural integrity by means of rigid Nomex polyurethane foam enclosed by carbon fibres aligned in the direction of stress. In order to design furniture to the material's limit in this way, accurate modelling and understanding of the material's behaviour is necessary. For wood-fibreglass beams, many different methods have been used to compare actual values with test values. Simple bending theory states that:

$$\text{deflection } (\partial) = \frac{WL^3}{48EI}$$

where W = load, L = beam length, E = modulus of elasticity and I = second moment of area of the beam. This method does not include deflections due to shear and

1.4.12 Continued

the hyperbolic relationship devised by Timoshenko (1955), which relates the span/depth ratio of the beam with its modulus of elasticity by the hyperbolic relationship:

$$E' = \frac{E}{1+0.3(^{2}/_{L})^{2}\,^{E}/_{G}}$$

where E' is the experimental value of E at a specified span/depth ratio (L), E and G are pure modulus of elasticity and modulus of rigidity, respectively. Wangaard (1964) used two methods. The first neglected core shear; the second took shear into account and was more accurate. Method 1 stated that:

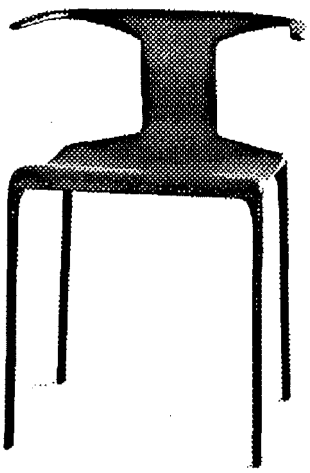


Figure 18. LightLight, Alberto Meda (1987-8)

$$E = \frac{E_f I_f + E_c I_c}{I}$$

where E is the elastic modulus, I is the moment of inertia, c and f are subscripts for core and fibre respectively. This (*equivalent sections*) method had a +15% to +52% error in prediction, since it still ignores shear deflections. Method 2 considered axial strain as a result of the compressive and tensile stresses set up under load and deformation of the core in shear. Errors of prediction went down to -3% to -20%. The component of shear deformation that contributes to the deflection of the beam is dependent on the span/depth ratio, and can be calculated by the hyperbolic relationship:

$$E' = \frac{E}{1+0.3(^{2}/_{L})^{2}\,^{E}/_{G}}$$ (Timoshenko, 1955).

Biblis (1965 a) showed that the effective span/depth ratio of a composite beam may be much lower than the actual span/depth ratio. Via Kuenzi (1959), Biblis states that the deflection of a beam (y) has a part due to bending:

$$y_1 = \frac{PL^3}{48EI}$$

and a part due to shear:

$$y_2 = \frac{PL}{4N}$$

where P is the load within the elastic region, L is the span, and

$N = \frac{(h + c)^b}{2} \times G_c$ (h = depth, c = core depth, b = width, G_c = modulus of rigidity of core).

Biblis' errors were low, except for low density timbers, where -10% to -30% errors were shown. Rowlands *et al*., (1986) stated that elastic stiffness

$$EI = \frac{Pl^3}{48\partial}\left[1 + 1.2(^{h}/_{l})^{2}\,^{E}/_{G}\right]$$

1.4.12 Continued

and $^{E}/_{G}=16$, where ∂ is deflection, h is beam depth l is beam span, and G is shear modulus. Results showed a structural stiffness EI decrease due to the addition of the fibre reinforcement. This shows the shear contribution in reinforced beams is greater than that expressed by the second term of the above equation with $^{E}/_{G}=16$. Moulin concludes by saying that the increased transverse shear effect of flexed laminated composites is well recognised. Moulin *et al*.,(1990) used a relationship for layered systems:

$$E_c = \frac{1}{I_c}\sum_i E^i \cdot I^i = \frac{1}{I_c}\left[\sum_i E^i_b \cdot I^i_b + \sum_j E_f \cdot I^j_f + \sum_k E_c \cdot I^k_c\right]$$

where c is subscript for composite. Good agreement was found between predicted and experimental results. Shear modulus was neglected as the span/depth ratio was 15.5:1. A value of 14:1 is the standard value for testing of wood samples. The effective MOE of wood varies hyperbolically according to the span/depth ratio (see Figure 7), with the composite beam having the same span, but a *vertically transformed* depth. This transformed depth will be the depth of a hypothetical beam having the same width, but in which the faces have been replaced with equivalent core material, creating an *equivalent section.*

1.4.13 Shear deflection of Wood Beams

In addition to the deflection of a beam due to the elongation and compression of fibres from axial stresses, there is a shear force, and a further deflection due to shear stresses. In computing deflections of wood beams, the deflection due to shear is usually not specifically considered. By neglecting the deflection due to shear, errors of considerable magnitude may be introduced in determining the distortion of a beam. This is especially true for short span/depth ratios, and for laminated beams of two or more species or materials (Biblis, 1965 b). Biblis also states that a difference between the modulus of elasticity in bending at 14:1 span/depth ratio and the pure modulus of elasticity in bending of as much as 37% was noted in his work. The modulus of elasticity of hickory is given as 13 to 15.5 GPa (Anon., 1989), depending on origin. Biblis calculates E to be 21.5 GPa at 14:1 span/depth ratio and 26.754 GPa for pure tangent modulus of elasticity in bending. Modulus of rigidity was calculated as 672.5 MPa. In his paper *Shear Deflection of Wood Beams* (1965), Biblis shows that for a hickory beam with a span/ depth ratio of 8:1, the shear deflection accounts for up to

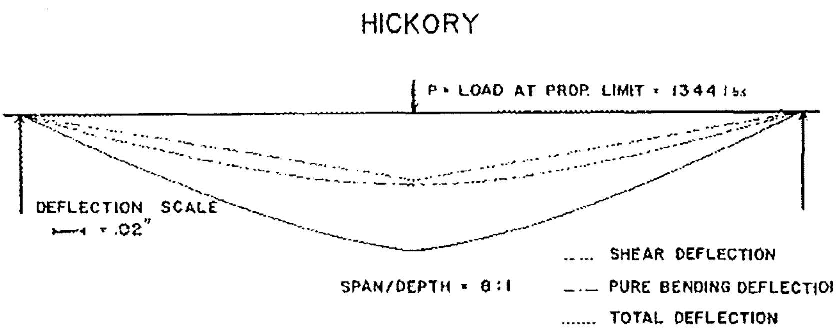


Figure 19. Elastic curve for hickory beam, 8:1 span/depth ratio

1.4.13 Continued

48.25% of the total deflection (see Figure 19). The contribution of shear deflection varies from species to species. This depends on the ratio of pure modulus of elasticity (E) to modulus of rigidity (G). Hickory has a E/G value of 39.79. Teak, with a E/G value of 10.12, had a 19.2% shear deflection contribution at the same span/depth ratio. For beams with a 24:1 span/depth ratio, shear deflections were much lower. For hickory, the shear contribution was 9.4%, for teak it was 2.6%. The elastic curve is not smooth from one support to the other. Since the elastic curve is the result of both shear and bending deflections, and since only the curve for the shear deflection component has a has a point of discontinuity, the degree of discontinuity of the elastic curve increases as the percentage of shear deformation increases. This is the result of Biblis' assumption that all plies are free to warp under shear stress. This is not the case directly under a point load at midspan, and the calculated deflection is consequently greater than the real deflection. This discrepancy does not change significantly the relative contribution of shear deflection, especially in beams of small span/depth ratios, or where the ratio of modulus of elasticity to modulus of rigidity is high. The shear influence on the deflection of wood beams can be considerable, approaching or exceeding the amount of deflection due to pure bending. Fibre reinforced wood beams may well include even larger shear deflection contributions, since their effective span/depth ratios are low.

1.5 Materials

Composite materials are stiff, strong and light. Though expensive, they are finding increasing use in aerospace, transport and sporting goods. They are very different in character from wood and metal, so existing components require careful redesign when composites are used. Design with composites requires a sound understanding of their properties, and they *will* alter the way furniture is made in the future. With these materials, more than any other, properties can be designed in; the characteristics of the material itself can be engineered. This gives designers with a good understanding of the material's behaviour a head start in an increasingly innovative market. Composites do have inherent faults, but these can easily be overcome once they are understood. For example the catastrophic failure of stiff, strong carbon, ceramics and glass can be avoided with fibrous composites. Polymeric matrices have low stiffness and are ductile, thereby allowing composites to exploit the great strength of carbon and ceramics while avoiding the catastrophe: the brittle failure of fibres leads to a safe and progressive failure.

1.5.1 Advantages of Composites

Making good fibre composites is not easy, but the technology is improving, and the benefits can be enormous. A 50% epoxy/50% uniaxial carbon fibre reinforced plastic can have a comparable Young's Modulus to steel with one fifth of the density. The stiffness, strength and toughness of

1.5.1 Continued

a composite are controlled by the type and volume fraction of the fibres. By engineering the material, holes and fixing points can be reinforced, orienting or laminating the fibre weave can give directional properties, and stiffness can vary in a controlled way across a component. Composites overcome many of the deficiencies of existing furniture materials. The problem lies in their cost. There is however very little waste created in their use, and they can be used with, for example, high quality cardboards to produce an ecologically sound hybrid. A similar technique was used in the fuselage of the *Mosquito* aeroplane, where a sandwich of plywood-balsa-plywood or 'stressed skin' plywood construction was pioneered (Logie, 1947). All the stress was carried by the two ply skins and the balsa kept the skins in position and so prevent them buckling, acting like a web of a rolled steel joist. They can certainly do the same job as other engineering materials but with less bulk. In the quest for improved performance, including less weight, higher strength and lower cost, current engineering materials frequently reach their useful limit. Composite materials can present solutions to this problem through careful selection and design. One of the key factors of composites is their very high strength-to-weight ratios.

1.5.2 Definition of Composites

A composite is a mixture of two or more constituents, the matrix and fibres. Both need to be present in a reasonable proportion (5%), and the properties of the composite must be noticeably different from that of the constituents. A composite may have a ceramic, metallic or polymeric matrix. Generally polymers have low strengths and Young's Moduli, ceramics are stiff, strong and brittle, and metals have intermediate strengths and moduli together with good ductility. The second constituent is the reinforcing fibre (or particles) which reinforce the mechanical properties of the matrix. Fibrous reinforcements have lengths much greater than their cross-sectional dimension. The ratio length/cross-sectional dimension (known as the aspect ratio) varies considerably. Long fibres with high aspect ratios give continuous fibre reinforced composites, while short fibres with low aspect ratios give discontinuous (chopped) composites.

1.6 Glass Fibres - Introduction

Glass fibres can be categorised into two sets: those with a modulus around 70 GPa and low to medium strength (E, A, C, ECR), and those with a modulus around 85 GPa and high strength (R and S2 glass). E glass fibres are reasonably strong but very susceptible to damage during manufacturing and processing which reduces strength. R and S2 glasses are very strong and must be carefully handled to ensure that the fibres are not degraded before incorporation into the composite. The density of glass fibres is about 2.5 g/cm^3, which is high in comparison to other reinforcing fibres but by metallic standards very low (aluminium: 2.8, steel 7.8 g/cm^3).

1.6 Continued

Family	Fibre	Elastic Modulus (GPa)	Tensile Strength (MPa)	Ultimate Strain (%)	Density (g/cm³)
GLASS	E	72.4	2400	3.5	2.55
	A	75	3030	2.5	2.51
	S2	88	4600	5.7	2.47
	R	86	4400	5.5	2.55
	C	69	3030	4.8	2.49
ARAMID	49	125	2750	2.4	1.44
	29	83	2400	1.3	1.48
CARBON	XASHS	235	3850	1.64	1.79
(Grafil®)	HMS6K	370	3450	2.9	1.79
CARBON	T300	230	3530	1.5	1.77
(Toray®)	T800H	294	5590	1.9	1.81
	T1000	294	7060	2.4	1.82
	M40J	390	4200	3.1	1.83

Table 8. Fibre properties (Broutman, 1969)

1.6.1 Advantages

Glass fibres are the most commonly used fibres. They have good properties with respect to weight, very good processing characteristics and are relatively cheap (see 1.3.11). There are many different grades for use with different matrices and varying manufacturing requirements. Strands of glass can be chopped into 2.5-5cm lengths to make chopped strand mat (low solid content, used for finishing), wound parallel to make roving, or twisted to form yarn for weaving into woven roving or glass fibre cloth (silk-like, for high grade applications).

1.6.2 Physical properties

E glass fibres with a modulus of 70 GPa can only produce composites with a modest moduli. As an absolute limit, assuming unidirectional fibres and the highest feasible volume fraction of about 0.7, the stiffest E glass composite has a modulus of 50 GPa. At right angles to this, in the transverse direction, the modulus approaches that of the resin itself at about 4 GPa. An E glass laminate with a volume fraction of 0.2 would have a modulus of only 5 GPa. E glass laminates are therefore relatively flexible. The use of R or S2 glass improves the composite modulus to about 60 GPa for unidirectional and 20 GPa for bidirectional woven fabrics, but they are more expensive than E glass and there are limited types and resin compatibilities.

1.6.3 Insulation

Glass fibres are insulators of electricity and heat, and are transparent to radio-frequency (RF)

1.6.3 Continued

radiation, hence their use in radar applications, and their compatibility with dielectric heating. Polymeric matrices will degrade at much lower temperatures than the reinforcing glass fibres.

1.6.4 Chemical properties

E glass is resistant to most chemicals but is attacked by both mild acids and mild alkalis. Again, chemical resistance depends on the matrix protecting the fibres. Other glass fibres, notably ECR glass, show improvement over E glass in a corrosive atmosphere.

1.6.5 Fatigue

E glass GRPs are more sensitive to fatigue than composites made with higher modulus fibres. Because of their low modulus they work at strains which approach the cracking strain of the matrix, so allowing a fatigue process to occur and so producing a reduced fatigue life.

1.6.6 Creep

Unidirectional reinforcement is the most creep resistant construction. This is followed by bidirectional woven construction which has the disadvantage that the fibres tend to straighten out under loading, thus increasing creep. The least resistant construction to creep is chopped

1.6.6 Continued

strand mat which suffers from relatively short fibres, thus making the composite creep performance more dependent on the matrix.

1.6.7 Fibre orientation

Fibre orientation plays a crucial part in the strength of a composite. Fibres that are unidirectional usually have the best performance, but woven fabrics are much easier to use, store and lay-up.

Material	*S.G.*	*Tensile Strength*	*Strength for Weight*	*E* (MPa)	*E/S.G.*
Parallel Glass Fibre	1.85	1000 Mpa	550 Mpa	35000	19000
Woven Glass Fibre	1.85	500 MPa	280 MPa	17000	9500
Mild steel	7.8	400 MPa	50 MPa	210000	27000
High Tensile Steel	7.8	2000 MPa	260 MPa	210000	27000

Table 9. Parallel and Woven Glass Fibre/Steel comparison (Rowlands et al., 1986)

Figures from Table 9 show that fibreglass is stronger than steel, especially for it's weight, but not nearly as stiff, even when it's lower density is taken into account. It is also worse than wood but like wood, comparisons depend on how many directions you want to be strong in. The best case is when all fibres are in one direction yet engineering applications for unidirectional

1.6.7 Continued

materials are limited. When 50/50% are crossed at right angles you get a material like plywood with half the strength of a unidirectional material at 0° and 90°, but rather less at 45°. For truly uniform properties in all directions in a fibrous sheet material there are several arrangements of fibres which will work, with a strength and stiffness 33% that of unidirectional. With chopped strand mat it is difficult to get 50% fibre into the mix, so strength and stiffness is not so great, although it is still better, strength for weight, than mild steel.

1.6.8 Stiffness

Stiffness is where reinforced plastics, particularly glass fibres, cannot compete with metal and wood. For car bodies, steel tubes are used as reinforcing. Metals are isotropic, with equal properties in all 3 dimensions. It is almost impossible to get isotropic properties in a fibrous material due to the difficulties of packing fibres tightly and pointing in 3 directions at once. Strength of a 3D random arrangement is 16% that of a parallel system. Fracture of glass fibre is very bad. Resin is little better, but together the composite is reasonably tough, hence the use of GFRP for crash helmets. A crack will soon encounter a fibre but the material, not the fibre, will break at the interface between glass and resin and spread along the fibre (called crack-break) so the fibre breaks from the matrix and the crack in the resin will fork when it meets a

1.6.8 Continued

fibre so the number of cracks multiplies. Before the composite can break, all the reinforcing fibres must break. Since the strength of glass is variable, fibres do not break in any one plane but fractures occur in a scattered or random manner through a considerable volume of material. Fibres must be pulled out of their holes which causes a great deal of friction and this is where most of the work of fracture of a composite comes from.

1.6.9 Manufacturing GFRP (Glass Fibre Reinforced Plastic)

As much fibre as possible must be packed into the moulding as fibres are at least ten times stronger than the matrix so the strength of the finished material is proportionate to fibre content. The solids content of loosely packed individual fibre mats is very low. Fibres pack best in parallel bundles, as threads or yarns. Each yarn contains hundreds of individual fibres, each of which is continuous so only a little twist will hold it together. Cheap moulds can be used (and easily changed) and hydraulic presses are unnecessary. Polyester and epoxy resins are best, as they set at room temperature on contact with a catalyst and with negligible pressure. This method is cheap, with alternate layers of cold-setting resin and glass mat or fabric laid up over a simple plaster mould and left to set. It is labour intensive but good for large or one-off mouldings. However no two mouldings are the same and it can be difficult to predict the strength of

1.6.9 Continued
individual parts. For reliability mouldings must be set in a dry, warm, controlled atmosphere. For large scale production a matched pair of heated steel dies are used, which are extremely expensive to produce and difficult to alter (see 1.1.2 Eames DAR chair).

1.6.10 Summary
The market for glass fibres is limited by their relatively low stiffness. They also suffer from stress corrosion whereby a GFRP under stress in a corrosive atmosphere can fail catastrophically at very low stress compared to the fracture strength in air.

Material	*Density* (Mg/m^3)	*E* (GPa)	*Strength* (MPa)	*E/Density*	*E/Strength*
CFRP 58%C/epoxy	1.5	189	1050	126	700
GFRP 50%G/polyester	2.1	48	1240	24	620
KFRP 60%K/epoxy	1.4	76	1240	54	886
High strength steel	7.8	207	1000	27	128
Aluminium alloy	2.8	71	500	25	179

Table 10. Density Comparisons (Rowlands et al., 1986)

1.7 Carbon Fibres
The properties of wood cannot be easily altered as it is a natural product, while the strength and toughness of metals can be modified, but not the stiffness. Stiffness is important as much of a structure is in compression and compression parts are usually struts and plates which are thin in proportion to their length. Members of this sort exhibit 'Euler collapse' caused by elastic buckling due to lack of stiffness. Young's Modulus/Specific Gravity is almost identical (25000 MPa) for iron, steel, titanium, glasses, aluminium, magnesium, and spruce parallel to the grain. Carbon is ten times as good as these.

Fibre	*Specific Gravity*	*Young's Modulus (E)* (MPa)	*Tensile Strength* (MPa)
Carbon	2.2	410000	2000
Kevlar® 49	1.45	130000	2700

Table 11. Carbon/Aramid comparison (Moulin et al., 1990)

1.7.1 Mechanical properties
There are 3 fibre types: Type I (high modulus) are expensive and mainly used in aerospace. Type II (high strength) are used for sporting goods. Type III (low modulus) have no structural applications. Toray T300 and Hysol Grafil XAS are good 'all-round' carbon fibres. They have very good values of modulus, strength and strain to failure, both absolute and relative to their cost. They have a tensile moduli of about 230 GPa, a tensile strength of 3200-3500 MPa and a strain to failure of 1.5%. Unidirectional composites produced from them have a longitudinal

1.7.1 Continued

tensile modulus of 125-135 GPa and a longitudinal tensile strength of 1700-1800 MPa. Toray T1000 has a tensile strength of around 7000 MPa and modulus of 294 GPa. The primary characteristics of carbon fibre composites is their very high specific stiffness. The elastic modulus of CFRPs can be very high, and unidirectional CFRP composites are of the same order as steel (around 210 GPa). Torayca M46 fibre in a unidirectional format has a modulus of 255 GPa and composite density of 1.6 g/cm^3, giving a specific modulus of 160. The comparative quantity for steel (density 7.8) would be 27, making the M46 composite 6 times better. As with glass fibres, fibres should be placed in more than one direction to sustain complex loading, so these figures are rarely achieved in practice, although very high specific moduli are still possible. Generally the choice is high modulus, high strength or a compromise between the two.

1.7.2 Fatigue

CFRP composites exhibit outstanding fatigue performance when compared to metals and other composites, especially in tension fatigue damage loaded in the fibre direction. If the matrix has a more dominant role, as with weaves, in compression or transverse to the fibre direction, then the fatigue life is substantially reduced. Even in these cases the fatigue resistance over steel and aluminium is three or four times as good.

1.7.3 Creep

Creep performance in the fibre direction is very good, much better than steel. They can resist long term creep when subjected to tensile load. When under compression or ‘off-axis’ then the matrix becomes significant. Polymers are visco-elastic and so deflect continuously under load.

1.7.4 Impact

CFRPs do not have good impact performance. They have low strain to failure (about 1.5%) and behave totally elastically to failure, so they cannot absorb much impact energy. To improve impact performance, fibres with high strain to failure are used. These include both glass and aramid fibres.

1.7.5 Galvanic corrosion

Carbon fibre conducts electricity, and it's composites are noble relative to some metals, causing galvanic corrosion. The extent of damage depends on the distance between the metal and the composite, the extent of polarisation and the electrolyte efficiency, and it can lead to the metal behaving as an anode and corroding away. A suitable coating (or the matrix) is generally used to ensure that composite and metal are isolated from one another.

1.7.6 Applications

High performance CFRPs are elastic to failure, which renders them creep resistant and not susceptible to fatigue, they have excellent thermophysical properties, are chemically inert, and exhibit very good damping characteristics. However they are brittle, have low impact resistance and low break extension, and very small coefficient of thermal expansion. They have a high degree of anistropy both in the fibre direction and perpendicular to it. Where weight saving is important and strength requirements are not too critical, such as artificial limbs, and stiffening car bodies, CFRPs have been very successful. But the lack of toughness prevents widespread use in civilian aircraft parts. When composites are made in the conventional way the work of fracture is not far short of the calculated theoretical limit, but even this is not sufficiently high to meet safety factors. Military aircraft, with their less stringent safety requirements, have enjoyed the benefits of carbon composites for some time.

1.7.7 Summary

Carbon fibres are not particularly strong, about the same as glass fibres, but for their weight they are 8 times as stiff as glass or other engineering materials. CFRPs are stiff but not very strong in tension. They lack the required toughness for some aerospace components. The world production of carbon fibres exceeds 12 000 tons yet they are still relatively expensive; they cost more than the equivalent strength synthetic organic fibre. There are many different types of fibre and new variations are constantly being developed, the main precursors for carbon fibres being rayon, polyacrylonitrile (PAN), and pitch. A major factor stopping large scale use of CFRP is the cost of high modulus carbon fibres. Costs now are 0.1 times that of 1960s prices, and they must continue to fall. One factor in favour of CFRP to replace metals is energy conservation. The energy cost of producing aluminium is 110 KWh/kg compared to 17 KWh/ kg for carbon fibres. The resulting cost differential will increase with the cost of energy. A 6 fold energy saving over aluminium pales beside the 45 fold saving of CFRP against titanium.

		Density (Mg/m^3)	*E* (GPa)	*Tensile Strength* (MPa)	*Failure Strain* (%)
RAYON	Standard	1.60	40	500	1.25
	HM	1.82	517	6500	1.50
PAN	HS	1.80	230	4500	2.00
	IM	1.76	290	3100	1.10
PITCH	P25W	1.90	160	1400	0.90
	P120S	2.18	827	2200	0.30

Table 12. Carbon Precursors: Rayon, PAN and Pitch (Doran, 1973)

1.8 Aramid Fibres

Aramid (aromatic ether amide) fibres are organic, man-made fibres available from 3 different

1.8 Continued

manufacturers: DuPont produces Kevlar in several versions; Enka produces Twaron, and Teijin produces Technora. Aramid fibres have reasonably high strength, medium modulus and very low density. Density and modulus is similar to a high grade cellulose such as flax, but the strength is four times higher than the best flax and aramids are unaffected by moisture. Their composites fit between carbon and glass fibres on a stress/strain curve. The fibres are fire-resistant and perform well at high temperatures, and they are insulators of electricity and heat. The raw fibres are very tough as opposed to brittle carbon and glass. The relative stiffness is almost as good as carbon and it is cheaper and can be more practical.

1.8.1 Mechanical properties

There are two distinct categories of aramids: those with an elastic modulus about the same as glass fibre, typically 60-70 GPa (Kevlar 29), and those with a twice this modulus (Kevlar 49). The higher modulus fibres are used in composites, while the lower modulus aramids are used where high strain or high work to failure are required. As the density of aramids is low (1.39-1.44 Mg/m^3) they show advantages over many carbon and glass fibres if either specific strength or specific stiffness is the main criterion. Some aramids have low compressive strength, and although a unidirectional ARP has a tensile strength of about 1400 MPa its compressive yield strength is only about 230 MPa. This results in poor flexural performance of about 300 MPa.

1.8.2 Fatigue

Unidirectional Kevlar 49 composites in tension fatigue show better performance than S and E glass composites and aluminium. Only unidirectional carbon composites are better. They have poor flexural fatigue, worse than E glass, reflecting it's poor static flexural strength.

1.8.3 Creep

Even unidirectional aramid fibres have creep rates much higher than glass or carbon.

1.8.4 Impact

Aramid composites are very good at withstanding impact damage, particularly ballistic impact. For this reason, combined with their low density, they dominate the body armour market. They are however very difficult to cut, and woven aramid cloth must be cut with specialist shears, even when the weave is open and the density is low.

1.8.5 Chemical properties

There are 2 categories: PPTA fibres (Kevlar 49) have high resistance to neutral chemicals, but strong acids and bases attack them. Technora aramids show no degradation in acids or alkalis.

1.8.6 Summary

It is better to avoid uncertainty and use aramid where strength is known to be sufficient but the stiffness needs increasing. This is especially applicable where glass fibre has been used as the sole reinforcement. Successive layers of aramid cloth in a previously all GFRP component can produce a lighter composite with increased stiffness. ARP have low compressive strength, this can be overcome by producing a 50:50 carbon/aramid composite which raises the compressive strength without much loss in modulus. To avoid possible compressive difficulties, aramid fibre can be used purely in tension. It then has the best specific strength of any reinforcement.

1.9 Hybrid Materials

Hybrids can be defined as 2 or more materials in fibrous form used in the same matrix, which can significantly expand the range of properties achieved by reinforced composites; at the same time they offer a way of controlling costs which might otherwise preclude the use of some fibres. For instance a GFRP which has small quantities of carbon fibres added as a stiffener could pay for itself by reducing the bulk of the component, thus cutting down resin usage. Hybrids are very flexible in the choice and disposition of reinforcements and core materials.

1.9.1 Dispersed Fibre Hybrids (Type A)

This consists of a mixture of two or more types of continuous fibre aligned, but randomly dispersed through a matrix. An example is very thin plates made up of layers of carbon and glass fibre tows. Woven cloths made from 2 distinct types of fibre also fit into this category.

1.9.2 Dispersed Fibre Ply (Type B)

This consists of a random or alternating mixture of 2 or more types of fibre ply . Laminates must be symmetrical about a centre plane to avoid distortion on cooling. The fibre plies may be unidirectional, angled, or built up from dispersed fibre material.

1.9.3 Fibre Skin and Core (Type C)

This type consists of outer skins of fibre laminate applied to a core made of another fibre laminate. Both skins and core may be made of unidirectional or angle ply materials or dispersed fibre hybrids. It is usual to put the stiffer fibre in the skins (eg carbon fibres applied over a GRP core) and to have a structure symmetrical about a centre plane. Hybrids have been produced in which the core is reinforced on one side only, eg carbon fibres applied to the compressive side of an ARP core, or dissimilar skins applied to both sides of the core.

1.9.4 Fibre Skin, Non Fibre Core (Type D)

These sandwich structures consist of fibre skins applied to a core of foam, honeycomb, solid

1.9.4 Continued

metal or wood. With some core materials, such as filled resin, solid metal and wood, strips of reinforcement can be used instead of skins. Examples include 'stressed skin' plywood (core of synthetic sponge rubber/ply skins) (Logie, 1947) and orthoses (CFRP/solid aluminium).

1.9.5 Woven Hybrids

Reinforcing fibres are unidirectional so they can be arranged to make a composite stronger in one direction or used to prevent deflection in one direction and not the other. But in general the processed bodies are expected to bear loads, resist deflection and give high performance in more than one direction, and this is a more efficient use of fibres. Woven fabric overcomes this problem, they are easy to handle and lay up quickly, are bidirectional and two types of fibres can be used for the warp and the fill. Labour cost in complex designs is much less, and this allows for the cost of the woven material. This selective reinforcement allows designers to fashion articles suited to their needs, for example using two different types of carbon fibre, one high strength to bear loads in one direction, one high stiffness to resist deflection in the other direction. Using carbon fibre and Kevlar in the same composite gives an impact strength better than carbon fibre alone, and compressive strength better than using Kevlar alone.

1.9.6 Fabric designs

Several designs of fabric are available, with plain or satin weave. Commonly used 8 harness satin weave fabrics retain most of the fibre characteristics in the composite and can easily be draped over complex mould shapes. Plain weave fabrics are less flexible and more suited to flat or simply contoured parts and have less translation of fibre properties into the composite. Woven composites have processing advantages, but their mechanical properties, particularly fatigue, are worse than non-woven material.

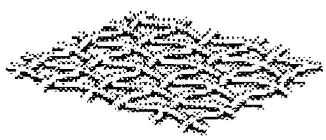
Property	*60% carbon fabric in epoxy resin*	*70% glass fabric in polyester resin*	*carbon (warp) and glass (fill) fabric*
Tensile Strength (MPa): Warp Fill	787 390	87.7	1325 94
Tensile Modulus (GPa): Warp Fill	88 52	5.8	124 12.4
Flexural Strength (MPa): Warp Fill	1025 627	137	1360 200
Flexural Modulus (GPa): Warp Fill	88 52	5.1	134 12.5

Table 13. Strength and stiffness of carbon and glass fibre hybrids (Broutman, 1969)

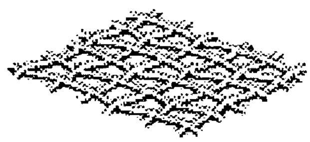
1.9.7 Woven CFRP fabrics

A conventional fabric is defined as a cloth produced by interlacing two sets of yarns whose elements pass each other at right angles, one set of yarns being parallel to the fibre axis. Also: (i) Nature of yarns used lengthwise and weft wise (fibre type and number of filaments per yarn), (ii) Average count of warp ends and filling picks, (iii) Weave is a pre defined pattern of warp and filling yarns (plain, satin etc). Mechanical characteristics depend on the weave and resin content. An 8-H satin will perform better than a plain fabric. Fabric count and yarn count are also important. Resin content is 35-40%, but a 200g/m^2 plain fabric made from 3000 filament yarns will require a higher resin content than a 400g/m^2 8-H satin. Porosity depends on fabric thickness, as resins fill voids during lamination. Porosity must be less than 50% by volume for mechanical properties, rising with higher resin permeability. Hybrid fabrics exhibit lower tensile strength values than their constituents because their breaking elongations are different and one material will break first. Finer tows, up to 12000 filaments, can be woven into carbon fabrics - tapes or broad cloths, or in combination with glass, aramid and other fibres in roving or yarn form, into hybrid fabrics. Bias cloths are available which have weft threads at right angles to the warp. Standard ranges include (in widths 7.5-140cm):

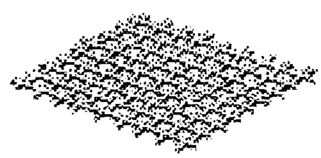
Unidirectional carbon (11 types)	Unidirectional hybrid (9 types)
Plain (square) weave carbon (19 types)	Plain weave hybrid (6 types)
Twill weave carbon (1 type)	Twill weave hybrid (2 types)
Satin weave carbon (38 types)	Satin weave hybrid (5 types)



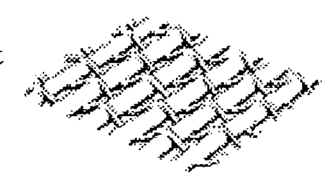
Plain weave, to much enlarged scale, strands alternately crossing over and under



Twill weave (2x1) where the weft yarn passes under 2 warp ends then over 1 warp end



Satin weave, like twill but number of ends & picks passing over each other before interlacing is greater



Unidirectional weave is stronger in one 'preferred' direction, can be of any weave.

Figure 20. Types of fabric weaves

1.9.8 Interface and thermal effects

Most fibre reinforced systems and hybrids using epoxide resins are cured at an elevated temperature to ensure good resin cross linking, and good adhesion between the resin and other components in the composite. As the materials have different coefficients of thermal expansion, when the structure cools to room temperature parts with the higher coefficient of thermal expansion will be put into tension and those with the lower coefficient of thermal expansion into

1.9.8 Continued

compression. For example CFRP on an aluminium core - on cooling the CFRP will be in compression and the aluminium in tension. For 1.5mm of CFRP on 0.5mm of aluminium, cured at 150°C, the stresses can be as high as 150MPa. A thin elastic glue line between the components reduces the stresses markedly, there then being a stress gradient in the glue line.

1.9.9 Hybrid effects

The lower elongation fibre (usually carbon) cannot break until sufficient energy is available to form fracture surfaces, so about 20v/o of GFRP should be dispersed through CFRP to avoid catastrophic failure, this also results in a 100% increase in effective fibre failure strain. Also, in

1.9.9 Continued

AFRP/CFRP systems the higher elongation fibres act as crack arrestors on a micromechanical scale, so there is a positive synergistic, or hybrid effect, causing deviation from the behaviour predicted by the rule of mixtures. For a symmetrical dispersed ply hybrid there is a 35-45% failure strain enhancement in CFRP. Hybrid effects are increased as levels of CFRP are decreased and GFRP increased, and as the individual layers get thinner.

1.9.10 Sandwich core materials

The 5 main types of core material are: balsa wood, honeycomb (metal, plastic, paper), foams (polyvinyl chloride, polyethylene, polyurethane, phenolic resin), syntactic resins (containing glass, carbon, ceramic or polymer spheres) and metals (aluminium, titanium). Balsa wood is generally used with the grain end-on to the sandwich skins and the core is thus limited in size to the diameter of the tree. Sheets of small pieces bonded to a fabric are available. Honeycomb is usually made of aluminium alloy or nylon paper (Nomex) although glass and carbon fibre resins have been developed by DuPont and Ciba Geigy. A range of cell sizes and foil thicknesses provide cores of different densities and strengths. A cheaper honeycomb is made from Kraft paper, fibreboard or cardboard. Foams can be produced by expanding thermoplastic and thermoset polymers. Syntactic resins are produced by adding hollow micro spheres of glass, carbon, ceramic, resin or thermoplastic to provide light, strong cores.

1.9.11 Overview

For a 50% CFRP/50% GFRP composite 50v/o of CFRP (half the material on a volume basis) provides 90% of the flexural properties of a solid CFRP bar, twice the impact strength, and the beam no longer breaks catastrophically but can support about 25% of the peak load after the CFRP skins have failed. Assuming the cost of GFRP in comparison to CFRP is small and that the beam is stressed in flexure, a much increased resistance to impact, with only a 10% decrease

1.9.11 Continued

in stiffness and strength can be obtained by using a hybrid which costs about half as much as a CFRP one. Other advantages are low notch sensitivity, slow, non-catastrophic crack growth, good failure characteristics, high impact resistance, freedom from corrosion, higher fatigue strength and inherent structural damping.

Material	*Density* (kg/m^3)	*Compressive* Strength	*Shear Strength*	*Tensile Strength*	*Modulus Shear* (MPa)
Nomex Honeycomb	64	2.95 MPa	1.67 MPa		61.00
Balsa Wood	96	5.25 MPa	1.26 MPa	9.62 MPa	
Polyurethane	96	1.05 MPa	0.58 MPa	1.36 MPa	
Aluminium Honeycomb	118.5	7.65 MPa	5.18 MPa		62.60

Table 14. Comparison of sandwich core materials (Rowlands et al., 1986)

1.9.11.1 Type D hybrids

These are analogous to the engineering concept of metal 'I' beams, a method of obtaining rigidity from relatively low modulus materials by the use of a suitable geometry. A sandwich panel or beam is composed of 2 thin, strong, stiff skins which resist bending, securely bonded to a relatively thicker, less dense core, which must resist shear forces, and keep the skins the correct distance apart and ensure they do not act independently, and can also provide impact resistance and thermal insulation. Failure of sandwich panels with lightweight cores, stressed in bending, may occur by skins debonding from the core, buckling or tensile failure of the skins, or shear failure or crushing of the core. Localised skin indentation and core crushing are a source of failure under point compression loading. In edgewise compression, failure is by overall buckling, skin delamination, core shear failure or crushing, and face wrinkling.

1.9.11.2 Types A, B and C hybrids

The advantage of the fibre composite hybrid structure is that it is possible to design an artifact to meet requirements at minimum cost by using higher elongation fibres to increase the impact energy, or lower elongation fibres to increase flexural, tensile and fatigue properties. An increase in impact energy of CFRP can be obtained by adding GFRP or AFRP. The glass or aramid fibres modify the failure characteristics and lead to extra energy absorption by debonding and fibre pull out. Properties of wood and GFRP reinforced with CFRP strips are improved by the inclusion of CFRP. Aluminium can also be improved, notably the fatigue strength. Failure is then due either to debonding between the components or micro cracking in the metal.

1.10 Fibres Summary

Composites are anistropic and as they are bound by polymers their properties change radically

1.10 Continued

with a small temperature changes. Polymers have low stiffness and are ductile. Brittle matrices will not perform well with woven fabric composites as they will not withstand the high shear forces set up by the interplay of two materials of such different elastic moduli. Ceramics and glass are stiff, strong and brittle. Fibrous composites exploit the great strength of the ceramic while avoiding the catastrophe; brittle failure of fibres leads to a progressive failure.

1.10.1 Fire resistance

The factors by which fire performance is assessed include surface spread of flame, fire penetration, ease of ignition, fuel contribution and minimum oxygen content that supports combustion. The degree of flammability of a composite is governed by matrix type, quantity and type of fire retardants added, quantity and type of fillers used, reinforcement type, its volume fraction and construction. The dominant factor is the polymer matrix, the order of flammability of which is (without fire retardants): phenolic (excellent fire resistance), epoxy, vinyl ester (some fire resistance), polyester (burns readily).

Material		*Density* (Mg/m^3)	*Young's Modulus* (GPa)	*Strength* (MPa)
Fibres:	Carbon I	1.95	390	2200
	Carbon II	1.75	250	2700
	Cellulose	1.61	60	1200
	Glass	2.56	76	1400-2500
	Kevlar	1.45	125	2760
Matrics:	Epoxies	1.2-1.4	2.1-5.5	40-85
	Polyesters	1.1-1.4	1.3-4.5	45-85

Table 15. Fibre and Matrix properties (Broutman, 1969)

1.10.2 Corrosion

Composites are inherently corrosion resistant and can show substantial cost benefits over traditional engineering materials. Order of corrosion resistance for polymers: orthophtalic polyester (least resistant), isophtalic polyester, vinyl ester, epoxy (most resistant).

1.10.3 Moisture effects

Polymers are susceptible to moisture absorption which lowers mechanical properties. Resin systems can have excellent moisture resistance. This is an important consideration since flexural strength can be reduced to 50% of the dry value by 1.5% moisture content.

1.10.4 Weathering

Composites are degraded by temperature, moisture, sunlight, wind, dust and acid rain

1.10.4 Continued

(hydrogen sulphide, sulphur dioxide, sulphuric acid). The mechanisms of weathering are: leaching chemicals from the resin; sunlight attack on the resin, making it brittle and eroding the resin, exposing the fibres to the environment. This can be overcome with ultraviolet stabilisers such as carbon black in the matrix and chemical resistant fibres (C or ECR glass or polyester) in the composite top layer.

1.10.5 Cost

Typical costs of carbon, Kevlar and glass reinforcement are currently in the ratio 8:4:1, yet raw fibre costs are not the only consideration. High strength fibre reinforcement allows the use of lower weight components, which aids transportation, installation and many other aspects in the workplace. Aramid fibres are now being used in a multitude of new applications and their price is set to fall to a more practical level. Carbon fibres are still expensive but new applications and research into new derivatives should soon make it more competitive (see Table 16). Labour and moulding costs may have more of an effect in many cases than the cost of the raw material alone. For small batch production and prototype work, the ability to hand lay up shapes without complex moulding procedures, and without specialist labour, would help to offset the increased material costs of composites over timber and metal (see 5.1).

Material	*Cost per 100 MPa strength (pence)*
Concrete	0.25-0.50
Timber	0.35-0.50
Wrought steel	0.50-0.95
Ferrous castings	0.60-1.55
Aluminium	1.85-2.10
Zinc castings	1.85-2.30
Plastics	2.20-7.85
Fibre composites	2.75-7.20

Table 16. Comparative cost of composites (von Vegesack et al., 1996)

1.10.6 Overview

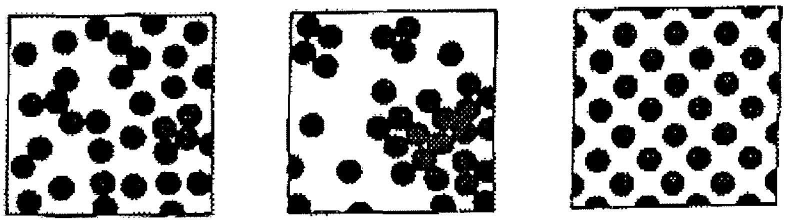
In addition to being strong, stiff and light, composites offer: (i) Excellent fatigue resistance: can withstand 10 million cycles at 70% of its ultimate tensile strength, metals fail at 50%, (ii) Thermal stability: dimensional changes caused by temperature are one fiftieth that of metals, (iii) Wear resistance: dry carbon/graphite parts are comparable to well lubricated metal bearings, (iv) Damping characteristics: acoustical and mechanical vibrations stop in 0.1 the time of metals. When using composites the designer has greater freedom to specify the material and its construction than with conventional engineering materials. They also increase the possibility of creating new shapes and new uses which would be difficult in wood and metal.

1.10.7 Fibre straightness

Composites based on wavy or off-axis fibres are less stiff and strong, being especially weak in compression. Some fibres are deliberately twisted as this aids weaving, while others are entangled to aid resin impregnation. Shaping processes may also distort the fibre orientation. On moulding, typically 10% of fibres can be up to 5° off alignment. Adjacent fibres may misalign cooperatively, so the whole orientation pattern changes. The structural performance of multi axial composites is not badly affected, but thick uniaxial stacks exhibit a 20% reduction in compressive strength, due to cooperative buckling in prepreg layers. Pre-crimping (stress relieving out of line) solves this, and many woven fibre composites are pre-crimped.

1.10.8 Fibre Organisation

A typical sample of composite will contain around 60% fibre, 39% matrix and 1% voids. Voids should be avoided, but they may be present within pre impregnated tape or ply, and they exist at the surface of rough plies. The structural significance of voids is considered to be small. A standard of 50-60% by volume fraction for fibre reinforced composites exists; higher volume fractions are difficult to produce at little mechanical advantage. Lower volume fractions decrease mechanical performance, especially if excess resin exists, where controlling fibre distribution is difficult. Fibres are distributed non-uniformly in the composite.The ideal distribution is shown below (c), while most composites demonstrate clumps as in (b), where there are large differences in the material. A realistic optimum would be (a).



(a) (b) (c) *Figure 21. Fibre packing and distribution*

1.10.8 Continued

In addition there are specific variations throughout the laminate, with resin rich layers existing between plies of prepreg. This is particularly important between layers of different orientation, since resin cannot then flow between layers. This layer is thicker for large diameter glass fibres (17 micrometres) than for thinner diameter carbon fibres (5 micrometres) or aramids (12 micrometres), and represents a greater proportion of the total prepreg thickness.

1.11 Matrices

Small additions of random fibres to a brittle matrix will improve the strength and toughness, for example straw in old bricks, and hair in household plaster. Fibres thicken the mixture and 2-3% of fibres result in a paste that is too thick to mix. It must then be hydraulically pressed. Beyond

1.11 Continued

2%, the matrix must be added to the fibres, in the form of paper or cloth soaked in resin or other bonding agent, as with papier mâche. Cracks are stopped or deflected by the fibres, and the work of fracture is dramatically increased. Generally this means substantial improvement in tensile strength, although the stiffness is not necessarily improved.

1.11.1 Function of the matrix

In early reinforced materials small amounts of fibre were used to correct the worst faults of a weak brittle matrix. Now the function of the matrix is to glue the strong fibres together and as it is the weak constituent we use as little as possible. It is difficult to get more than 50% by volume of fibres into a material. The resin contributes nothing to the stress situation but adds weight. A 50% fibre/50% resin composite will therefore have half the strength and half the Young's Modulus of the fibre alone.

1.11.2 Thermoplastics

The advantages of thermoplastic composites include good hygrothermal properties (maximum moisture absorption only 0.3%), fabrication cost reduction due to single step forming of thermoplastic composites which reduces turn around time to 20% that of thermosets and 50% more damage tolerance due to higher fracture toughness. With the same thickness to meet the requirement for low level impact durability, the frequency of repair of thermoplastics is less than thermosets. In addition, low cost repair is possible with reprocessible thermoplastics. Research from the aerospace industries concentrates on thermoplastics. PEEK (polyetheretherketone) is the most widely used thermoplastic matrix, with costs substantially higher than equivalent thermosets. Stress cracking is a major problem, especially with polyethylene.

1.11.3 Thermosets

The greater part of composites currently in service are based on crosslinkable thermosetting resins, usually epoxies. They resist swelling and solvent attack better than most thermoplastics. The hardener used makes a significant difference to the cross linked structure. Ether links are formed by catalytic curing agents such as boron trifluoride, and these are very environmentally resistant. Unsaturated polyester resins are widely used in reinforced plastics, and are cheaper than epoxies. They have fair or good resistance to most things, although raising temperature greatly accelerates attack on resins, and a mechanical load will also speed up decay. There are many chemicals for which composites are more suitable than mild steel or other metals.

1.11.4 Resin systems

Factors governing choice of resin matrix include: (i) Types, ratios and configuration of fibre

1.1.4 Continued

reinforcement requiring impregnation and bonding into composite structures; (ii) Process requirements and limitations in terms of initial impregnation, moulding process, gelation, cure and post cure conditions; (iii) Post finishing or further bonding operations; (iv) Design performance criteria to be achieved in the operating environment of the composite is governed by the resin/fibre long term compatibility. The matrix must be capable of providing the required mechanical properties and chemical resistance as it's main contribution to the performance of the final structure. Criteria in these respects include:

- Physical strength properties and their retention under operational conditions. These include tensile, compressive, flexural, fatigue and fracture properties.
- Environmental resistance in conditions of moisture or water exposure, heat or cold, or in atmospheres of chemical vapour, aggressive chemicals or external exposure.

The resin/fibre interfacial properties must be carefully controlled, as this greatly affects shear strength and other properties. The fibre surface treatment, wetting by the matrix, initial bond strengths, and strength retentions are crucial to composite performance.

Resin	*Flexural strength* (MPa)	*Tensile strength* (MPa)	*Tensile modulus* (MPa)	*Resists:*			
				Water	*Solvent*	*Acid*	*Alkali*
Unsaturated polyester							
ortho-phthalate	100-135	50-75	3.2-4.5	fair	poor	fair	poor
iso-phthalate	110-140	55-90	3-4	good	fair	good	poor
modified bisphenol	125-135	65-75	3.2-3.8	v.good	fair	good	fair
epoxy (bisphenol)							
aliphatic polyamine cure	85-125	50-70	3.5	good	fair	fair	fair
boron trifluoride complex	110	85	3-4	good	fair	good	good
aromatic amine cure	80-130	60-75	3-3.5	exclnt	good	fair	good
aromatic anhydride cure	90-130	80-105	2.6-3.5	fair	fair	good	poor
Others							
vinyl ester	110-130	70-85	3.3	good	fair	good	good
polyimide	75-130	50-120	3.1-4.7	poor			poor
friedel-crafts	110-120	95-110	4.1	exclnt	good	good	fair
phenolic/furane	100-120	60-75	2.5-3.5	good	good	good	poor

Table 17. Matrix Comparison (Newman, 1972)

1.11.5 Unsaturated polyester resins

These are used for the majority of GFRPs. They are based on a recurring ester (-CO-O-) and are available in a wide and versatile range, at low cost and good availability. They are mainly used where a good balance between mechanical and chemical resistance properties are required at

1.11.5 Continued

moderate temperatures. Weaknesses are in their relatively high shrinkage on cure (7-8%), their sensitivity to some aggressive solvents and chemicals (especially alkaline), brittleness and sometimes water absorption. Like epoxies, there is no evolution of volatile materials on cure, although their odour is strong and unpleasant, requiring thorough extraction.

1.11.6 Vinyl ester resins

Advantages include: (i) Low molecular weight resins of controlled structure, (ii) Epoxy backbone with reduced ester groups provides improved chemical resistance, high resilience and toughness and uniform cured structure with reduced internal stress, (iii) Hydroxyl and acrylate provides good wetting and adhesion, even to glass.

1.11.7 Epoxy resins

Hardening occurs through reaction of the epoxy group aided by the selective use of curing agents, hardeners, catalysts or activator components. The gel and curing characteristics can be modified by the use of accelerators. Composites incorporating a range of fibres have been successfully produced with such systems where good interlaminar shear fatigue and related properties are required. Key features of epoxies include: (i) Extreme versatility in processing and curing; (ii) Can be modified (eg addition of high molecular weight polymers); (iii) Low shrinkage (2-3%); (iv) High adhesive strength; (v) Excellent mechanical strength; (vi) Chemical resistance (provided the correct system is selected).Prepregs manufactured from epoxy matrices possess good drapability and excellent tack. Typical cure cycles are one hour at 120°C to two hours at 180°C (see Appendix 3).

1.11.8 Polyimide resins

These resins have the highest levels of thermal and environmental resistance. They are available in a range of forms: films, varnishes, moulding powders, laminating resins and adhesives, yet they are brittle and have limited toughness. The cure cycles are long high temperature programmes followed by a long curing cycle. Micro cracks tend to develop during thermal cycling or mechanical loading and significantly reduce mechanical properties.

1.11.9 Phenolic resins

Phenolics, the oldest thermosetting resins, exhibit good resistance to water, solvents and most acids. There are however very brittle and evolve volatile materials on cure.

1.11.10 Summary

The functions of the matrix are: (i) Bind fibres together, keep alignment in stressed directions,

1.11.10 Continued

allow composite to withstand compression, flexural and shear forces as well as tensile loads. (ii) Isolate fibres so they act as separate entities. Failure isn't catastrophic and the strength of fibre bundles is less variable than the equivalent solid. Also, separate fibres impede crack growth through contact with many fibres. (iii) Protect filaments from mechanical damage such and environmental attack. The matrix must be chemically and thermally compatible with the fibres. (iv) A ductile matrix provides a means of slowing down or stopping cracks originating at broken fibres; conversely, a brittle matrix may depend on the fibres to act as matrix crack stoppers. (v) Through quality of fibre grip (interfacial bond strength) the matrix can increase toughness. (vi) The matrix is weak and flexible and strengths and moduli must be included in calculations.

1.11.11 Thermal stress

Higher temperature resins will have higher thermal stresses and strains than lower temperature set resins. This shows itself in 'spring forward' or 'tow in' on moulding. A 90° bend will spring forward by 2° and this should be allowed for.

1.11.12 Delamination

The resin matrix has to disperse as much of the internal stress of the composite as possible. As a composite moulding cools from the melt, the fibre has no way of relieving the compressive stresses, and the compressive strain induced is about 0.13%. This can cause delamination of a surface ply, which appears as a blister.

1.12 Manufacturing Processes

If a part is required to operate under conditions which approach the design limitations of the material then the composite must be of optimum quality to satisfy such stringent requirements. In the case of high mechanical loads the composite must be well consolidated, with as low a void content and as high a volume of fibre reinforcement as is likely to be achieved by a high pressure moulding process. Certain constraints may also restrict the choice of process, for instance the ability of a sandwich core to withstand temperature and pressure. Wet lay-up is not applicable for high performance composites due to the lack of consolidation. Use of prepreg protects the fibre from damage and aids handling, and also allows high fibre volume contents, to close tolerances in moulding composites, thereby optimising performance. Use of prepreg also allows close control of the fibre alignment in each reinforcing ply of the lay-up, thus achieving the most effective use of the fibre in meeting the design loads.

1.12.1 Hand lay-up

This is the simplest fabrication method, where a layer of random fibre mat or woven fabric is

1.12.1 Continued

laid on a form. Thermosetting plastic is then brushed on the reinforcing materials, and repeated until the desired thickness is reached, and trapped air is squeezed out by a roller. The catalysed resin is then allowed to cure at room temperature. Polyester and epoxy are the most common resins. Content of resin reinforcement achieved by this method is relatively low, about 30% by weight. Moulds can be made of wax, clay, wood, metal and plastic. Mould releases such as polyvinyl alcohol, silicone and mineral oils are used for releasing the final product from the mould. Commonly used for limited production, prototypes and models, also complex products that would be impractical to mould with matched dies, and large parts such as boat hulls.

1.12.2 Spray-up

Fibres are fed through a chopper and cut to desired lengths, usually 25-50mm. This method is not suitable for aramids due to their toughness. A spray of chopped fibres passes through a cloud of freshly catalysed resin, created by twin spray cones of resin and hardener about 300mm in front of the sprayer. Cut fibres drenched in resin impinge on the mould about 1 metre away. A good operator can deposit 3-6kg per minute. An excess of resin and air bubbles are removed by hand rolling the surface with grooved rollers to consolidate. Results tend to have variable thickness and fibre content and more voids than other techniques.

1.12.3 Bag moulding

Bag moulding is used to improve the quality of hand lay-up by further removing the entrapped air. The 3 methods are vacuum bag, autoclave and pressure bag.

(i) *Vacuum Bag:* The lay-up of resin and reinforcement is covered with a perforated parting film and a layer of jute bleeder material. This combination allows the bleeding of air and excess resin. Then the lay-up is covered with a flexible cellophane or nylon diaphragm, which is sealed to the mould. The vacuum is then drawn upon the whole system with a pressure of about 12 psi. The bagging process should immediately follow the lay-up in order to avoid the resin hardening. The entire bagged system can be cured in an oven or an autoclave system.

(ii) *Autoclave*: A large metal pressure vessel is pressurised with nitrogen to 50-100psi.The autoclave system is heated and the hot gas is circulated to provide a uniform temperature within the vessel. Sophisticated autoclave systems provide electronic controls which produce programmed temperature/pressure-time cycles. After the laminate has been bagged and subjected to vacuum, it is placed inside the autoclave for cure. The vacuum system continues to function during the cure cycle in order to remove additional air and volatiles emitted during the polymerisation of the matrix system. Next, the temperature/pressure-time cycle is initiated and carried out. The laminate is then removed from the autoclave for debagging.

(iii) *Pressure Bag:* This is an economical alternative to the autoclave system where a heated

1.12.3 Continued

platen press or comparable pressure bag may be pressurised with air and is confined by the platen of the press, yet pressure bags do not have the flexibilty of autoclave systems.

1.12.4 Compression (matched die) moulding

Plies of prepreg in sheet, tape or woven form, are cut and laid on top of each other to form a preform which roughly corresponds to the shape of the component being moulded. Heat and pressure are applied to the mould. Size is normally limited to $1m^2$ by the cost of tools and high quality presses. Down-stroking hydraulic presses are best, with a space between platens of 500mm when open. A $1m^2$ platen with effective pressure of 3.5 MPa is adequate, heated to 120-180°C. Wood, epoxy resin and aluminium moulds are adequate for short runs, using restricted temperature/ pressure cycles. Pre-hardened steels are used for batch runs.

1.12.5 Leaky mould technique

Weighed quantities of aligned carbon fibre tow are introduced into an excess of a low viscosity and low temperature curing resin contained in a mould. The resin is allowed to wet the fibres, and the excess resin is then forced out of the leaky mould by applying slight pressure. The gap between the top face and the walls of the mould is 0.05mm, allowing rapid draining of the resin but preventing extrusion of the carbon fibre. Carbon fibre in the form of straight tows are used, while the resin is freshly catalysed with a fifty minute pot life. As air bubbles through the top layer of fibres (at about 10 minutes) the mould is closed. A typical CFRP will contain equal parts by weight of resin and fibre, corresponding to a fibre volume fraction of 40-43%.

For solid polymers with particles or fibres	*For linked or pasty cross-linkable resins mixed with fibres or cloth*		
calendering	prepreg pressing	lamination	vacuum impregnation
centrifugal moulding	compression moulding	casting	sheet moulding
extrusion	dough moulding	pultrusion	reinforced reaction
injection moulding	filament winding	spray lay-up	injection moulding
transfer moulding	vacuum forming	hand lay-up	

Table 18. Suitability of manufacturing processes (Whale et al., 1988)

1.12.6 Prepreg (Pre-impregnated) materials

For manufacturing polymer matrix composites, fibre bundles are put into a semi-processed polymer to form a dough-like ribbon or sheet, known as 'prepreg', in which liquid resin is incorporated into the fibre rovings. The impregnated material is processed and dusted so that it can be handled as a soft, dry entity, which is then laid in a mould, sometimes being partially cured while progressive build-up occurs. For lower strength situations prepreg sheets can be

1.12.6 Continued
made using chopped glass or other fibres, which have the advantage of being mouldable into doubly curved shapes without serious buckling. Lack of really long fibres means that ultimate strength is reduced although probably still acceptable for most applications.

1.12.7 Carbon fibre prepregs
With the growing interest in thermoplastic matrices for composites and the difficulty of processing the conventional thermoplastic pre-impregnated tapes and fabrics into cured composites because of their stiffness, the development of flexible prepreg in the form of hybrid yarns and fabrics has been rapid. Yarns with either mixed carbon and polymer filaments (commingled) or powder coated carbon tows (BASF), encapsulated in a polymer sheath (Ciba Geigy's FIT) or plied yarns where reinforcement and polymer filaments are twisted together are available as well as the earlier cowoven fabrics with their separate ends of different materials. These yarns can be formed into fabrics by most of the ordinary textile processes - weaving, knitting, braiding - and may have begun to replace the earlier cowoven fabrics because of the more intimate mixing of the components. In thermoset resin prepregs progress has been made in improving the 'hot-wet' properties and toughness of composites with new epoxy and bismaleinide resins. Prepregs are commercially available in a range of widths from 20mm tape to 300 mm. They are supplied on rolls in lengths of up to 250m between moisture barrier films. A typical prepreg description is (from Ciba Geigy): *Fibredux 920C-TS-6-44;* 44: resin content (% by weight); Fibredux 920: Trade name; S: surface treatment (carbon only); C: Carbon (G: Glass, K: Kevlar); 6: cured ply thickness (in 1/1000 inch); T: Fibre grade (E: glass, R: glass, T: high tensile carbon, M: high modulus carbon)

1.12.8 Prepreg moulding
Before moulding, the solvent solubility of the matrix and the ease of wetting of the fibres must be checked, together with the stability of the system, known as its 'shelf life'. The curing characteristics and the flexibility of the prepreg sheet begin to change soon after manufacture; time limits and recommended temperatures for 'room temperature' and refrigerated storage must be determined. The moulding variables (time, temperature, pressure) and the degree of pre-cure (a low temperature advancement of cure to control flow) must also be checked. There follows an example of compression (matched die) moulding using a glass fibre/ epoxy prepreg: Epoxies are very free-flowing when hot, so an excess is used, with generous flash grooves. The prepreg is dried to a low solvent content so it is thermally stable and dry to the touch. Shapes are then cut from the prepreg, heated to 125°C, assembled in two halves and after bonding together with the minimum of resin, the assembly is moulded at 7 MPa in a positive mould held at 175°C. By the use of very high pressure and restricted flow, fibre

1.12.8 Continued

distortion is avoided, and voids due to traces of solvents are prevented by dissolving solvent back into the moulding.

1.13 Joining Composites

Ideally, composite structures should have as few joints as possible. However, size limitations are imposed by materials and manufacturing processes, and the structure may have to be disassembled for transportation. There are two basic types of joints available: mechanically fastened or bonded.

1.13.1 Mechanically fastened joints

Advantages include no surface preparation of component, disassembly is possible without component damage, and there are no abnormal inspection problems. Disadvantages are that holes cause unavoidable stress concentrations, and fasteners incur a large weight penalty. The behaviour of mechanically fastened joints is influenced by fastener parameters such as fastener type (screw, rivet, bolt), fastener size, clamping force,washer size, hole size and tolerances. Of these, the clamping force, the force exerted in the through-thickness direction by the closing of the fastener, is of paramount importance.

1.13.2 Fasteners

Self-tapping screw: Not recommended as the low through-thickness strengths can lead to thread stripping. If a demountable joint is required patented 'heli-coil' inserts can be used.

Rivets: Can be used on laminates up to 3mm thick. Either solid or hollow types can be used, but care must be taken to minimise damage to the laminate when drilling holes and closing the rivet. Countersunk rivets is will limit the minimum laminate thickness, countersink angles should be 120° rather than the usual 90° to reduce the risk of rivet pull-through.

Bolts: The most efficient form of mechanical fastening as the through thickness constraint prevents early failure in bearing. Even a bolt with finger tight washers raises the pin bearing strength by a large margin, which improves as the bolt is tightened. Even if a nut loosens considerable load-carrying capacity is retained. Many bolts and rivets specially configured for composites are available.

1.13.3 Bearing strength

Joint failure will normally be in bearing, where the bearing strength is generally greater than the compressive strength of the material and the through-thickness constraint afforded by the fastener. Support for the load carrying fibres (those parallel with the direction of the load) is essential and laminates containing ±45° and/or 90° fibres have a good bearing performance. It

1.13.3 Continued

follows that GFRP chopped strand mat laminates, which are isotropic, are better than the more directional woven roving materials. Homogeneous lay-ups with many ply interfaces give a higher bearing strength, up to twice that of blocked laminates, where large numbers of plies of the same orientation are grouped together. The 'ideal' values in Table 19 assume a single perfectly fitting fastener loaded in double shear. Single shear loading and ill fitting fasteners can each cause strength reductions of at least 10%. Bearing stresses give rise to through-thickness tensile strains, so bolts which prevent expansion in the low strength through-thickness direction are best, with high through-thickness shear stresses between the washers.

Material	*Density* (Mg/m^3)	*Bearing strength* (MPa)	*Specific strength* *(Density/bearing strength)*
Steel	7.85	973	124
Aluminium alloy	2.70	432	160
CFRP (Vf 0.6)	1.54	1070	695
GFRP (Vf 0.6)	2.10	900	428
GFRP (woven roving) (Vf 0.6)	2.10	682	324

Table 19. Specific bearing strengths for single hole joints (Mark, 1961)

1.13.4 Multi-hole joints

Joints will normally consist of several fastenings. The figures in Table 19 can be used if the fasteners are arranged in a line at right angles to the load, provided the pitch of the fastenings is large enough for there to be minimal interaction between adjacent fastenings. For CFRP and GFRP this spacing should be >4d (where d is the diameter of the fastening) whilst for GRP in the form of CSM, spacings must be 6d or more. When fasteners are arranged in a row, parallel to the load, each fastener will react only part of the load in bearing, the remainder by-passing each hole. The joint will then behave as a single hole joint. It is difficult to improve upon the single hole (or row) joint, with two fasteners being only about 10% stronger than one, as although the bearing stress is halved, the stress concentration arising from the by-pass load can be almost as high as that caused by the bearing load.

1.13.5 Bonded joints

Advantages are that stress concentrations can be minimised, and there is no weight penalty. Disadvantages are that disassembly is difficult or impossible without component damage, they can be severely weakened by environmental effects, they require careful surface preparation, and joint integrity is difficult to confirm by inspection. Bonded joints can be made by gluing together pre-cured laminates or by forming joints during the manufacturing process, in which case the joint and the laminate are cured at the same time (co-cured). With co-cured joints the matrix is

1.13.5 Continued

the adhesive and this construction will behave differently from joints with a separate adhesive.

1.13.6 Surface preparation

Polymer matrix composites are usually based on epoxy or polyester resins which are highly polar, therefore very receptive to adhesive bonding. Surface pre treatments are required to remove contaminants such as oils, dirt and mould lubricants and release agents. There are two main techniques:

(i) *Peel-ply:* One ply of fabric is installed at the bonding surfaces and removed just prior to bonding. This usually leaves some contaminants, which are removed by (ii):

(ii) *Abrasion:* A light grit blast with alumina particles removes any contamination, this is followed by a solvent wipe to remove abrasives. Methodical hand abrasion, especially using commercial abrasive pads, can be equally effective.

1.13.7 Joint strength

In single or double lap joints the failure load of a bonded joint can be as high as 90% of the failure load of the basic laminate. When loaded in fatigue, the strength at one million cycles is only about 30% of the static value. A typical epoxy adhesive will have a shear modulus around 1GPa with a shear strength of 50 MPa. Surface preparation of the metal can affect the durability of composite to metal joints. The durability of composite to composite joints is adversely affected by absorbed moisture, both in the adhesive and the matrix of the composite itself; strength loss can be 50% or more compared with a dry joint.

1.13.8 Absorbed moisture

To ensure reliability it is acceptable to choose an adhesive whose shear strength is about 50% above that of the adherents. The actual value of adhesive shear strength could be 20% less than expected due to incomplete wetting of joints. When bonding laminates absorbed moisture in the composite may be evolved during the adhesive bonding cycle and this can lead to poor adhesion and voids in the adhesive layer. The composite must therefore be dried before bonding, and when undertaking adhesive bonded repairs it is necessary to remove any absorbed moisture or oils. Drying for 48 hours at 75°C cures most problems, although use of less moisture sensitive adhesives is recommended, such as 175°C curing adhesives. As a rule, a laminate should have less than 5% moisture, which means drying a 16 ply laminate will take 24 hours.

1.13.9 Repair of composites

A repair is essentially a joint, and requirements for repairability should be considered at the outset of a design, to ensure that the component is repairable (ie has a good joint strength).

1.13.9 Continued

Defects may be introduced during manufacturing, through environmental exposure, by accumulation of minor damage sustained in normal use, or from impact. Ultrasonics and X-radiography are used to establish the size and location of damage. The objective of any repair must be structural integrity, but the exact repair procedure will depend on the component, joint efficiency, considerations of surface smoothness and the repair environment.

1.13.10 Bonded repair techniques

(i) Bonded techniques can be used in cosmetic repairs (where damage is not structural, eg dents and missing surface plies) and primary structural repairs. For a cosmetic repair the aim is to restore surface smoothness, and a potting compound or liquid adhesive is spread into the damaged area and formed to the component's contour. Injection repair, used for minor disbonds and delaminations, consists of a number of holes drilled to the depth of the damage and filled with heated resin, injected under pressure. Pressure can then be applied to the repaired area to ensure mating to adjacent regions.

(ii) For structural damage, flush scarf patches and external patches can be used.

(a) An external patch is simpler to apply, less surface critical and produces less interference to the substructure. The patch is bonded to the damaged area, and the load is taken over and around the damaged area. The patch must be capable of withstanding the high peel and shear stresses which develop at the edge of the damage. In order to minimise this, and to diffuse loads to the substrate, the patch plies are stepped in diameter. The low through-thickness tensile strengths of laminates means this technique is restricted to thinner laminates, although peeling can be reduced by small fasteners pitched at 25mm spacing around the hole.

(b) Flush scarf repairs are used where surface smoothness is essential, and joint efficiency is important. Load concentrations, especially through compressive loading, is avoided. Thick mouldings should be scarf repaired to avoid out of mould line thickness and high bond line peel and shear stresses. Careful surface preparation is needed, with the correct scarf angle (a taper ratio of 20:1) and laminate orientation of the patch being important. An outside layer of woven material or $\pm 45^{\circ}$ layers should be used, making surface defects such as cuts, scratches and abrasions less strength critical.

1.13.11 Bolted repair techniques

Bolted repairs are used where bonded patch repairs of thick laminates may result in shear stresses beyond the limit of the adhesive, or where a bonded scarf joint would be too complex. Bolted patches can be applied from one side, or from two sides with a backing plate. If the plates are thick, and bolt tolerances are tight, the backing plate can also carry a load. Patches may be thick enough to accept flush head fasteners, and have bevelled edges to improve surface

1.3.11 Continued

conformability. A flush patch can be used where the damaged area is removed and a section is inserted, fasteners are inserted through the patch to a doubler. Care must be taken to avoid damaging the laminate when drilling. Bolted repairs cannot be used for honeycomb structures due to the limited core compressive strength.

1.13.12 Drilling composites

CFRP and GFRP composites can be drilled with tungsten carbide or diamond drills. High speed steel tools will blunt rapidly, causing heating, tearing and some delamination. Drill break through will also cause delamination, so a backing plate must be used to support the rear surface, and a pilot hole should be drilled first. Twist drills can be used if the included angle of 120° is reduced to 60° for thin laminates and 100° for thicker parts. KFRP is more difficult to drill, particularly unidirectional laminates. Better results can be achieved with multidirectional and woven fabrics, and by incorporating one layer of glass fabric in the laminate surface.

1.13.13 Importance of lay-up

By considering stresses around a loaded hole a joint in a unidirectional laminate will fail by shear at a very low load when loaded parallel to the fibres. When the fibres are normal to the load the failure will be in tension. Multi-directional laminates are more complex, and their behaviour will depend on the proportions of fibres in the various directions. As an example, a 0/±45° lay up will have an increasing shear strength as the proportion of ±45° material is increased, until bearing becomes the predominant failure mode. Further increase will eventually change the mode of failure to tension, since ±45° laminates have a low tensile strength. Examination of all failure modes shows that a near quasi-isotropic lay up will give the best performance for a tightened bolt. As a general rule there should never be less than 1/8 or more than 3/8 of the fibres in any one of the basic directions 0°, +45°, -45° and 90°. This implies that highly orthotropic lay ups, used for high stiffness requirements, will need significant reinforcement at the joints to achieve the required load transfer, and hence be heavy and difficult to repair.

1.13.14 Stacking sequence

If the plies of a laminate are homogeneously mixed, ie the fibre direction changes from layer to layer, the stacking sequence has little effect on the bearing strength of bolted joints. Pinned joints, and riveted joints, are affected, with pinned joints showing a 30% difference between the strongest and weakest for a quasi-isotropic lay up in GFRP, but rather less difference in CFRP. Bolted joints are significantly weakened if plies of the same orientation are grouped together (a 'blocked' laminate). Reductions in bearing strength can be as high as 50% compared to the homogeneous case.

1.14 Laminating

The use of an adhesive to bond together pieces of timber is not new, but the use of an adhesive and thin layers of timber (veneers) to make structural members is a development of the twentieth century. At present the adhesives mainly used for glued laminated timber members (glulam) are casein, urea formaldehyde and mixed phenol-resorcinol formaldehyde. Higher strength adhesives like epoxies can significantly increase the quality of the structure. The major hurdle facing the glulam industry is finding an adhesive and manufacturing process that will eliminate the current costly technique and still produce good uniform glue lines.

1.14.1 Advantages

Glulam (glued laminated timber) or LVL (laminated veneer lumbar) refer to constructions where laminations are arranged parallel to the axis of a member, with the grain approximately parallel and glued together to form a member which functions as a single structure. It differs in construction from plywood where plies are arranged with the grain of adjacent plies at 90° to the grain of the others. Strength is not necessarily improved over solid timber, but the effects of defects are minimised and the adhesive permits a more economical use of timber, increasingly important as timber becomes more expensive and quality subsequently suffers.

1.14.2 Considerations

Because laminations are relatively thin, they can easily be dried to a specified moisture content before use, with less seasoning defects and with greater working stresses. The method of manufacture permits the use of low grade laminations in areas of low stress (usually the core) and high grade materials where higher stresses occur (usually the outer surfaces). The section of a laminated beam can be varied along its length in accordance with strength requirements. Compared with sawn timber sections glulam beams cost more to produce. The waste factor during manufacture is high, ranging from 30% to 50%, due to finishing to size and design considerations. The strength of a laminated structure depends on the strength of the glue joint, so great care and quality control have to be exercised during manufacture, to an extent not required for other timber structures.

1.14.3 Moisture content of laminations

The optimum moisture content of the timber is that which will produce the strongest glue joint and, when increased by the water in the glue, approach as nearly as possible the average equilibrium moisture content likely to be attained in service. It therefore follows that the moisture content of laminations should depend on the type of glue used. Glues that emit water as they set through condensation polymerisation (eg Urea Formaldehyde) will require a drier timber than glues which set by chemical reaction and emit no water (eg Epoxies). If laminates used with

1.14.3 Continued

epoxy resins are too dry, there is a chance that after the glue has set there will be stresses set up in the laminate as the timber adjusts to the humidity in the environment. Epoxy resins are tolerant of moisture differences in the substrate, as well as surface imperfections, oil and grease. The maximum moisture content at the time of gluing is 15%. A small tolerance of 3% moisture content is permitted between adjacent boards in an assembly.

1.14.4 Corresponding movement

It is of great importance to reduce as much as possible any alteration in moisture content of the laminated member after manufacture, as the timber will shrink when it dries and swell when it gets wet. These movements will produce stresses in the timber and glue lines, and may lead to delamination and damage to the surface finish of the timber. Tests have shown that these internal stresses, which are proportional to the dimensional changes, are particularly damaging when the moisture content is lowered below that of curing. For laminated sections in furniture, the main cause of rejection is distortion. This usually takes the form of twisting of laminates, with cross sections curling and bends opening up unevenly. To gauge how a laminated section will behave after it leaves the mould is mostly guess work and is usually left to experience.

Species	*Equilibrium moisture content at 90% humidity (%)*	*Equilibrium moisture content at 50% humidity (%)*	*Tangential Movement* (%)	(mm/m)	*Radial Movement* (%)	(mm/m)
Small movement						
Balsa	21	11	2.0	19.05	0.6	6.10
Douglas Fir	19	12.5	1.5	13.75	1.2	10.65
African Mahogany	20	13.5	1.5	13.75	0.9	8.40
Medium movement						
English Oak	20	12	2.5	23.65	1.5	13.75
Scots Pine	20	12	2.2	19.85	1.0	9.15
Large movement						
Beech	20	12	3.2	28.95	1.7	15.25
Birch (yellow)	21.5	12	2.5	22.10	2.2	19.80

Table 20. Movement of timbers (Anon., 1974)

1.14.5 Thickness of laminations for bending

Curved laminated members require the use of thinner laminations than straight members, the thickness governed by the design requirements and the radius of curvature. Different species of timber have different bending properties, and the species may also influence the maximum thickness. The smaller the number of laminations the less it will cost to produce, as there will be a saving in adhesive, man and machine hours.

1.14.6 Radius of curvature

It is uncommon, except in the manufacture of structural members, to incorporate laminae much over 0.125 inches (3mm), but in selecting the thickness of laminae to be used one of the most important factors to be considered is the limiting radius of curvature to which the wood can be bent without fractures occurring. The table below has been compiled from data obtained at the Forest Products Research Laboratory and indicates the safe radius of curvature to which certain laminae may be bent so that only 5% of the total number of bent pieces will fracture during the process. Material is assumed to be good quality, free from all defects, straight grained, bent cold and dry around unheated forms with the grain at 90° to the axis of curvature. In general, hardwood laminae can be bent to smaller radii than softwood laminae of the same thickness.

Species	*Thickness of laminae* (mm)	*Radius* (mm) *at which breakages less than 5%*	*Ratio: radius/ thickness of laminae*
Ash (home grown)	3.175	121.90	38
Beech (home grown)	3.175	111.75	35
Mahogany (African)	3.175	152.40	48
Oak (home grown)	3.175	147.30	46
Sycamore	3.175	104.15	32

Table 21. The limiting radii of curvature of various species of laminae (Anon., 1989)

1.14.7 Movement and distortion of laminated beams

When laminated bends are removed from forms, outward movement occurs and shear stresses are induced in the glue lines. Movement continues until the induced moment of resistance in the piece just balances the residual bending moments in the laminae. Shear forces in the glue tend to be greater near the ends than at the centre of a bend, and movement or straightening is more pronounced near the ends. The extent of this outward movement is usually small when thin laminae are used, and the thinner the laminae the less the tendency for a set bend to open on release of the pressure, but the thinner the laminae the greater the quantity of glue used.

1.14.8 Distortion

When bending an elastic material, compression and tensile stresses are respectively induced along the concave and convex surfaces. These stresses produce strains in their own direction, but at the same time produce opposite strains in perpendicular directions. The longitudinal shortening of the compressed concave surface is therefore accompanied by a lateral expansion, and similarly the longitudinal stretch of the convex surface is accompanied by a lateral shortening. It follows that by bending the material in one plane a tendency will be induced for it to bend in a plane at right angles to the first but in the opposite sense. Such curvature (ie induced from bending moments) appears in the form of cupping of the cross section of a bent piece, but usually the extent of the distortion so produced is small and of little consequence.

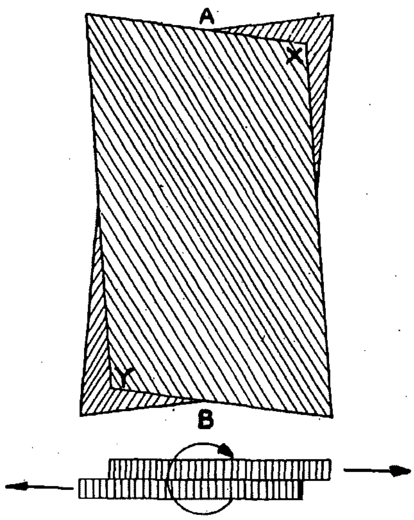
1.14.9 Causes of Distortion

Curved or flat laminated assemblies containing grain that deviates from the straight are subject to distortion as the result of moisture change. If wood with curved grain is used there will be a tendency on drying for the piece to curve in the same direction as the curvature of the grain. Similarly, if the grain is in spiral form there will be a tendency for the assembly to twist on drying. This can be eliminated by selecting only straight grained timber and by ensuring the pieces are conditioned to one and the same moisture content before assembly. Straightness of grain does not preclude the possibility of the laminated assembly twisting as a result of moisture change unless the grain is absolutely parallel with the sides, or parallel grain exists throughout the assembly. To illustrate the effect that inclination of grain may have upon the twisting of laminated bends, Figure 22 represents an assembly made of two laminae with the grain of the top piece inclined at an angle to the grain of the bottom. The diagonal lines represent grain lines as they appeared before assembly on the top and bottom pieces.

1.14.10 Discussion of Figure 22

If it is assumed that virtually no shrinkage takes place in the direction of the grain but that there is shrinkage in the direction normal to the grain as a result of drying, it is apparent that the top right corner X and bottom left corner Y of the top lamina will tend to approach one another, and the other two corners will also tend to approach one another, but to a much lesser extent. The face of the lamina will in effect diamond, and the longer edges tend to orientate themselves in the direction of the grain. The lower lamina will behave similarly, but the orientation will be in the opposite direction. If free to move, the end sections would assume relative positions as illustrated in Figure 22. The glue inhibits the relative movement, and consequently forces are developed, with the top lamina pulling in one direction, and the bottom in the other direction with an equal force. These two forces form a couple or turning moment which tends to twist one end in an anti clockwise direction as viewed from the other end. The whole piece is subjected to torsion, and twisting is the probable outcome. It follows that by crossing the grain of two or more laminae in a pack, a tendency for the glued assembly to twist is induced as a result of subsequent moisture change. The intensity of twisting likely to develop will be dependent upon a number of factors, such as degree of moisture change, the angle of crossing of the grain lines, the relative positions and thicknesses of the parts having opposed grain, and strength characteristics. Cook of Buckinghamshire College (1986) studied the use of cross lamination - the turning of adjacent plies by 90° as in plywood. The laminate is then restrained by less swelling in adjacent plies. This fundamentally alters the properties of preformed laminated shapes, as the laminate is much harder to bend around complex (concave) forms, but the same result could well be achieved by using woven sheets of stiff yet drapable, stable composite materials in place of some of the timber cross laminations.

1.4.10 Continued



TOP: Plan
BOTTOM: End Section
Arrows indicate forces induced at B if relative movement of laminae is inhibited by gluing.

Figure 22. Diamonding effect leading to twist

1.14.11 Distortion - Summary

The movement associated with bent laminates has 3 distinct aspects:

(a) The inherent opening movement of the laminae attempting to return to its flat condition on being released from pressure. This problem is less pronounced with thinner laminates.

(b) The contraction of the bend caused by a reduction in moisture content. This can be lessened by choosing timber of the correct moisture content, applying as little adhesive to each laminae as is practicable, and adding the minimum amount of water to the adhesive consistent with the production of a good bond.

(c) Shrinkage distortion which takes the form of cupping or twisting, caused by differential shrinkage between various laminae within an assembly. Careful selection and balancing of adjacent laminae can reduce the movement, but this is tedious and uneconomical.

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2.1 Introduction

Many factors influence the choice of materials used for furniture production. These include cost, strength, stiffness, weight, appearance, availability, health and safety issues, and increasingly, ethical and environmental issues. How easily materials can be processed has a major impact on the costs involved, as does the ease with which existing machinery can be adapted to the new material. The furniture industry has in the past been reluctant to invest in new technologies, therefore materials that can be processed by adapting existing machinery would have a greater chance of being used. Many new design ideas are initially presented as small batch produced items, so low cost tooling and low set-up costs are more important than fast turn around times.

2.1.1 Chosen Materials

The reinforcement chosen for this study is woven glass fibre cloth. This was chosen as it is the cheapest fibre reinforcement, but offers a tensile strength, impact strength and stiffness far superior to wood, is readily available in a wide variety of forms, presents few known health risks, and is a neutral colour. Carbon fibre and aramid fibre (Kevlar) were also tested for comparison. Adhesives used are urea formaldehyde (Cascamite and Borden UL39), and two 2-pack epoxy resins (SP Systems SP110 and West Systems 105B). Urea formaldehyde is the most widely used adhesive in the furniture industry due to its low cost, high strength bonds to wood, and its ability to be cured quickly at an elevated temperature. Epoxy resins have higher strengths than urea formaldehyde and form a much better bond with the surface of fibre composites. Epoxy resins, being non-polar in nature, cannot be cured by Radio Frequency (RF) heating, which is widely used for fast (1-2 minute) joint curing of polar urea formaldehydes.

Adhesive	*Tensile Modulus* (GPa)	*Tensile Strength* (MPa)	*Break Strain* (%)	*Flexural Strength* (MPa)	*Flexural Modulus* (GPa)	*Coeff. of thermal expansion*
Urea Formaldehyde (Borden UL39)	2.12	48	0.90%			35x10^{6} °C
Urea Formaldehyde (Cascamite)	2.02	45	1%			30x10^{6} °C
Epoxy Resin (SP System SP110)	3.35	62	2.85%	101.2	3.65	56x10^{6} °C
Epoxy Resin (West System 105B)	3.55	65	5%	98.65	3.50	60x10^{6} °C

Table 22. Chosen Adhesives: Mechanical Properties (Epoxy values are for 20°C cure) (see Appendix 3 for Post Cured Values)

2.1.2 Manufacturing Method

Laminating is a widely used manufacturing process in the furniture industry, but suffers from a high rejection rate due to distortion. Distortion of laminated sections is caused by all the grain following the curve of the form, to counteract this tendency cross laminations are inserted to give the section more stability. Since the grain of these pieces is at 90° to the curve, the section becomes difficult to bend, and therefore complex shapes are avioded as bends tend to straighten

2.1.2 Continued

out. Pre-formed laminates tend to be thick in section to help stability, and are therefore ungainly and heavy. The use of fibre reinforcement could perhaps replace cross laminations as a way of providing stability but without causing lay-up difficulties, especially in the stable woven form.

2.2 Sample Dimensions

The fixed dimension for testing in a 3-point bending jig is the length. The span between the two outer supports of the jig is 280mm. British Standard samples have a 20mm x 20mm cross section for small clear wood specimens, but since the behaviour under load of wood/fibre composites will be different, especially with respect to shear, the BS dimensions are not that relevant here, although a standard BS 373 testing rig is used for all samples (see Figure 24).

2.2.1 Span/Depth Ratio

With a span of 280mm and a depth of 20mm, the BS sample will have a span/depth ratio of 14:1. If this remains constant, shear can be ignored when comparing wood beams of similar species. By varying the dimensions, the effect of span/depth ratio on shear can be studied.

2.2.2 British Standards

BS 373 (Anon., 1957) deals with testing of small clear wood specimens. The 2cm standard beam has a 2cm x 2cm cross section, with a length of 30cm, the span between supports being 28cm. For 4 point loading, the samples are 4cm x 4cm cross section, with a 40 cm span.

2.2.3 Statistical Requirements

Ten samples of each configuration were tested. It was assumed that although some of the samples, especially those reinforced with carbon fibre, would have great improvements in mechanical properties, there would be fair amount of agreement between many of the sample groups, therefore deviation from the mean would not be excessive.

2.2.4 3-point Bending: Problems

The use of 3-point bending jigs is standard in the timber industry for calculating modulus values. It introduces shear forces into the sample as discussed in 1.3 Composite Beams (page 6). These shear values can be calculated as discussed, yet they could be avoided altogether by using a 4-point bending jig. A 4-point jig was not used in this case as there is little precedent for its use in timber testing. Shear stress is always accompanied by tensile and compressive stresses which contribute to the deflection of the beam. The contribution to the deflection of the beam caused by shear is illustrated in Figures 38 and 39. The effect of shear will be greater for the composite beams than the solid and laminated timber control samples, as discussed in 1.3.

2.3 Modulus of Rupture

The General Bending Equation states:

$$\frac{M}{I} = \frac{\partial}{y} = \frac{E}{R}$$

where M = bending moment (Nm), I = second moment of area (m^4), ∂ = Modulus of Rupture or stress due to bending (N/m^2 or Pa), y = distance from neutral axis to extreme fibre (m), E = Modulus of Elasticity (N/m^2 or Pa), R = radius of curvature. I (second moment of area) of a rectangular section will be equal to:

$$\frac{bd^3}{12}$$

thus:

$$\partial = \frac{My}{I} = \frac{Fld}{8I},$$

and for a rectangular sample this can be written:

$$\text{Modulus of Rupture } (\partial) = \frac{3Fl}{2bd^2},$$

where F = Peak load (N), l = span of 3 point bending jig (m), b = breadth of sample (m), depth of sample (m). The modulus of rupture value is approximately double the true tensile strength for timber (for laminated timber, tensile strength ≈ 45% of MOR), and is a measure of flexural strength. Modulus of rupture is the maximum transverse breaking stress that the sample can withstand before rupture.

2.4 Modulus of Elasticity

$$\text{Modulus of Elasticity (E)} = \frac{Fl^3}{4ebd^3}$$

where F = Peak load (N), l = span of jig (m) , e = extension at peak load (m), b = breadth (m), d = depth of sample (m). Units of Modulus of Rupture and Modulus of Elasticity are N/m^2 or Pa (Pascals).

2.5 Impact Strength

The test used was a notch impact test, with the impact value quoted as energy for fracture per unit area, preferred units being kJ/m^2. The area is the cross sectional area of the sample, excluding notch. This test measures the work done in breaking the notched test pieces on the Hounsfield Plastics Impact Tester, and therefore indicates the resistance to stress concentrations. The standard size of specimen is 0.25 inches (6.35mm) width and 0.144 (3.65mm) inches thick, the dial reading is taken as energy in ft lbs, this is subsequently converted to kJ/m^2. The impact blow occurs at mid span directly behind the notch, and is supplied by a tup of 1-2lbs

2.5 Continued

(0.45 - 0.9kg). Ten specimens are recommended for each type of sample to give representative results and allow accurate statistical analysis, so ten samples of each group were tested.

2.6 Curved Samples

The General Bending Equation is applicable to standard straight beams. For beams with a different geometry, the results given by this analysis will not be accurate. In order to analyse the stiffness of the curved samples, a more accurate curved beam theory was used, that has been devised for this geometry in conjunction with Dr George Simpson of Brunel University. The derivation follows:

The geometry of the curved beams does not fit any standard cases, so consider an *almost straight* beam with a radius of 10m and an enclosed angle Ø of π/360 or 0.5°.

This gives:

$R\sin Ø = 10\sin(\pi/360) = 0.087265$

or an almost straight simply supported beam of length 0.17453m. For a dead straight simply supported beam:

$$\partial = \frac{Wl^3}{48EI} \text{ or } k = \frac{48EI}{l^3} \text{ therfore } k = \frac{48}{(0.17453)^3}EI = 9028.7EI$$

Where k = stiffness, curved beam has constant flexural rigidity EI, ∂ = deflection due to force W, with W = 2P, l = horizontal length of beam.

Castigliano's 2nd Theorem:

$$\text{Strain Energy } U = \int_{\mu=0}^{\mu=ø} \frac{M^2 ds}{2EI},\ ds = R\,dø \text{ and } M(\mu) = WR[\sin ø - \sin(ø-\mu)]$$

$$\text{deflection due to W, } \partial = \frac{\partial U}{\partial W} = \int_{\mu=0}^{\mu=ø} \frac{M}{EI}.\frac{\partial M}{\partial W}.ds,$$

$$\partial = \int_{u=0}^{\mu=ø} WR[\sin ø - \sin(ø-\mu)]R[\sin ø - \sin(ø-\mu)]R.d\mu$$

$$\text{therefore } \partial = \frac{WR^3}{EI}\int_{\mu=0}^{\mu=ø}[\sin ø - \sin(\mu - ø)]^2.d\mu$$

$$I = \int_{\mu=0}^{\mu=ø}[\sin ø - \sin(ø-\mu)]^2.d\mu,\ \text{let } u = ø-\mu, \text{ so } \frac{du}{d\mu} = -1,\ d\mu = -du,\ \mu=0 \text{ then } u=ø,\ \mu=ø \text{ then } u=0$$

$$\text{So } I = -\int_{u=ø}^{u=0}[\sin ø - \sin u]^2.du = \int_{u=0}^{u=ø}[\sin ø - \sin u]^2.du = \int_{u=0}^{u=ø}(\sin^2 ø - 2\sin ø.\sin u + \sin^2 u).du$$

$$= [u.\sin^2 ø]_0^ø + 2[\sin ø.\cos u]_0^ø + \int_0^ø 1/2(1-\cos 2u).du = ø.\sin^2 ø + 2(\sin ø.\cos ø - \sin ø) + [u - 1/2\sin 2u]_0^ø$$

$$= ø\sin^2 ø + \sin 2ø - 2\sin ø + 1/2(ø - 1/2\sin 2ø) = 1/2ø + ø\sin^2 ø + 3/4\sin 2ø - 2\sin ø$$

2.6 Continued

Therefore deflection due to W, $\partial = \frac{WR^3}{EI}(1/2\phi + \phi\sin^2\phi + 3/4\sin^2\phi - 2\sin\phi)$

Stiffness $k = \frac{P}{\partial} = \frac{2W}{\partial} = \frac{2EI}{R^3}\frac{1}{(1/2\phi + \phi\sin^2\phi + 3/4\sin2\phi - 2\sin\phi)}$ (with ϕ in radians)

Maximum stress occurs under load P and is the principal stress arising from:

$\partial_x = \frac{M_{max}Y_{max}}{I}$

This occurs in bending, but assumes an isotropic material.

Shear $\Delta_{xy} = \frac{P}{2A}$ where A = area, $\partial_y=0$, $M_{max}=\frac{P}{2}R\sin\phi$

This formula can be proven thus:

Using: $k = \frac{2EI}{R^3}\frac{1}{(1/2\phi + \phi\sin^2\phi + 3/4\sin2\phi - 2\sin\phi)}$ with R = 10m and $\phi = \pi/360$ gives:

$k = \frac{2EI}{1000}\frac{1}{(\pi/720) + \pi/360.(\sin\pi/360)^2 + 3/4\sin\pi/180 - 2\sin\pi/360}$

$k = \frac{2EI}{1000}\frac{1}{4.363\text{x}10^{-3} + 6.645\text{x}10^{-7} + 0.01309 - 0.017453} = \frac{2EI}{1000}\frac{1}{2.211892\text{x}10^{-7}} = 9042.03EI$

For a dead straight simply supported beam, k = 9028.7EI

For this case, derived formula states that k = 9042.03EI, *so formula is proved to be correct.*

'What would life be without mathematics, but a scene of horrors?' (Rev. Sydney Smith, 1835)

2.6.1 Testing of Curved Samples

For the previous equation (2.6) to be applicable, the two ends of the curved beam must be free to move outwards as the load is applied. In order to achieve this, two bearings were fixed on to a specially made plate on each end of the beam. These bearings had a 1kN rating, and can therefore be assumed to be working at well under capacity, and thus be frictionless. These bearing plates were allowed to move freely on the bed of the testing machine (see Figure 24).

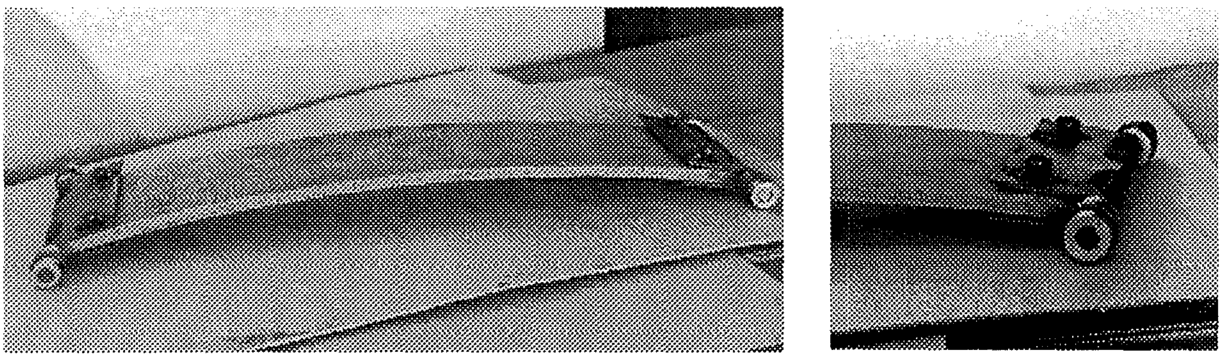


Figure 23. Frictionless Bearing Plates for Testing of Curved Beams

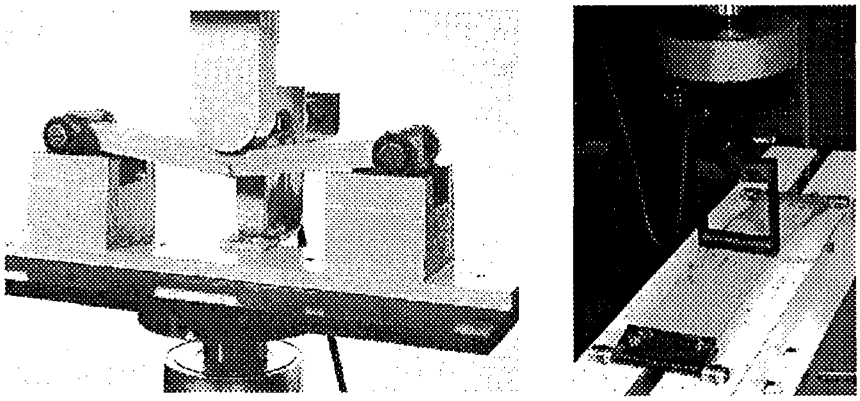


Figure 24. 3-point bending jig for testing of flat samples, and jig for curved samples

The two jigs are not dissimilar, although the 3-point jig allows the sample to be tested to failure, whereas the jig for curved samples only allows testing within a small section of the elastic region. This is sufficient to calculate the modulus of elasticity, if not the modulus of rupture.

2.6.2 Curved Samples - Adhesives

All curved samples were glued using Borden UL39 urea formaldehyde adhesive suitable for curing using Radio Frequency (RF) heating. RF heating has the advantage of much faster curing over normal elevated temperature curing of UF. The radio frequency field is applied by a series of crossing wires which cure the adhesive immediately in the areas around the wires. The remaining adhesive is allowed to cure naturally, with the joint held firmly by the small amount of cured adhesive. This process allows the laminate to be cured in 45 seconds, with longer cure times causing boiling of the adhesive. Epoxy resins are not suitable for RF curing, although some phenol resorcinol formaldehyde adhesives can be cured with the inclusion of a small amount of sodium chloride, which increases the polarity of the adhesive (see Appendix 6).

2.6.3 Radio Frequency Heating

Radio frequency or *dielectric* heating is a system that utilises an alternating current to effect energy absorption by the material (the dielectric) placed in the electric field. To obtain resonance, with the necessary molecular vibration to generate useful heat, requires that the frequency of the alternating current shall be high and that the substance to be heated shall have an appropriate loss factor at that frequency. The loss factor is the product of the dielectric constant (permittivity) of the material and its power factor. Deionised water has a power factor of 1 and a dielectric constant of 80, giving it a loss factor of 80 compared with 0.001 for polystyrene. This means that water is 80,000 times easier to heat by the dielectric method than polystyrene; it follows that the higher the loss factor the more quickly the material heats up, other things being constant.

2.6.4 Radio Frequency Theory

The quantity of heat generated in the material is a function of its dimensions, its loss factor, the square of the voltage, and the frequency. The power available for conversion to heat in the dielectric material is given by:

2.6.4 Continued

$$Power\ (\text{kW}) = 1.41\,\frac{V^2 f.FA}{d} \times 10^{-15}$$

Where V = applied voltage, f =frequency, F = loss factor, A = area of material, and d = thickness of material. It is difficult to apply this equation accurately in considering glued wood joints because two loss factors are involved: that of the wood and of the glue; the arrangement of the gluelines relative to the electrodes is also important (see Figure 25). For a given loss factor and voltage, the heat generated is proportional to the frequency. The most suitable materials to heat by dielectric heating are organic polar substances, or those that behave as polar substances through the water they contain. Wood that is completely dry has a low loss factor, but the loss factor increases sharply as normal moisture content is assumed because of the high loss factor of water. In the gluing of wood by dielectric heating, it is undesirable to raise the temperature of the wood, although this is often inevitable. In many gluing applications, since an aqueous adhesive has a higher loss factor than the wood - at least until water has been evaporated from the adhesive - heating takes place preferentially in the glue and to a lesser extent in the wood.

2.6.5 Mould Tuning

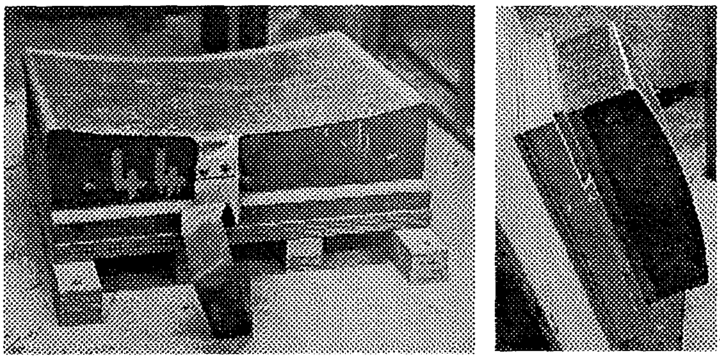
An electronic generator supplies a voltage of 1000 to 20000 V at a frequency of from about 2 x 10^6 to 20 x 10^6 Hz. A common frequency for gluing wood is 10-15 x 10^6 Hz, an internationally agreed value has been fixed at 13.56 x 10^6 Hz (Houwink and Salomon, 1967), which was used for the experiments here. The RF generator must be tuned to the correct frequency for the particular mould being used. This frequency depends on the area and thickness (hence the volume) and the specific metal used for the conductors that surround the laminate. Tuning involves adding capacitors until the correct impedance is reached to tune the circuit. Incorrect tuning causes excessive heat generation in the circuit, with the result that the adhesive will boil and the capacitors will overheat, and may explode. Experimentation did involve some trial and error to find the correct capacitance, during which some capacitors did explode, with the casing of the capacitor being thrown two metres away. Once the correct tuning has been reached, this was written on the mould along with cure time, as this will apply to all laminates of the same thickness, using the same glue and wood species.

2.6.6 Radio Frequency Heating - Advantages

A difficulty in the production of laminated and plywood assemblies is the length of time needed for heat to penetrate to the glue in the centre. This time factor is proportional to the square of the thickness of the materials. Thus a two inch thick assembly will take sixteen times as long to set as an assembly half an inches thick. RF heating uses current similar to AC but it has a frequency of around 1MHz rather than 50Hz. The effect of the current is to agitate the polar particles in the

2.6.6 Continued

molecules of the timber and glue, and in the process heat is generated. The rate of heating is constant throughout, irrespective of the distance from the metal plates. The rate of heating depends on the material - wet timber and synthetic resins heat up more rapidly than dry timber. This allows laminates to be cured evenly with an absence of 'checking' and 'honeycombing' due to uneven rates of drying. As RF heating cures in a check pattern like a microwave oven, the cured glue holds the laminate together as the remaining glue dries naturally.



Left: Bottom section of mould showing metal face of mould and electrode. Glue lines in the mould are all PRF and are horizontal to prevent heat transfer to the platens of the press. *Right:* Top section of the mould, with metal face of the mould and earthing strap. The great bulk of the mould is necessary for RF insulation.

Figure 25. Radio Frequency Mould (Curved Samples)

2.6.7 Data for Radio Frequency Moulding

Time for Cure: 45 secs *Before release from mould:* 1.5 minutes *Time for Full Cure:* 1 hour
Cycle Time (total time for each moulding operation): 2.5 minutes
Capacitance Used: 5pF and 15pF capacitors used to 'tune' mould to 13.56 x 10^6 Hz (see 2.6.5)
Current Used: 100 A *Adhesive:* Borden UL39 (2 pack resin/hardener urea formaldehyde).
All radio frequency cured samples were made using the curved mould shown in Figure 25 using Borden UL39 and 1.5mm beech structural veneers. Samples 1-4 contain 7 beech veneers and a glass fibre layer in the centre and on each face, samples 5-7 and 10-12 contain 7 veneers only, with 2 veneers at 90° to the curve for samples 10-12, samples 8 and 9 contain 7 veneers and glass fibre between each veneer, and samples 13-15 contain glass fibre on each face only.
Pulfer (1991) found the optimum RF cure time for a similar sized urea formaldehyde bonded sample to be 45 seconds, and this was the cure time used here. This gave greater strength and a higher percentage of wood failures as opposed to bond failures than 'naturally cured' joints.

RF Cure Time	*Mean Stress*	*S.D.*	% Wood Failure
30 secs	7.90 MPa	3.13	59
45 secs	9.44 MPa	1.51	74
60 secs	7.21 MPa	2.16	60
75 secs	7.67 MPa	2.70	60
Natural Cure	6.51 MPa	3.36	36
Solid Timber (mc 11%)	12.43 MPa	1.79	100

Table 23. The Effect of Curing Urea Formaldehyde with Radio Frequency (Pulfer, 1991)

2.6.8 Data for Press Cured Moulding

Time for Cure (before release from mould): 1.5 hours (Cascamite)
Cycle Time (total time for each moulding operation): 1.75 hours
Temperature: limited to approximately 80°C
Adhesive: Borden Cascamite (single-pack water soluble powder urea formaldehyde).

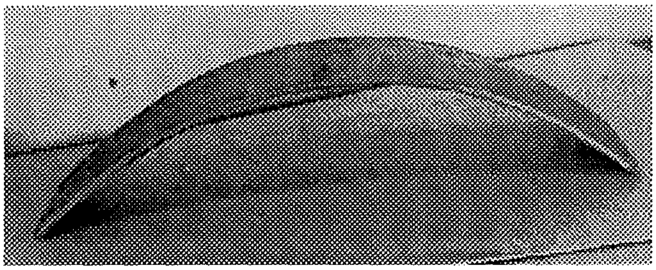


Figure 26. Glass Fibre Reinforced Sample

Time for Cure: 8 hours (Epoxy)
Cycle Time: 8.25 hours
Temperature: Approximately 40°C
Adhesive: SP Systems SP110 and 110SD standard hardener (2 pack epoxy resin) (see Appendix 3 for specifications)

2.7 Lay up of Samples

Sample numbers 1-10 were made from laminated birch, using conditioned 1.5mm (nominal) structual birch veneers and Cascamite. Seven veneers gave an actual sample thickness of 10mm.
Samples 11-20 were made from six birch veneers and Cascamite, with carbon fibre under the first, last and centre veneers, as far from the neutal axis as possible, yet with a timber skin.
Samples 21-30 contained six beech constructional veneers and SP110 epoxy resin, with carbon fibre under the first and last layers of beech.
Samples 31-40 contained six layers of 1.5mm oak veneer and Cascamite, with glass fibre under the first and last layers, and one layer of glass fibre in the centre of the laminate.
Samples 41-50 contained six layers of 1.5mm oak veneer and Cascamite, with glass fibre under the first and last layers of oak.
Samples 51-60 contained six layers of 1.5mm oak veneer and Cascamite, with carbon fibre under the first and last layers of oak.
Samples 61-70 were solid birch control samples, 5mm thick.
Samples 71-80 were solid beech control samples, 15mm thick.
Samples 81-90 were solid pine control samples, 20mm thick.
All veneers were conditioned in the testing environment for 21 days prior to testing.

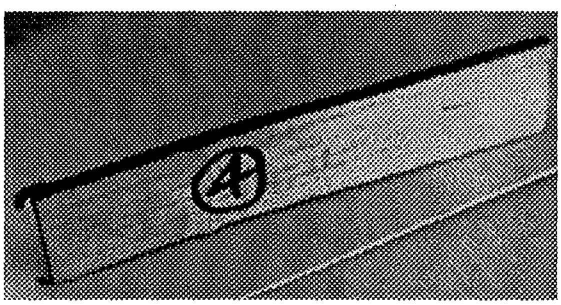


Figure 27. Carbon Fibre Reinforced Wood

Fibre reinforcement was placed towards the outer edge of the samples for most gain in stiffness and strength. Although the carbon fibre reinforced samples have black lines between the wood layers, they look quite decorative, and there is no fraying of fibres when cut. The fibre layers look similar to ebony inlays on the edges. Glass fibres blend into the glue lines and become very difficult to notice.

2.7.1 Application of Adhesives

The curved samples were cured by radio frequency using Borden UL39 urea formaldehyde adhesive. The low viscosity of this adhesive is the same as the Borden/Humbrol Cascamite urea formaldehyde used for samples 1-10, 11-20, 31-40, 41-50 and 51-60. Both were applied using gravity fed roller applicators which coat the veneers with a consistent amount of adhesive. The epoxy used, SP110, is a medium viscosity epoxy which is difficult to spread evenly at room temperature, although the viscosity decreases significantly with temperature, which can cause the adhesive to creep out of the joint while pressing. Application of epoxy resin was carried out by grooved rollers, supplied by SP Systems (see Appendix 3) to ensure even coverage.

2.8 Discussion of Experimentation

Preparation for experimentation immediately presented the problem of cutting the woven Kevlar fabric. Without aramid shears, there is no way of cutting the fabric cleanly, without ripping fibres out of the weave. This would cause a great deal of wastage, and due to the high cost of the fibre, Kevlar was not used for this study, even though the anticipated performance of aramids was high, as discussed in 1.8. It is anticipated that, in view of the points raised in 1.8, Kevlar would give very good performance in impact, and strength and stiffness values in between glass fibres and carbon fibres. Previous work has also highlighted the poor bond quality of many adhesives to aramids (see 1.3.17 Ng). Two epoxy resins were assessed for ease of use, viscosity, cost, speed and versatility of cure. SP110 was found to be better in some important respects, as it had a slightly lower viscosity which makes for much easier adhesive spreading, and also it could be cured at elevated temperatures, thus considerably reducing cure times. West 105B has the better mechanical properties when room temperature cured, but it cannot be heated above 40°C as it will not cure. Due to a faulty thermostat on the press being used, several samples were overheated, and the epoxy lost all its viscosity, and deposited itself rather expensively over the press. SP Systems SP110 was therefore used, as when cured at an elevated temperature, cure time is quicker, and mechanical properties are improved. The curing of epoxies with low voltage heating (see 6.3) would have been an interesting proposition, but facilities were unavailable to try this. The use of radio frequency heating for the curing of urea formaldehyde was hindered by a general lack of information on tuning of moulds, and without specialist equipment, getting the mould to heat up correctly involved a lot of experimentation with different capacitors. Some early attempts at RF curing were hindered by the adhesive boiling at points along the laminate, whilst other areas had received no heat at all. Mould construction for use with RF heating is also a time consuming and costly exercise, as phenol resorcinol formaldehyde glues are used, which are relatively unaffected by radio frequency heating. All glue lines must however be staggered and be parallel to the press platens so as not to allow an easy path for heat to travel to the body of the press.

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Sample No.	*Materials:* Wood, adhesive, % fibre reinforcement	*Dimensions:* (mm) (w x d)	*∂: MoR* (MPa)	*E: MoE* (GPa)	*Mean & S.D. of group*
1	Control: Birch/UF	35 x 10	138.086	6.575	*∂ Mean* =
2	Control: Birch/UF	35 x 10	121.800	6.262	117.726 MPa
3	Control: Birch/UF	35 x 10	117.858	7.143	*S.D.* = 14.36
4	Control: Birch/UF	35 x 10	93.943	6.263	*CoV* = 588.6
5	Control: Birch/UF	35 x 10	114.235	6.244	*t* = 3.08
6	Control: Birch/UF	35 x 10	131.314	6.852	*E: Mean* =
7	Control: Birch/UF	35 x 10	119.143	7.208	6.708 GPa
8	Control: Birch/UF	35 x 10	95.143	5.766	*S.D.* = 0.611
9	Control: Birch/UF	35 x 10	115.878	6.899	*CoV* = 33.54
10	Control: Birch/UF	35 x 10	129.857	7.870	*t* = 7.50
11	Birch/UF/50% Carbon	45 x 10	121.421	1.821	*∂: Mean* =
12	Birch/UF/50% Carbon	45 x 10	109.444	1.642	111.637 MPa
13	Birch/UF/50% Carbon	45 x 10	114.999	1.725	*S.D.* = 4.61
14	Birch/UF/50% Carbon	45 x 10	111.019	1.645	*CoV* = 558.2
15	Birch/UF/50% Carbon	45 x 10	108.518	1.621	*t* = 5.55
16	Birch/UF/50% Carbon	45 x 10	116.851	1.767	*E: Mean* =
17	Birch/UF/50% Carbon	45 x 10	109.259	1.694	1.670 GPa
18	Birch/UF/50% Carbon	45 x 10	109.259	1.645	*S.D.* = 0.077
19	Birch/UF/50% Carbon	45 x 10	107.036	1.565	*CoV* = 8.350
20	Birch/UF/50% Carbon	45 x 10	108.564	1.625	*t* =147
21	Beech/Epoxy/30% Carbon	70 x 10	159.785	8.201	*∂ Mean* =
22	Beech/Epoxy/30% Carbon	70 x 10	117.342	7.857	139.202 MPa
23	Beech/Epoxy/30% Carbon	70 x 10	129.213	7.965	*S.D.* = 14.72
24	Beech/Epoxy/30% Carbon	70 x 10	157.970	8.776	*CoV* = 696.1
25	Beech/Epoxy/30% Carbon	70 x 10	127.071	7.701	*t* = 7.65
26	Beech/Epoxy/30% Carbon	70 x 10	154.328	7.866	*E: Mean* =
27	Beech/Epoxy/30% Carbon	70 x 10	138.231	7.356	7.806 GPa
28	Beech/Epoxy/30% Carbon	70 x 10	128.056	7.805	*S.D.* =0.465
29	Beech/Epoxy/30% Carbon	70 x 10	146.914	7.143	*CoV* =39.03
30	Beech/Epoxy/30% Carbon	70 x 10	133.114	7.395	*t* = 17.27
31	Oak/UF/50% E Glass	80 x 10	72.680	1.768	*∂: Mean* =
32	Oak/UF/50% E Glass	80 x 10	83.213	1.067	79.319 MPa
33	Oak/UF/50% E Glass	80 x 10	86.475	2.111	*S.D.* =5.969
34	Oak/UF/50% E Glass	80 x 10	79.351	2.001	*CoV* =396.6
35	Oak/UF/50% E Glass	80 x 10	69.938	2.145	*t* =12.83
36	Oak/UF/50% E Glass	80 x 10	78.562	1.975	*E: Mean* =
37	Oak/UF/50% E Glass	80 x 10	73.763	2.083	1.910 GPa
38	Oak/UF/50% E Glass	80 x 10	81.235	2.143	*S.D.* = 0.321

Table 24. Results: Moduli (Mean, Standard Deviation, Coefficient of Variation, t value)

Sample No.	*Materials:* Wood, adhesive, % fibre reinforcement	*Dimensions:* (mm) (w x d)	*∂: MoR* (MPa)	*E: MoE* (GPa)	*Mean & S.D. of group*
39	Oak/UF/50% E Glass	80 x 10	88.652	1.967	*CoV* = 9.548
40	Oak/UF/50% E Glass	80 x 10	79.321	1.817	*t* =32.60
41	Oak/UF/30% E Glass	85 x 10	65.129	2.714	*∂: Mean* =
42	Oak/UF/30% E Glass	85 x 10	55.753	2.445	62.253 MPa
43	Oak/UF/30% E Glass	85 x 10	53.545	3.191	*S.D.* = 6.363
44	Oak/UF/30% E Glass	85 x 10	60.165	3.856	*CoV* = 40.48
45	Oak/UF/30% E Glass	85 x 10	52.721	2.751	*t* = 20.52
46	Oak/UF/30% E Glass	85 x 10	67.279	3.506	*E: Mean* =
47	Oak/UF/30% E Glass	85 x 10	69.265	3.193	3.084 GPa
48	Oak/UF/30% E Glass	85 x 10	69.151	3.592	*S.D.* = 0.457
49	Oak/UF/30% E Glass	85 x 10	66.785	2.865	*CoV* = 0.209
50	Oak/UF/30% E Glass	85 x 10	62.737	2.726	*t* =15.01
51	Oak/UF/25% Carbon	75 x 10	88.520	1.788	*∂: Mean* =
52	Oak/UF/25% Carbon	75 x 10	94.160	1.067	89.522 MPa
53	Oak/UF/25% Carbon	75 x 10	96.240	2.111	*S.D.* = 4.983
54	Oak/UF/25% Carbon	75 x 10	92.240	2.001	*CoV* = 24.83
55	Oak/UF/25% Carbon	75 x 10	93.520	2.145	*t* = 8.90
56	Oak/UF/25% Carbon	75 x 10	79.440	1.975	*E: Mean* =
57	Oak/UF/25% Carbon	75 x 10	87.520	2.083	1.909 GPa
58	Oak/UF/25% Carbon	75 x 10	90.600	2.143	*S.D.* = 0.322
59	Oak/UF/25% Carbon	75 x 10	88.360	1.967	*CoV* = 0.103
60	Oak/UF/25% Carbon	75 x 10	84.600	1.817	*t* = 32.89
61	Control: Solid Birch	55 x 5	93.333	8.589	*∂: Mean* =
62	Control: Solid Birch	55 x 5	72.424	6.957	97.723 MPa
63	Control: Solid Birch	55 x 5	96.666	8.838	*S.D.* =9.954
64	Control: Solid Birch	55 x 5	105.302	10.641	*CoV* = 488.6
65	Control: Solid Birch	55 x 5	95.302	9.149	*t* = 1.85
66	Control: Solid Birch	55 x 5	102.424	9.818	*E: Mean* =
67	Control: Solid Birch	55 x 5	97.878	9.396	9.335 GPa
68	Control: Solid Birch	55 x 5	103.967	9.978	*S.D.* =1.042
69	Control: Solid Birch	55 x 5	105.934	10.163	*CoV* = 46.67
70	Control: Solid Birch	55 x 5	103.999	9.818	*t* = 12.00
71	Control: Solid Beech	20 x 15	110.267	6.251	*∂: Mean* =
72	Control: Solid Beech	20 x 15	105.532	6.253	117.339 MPa
73	Control: Solid Beech	20 x 15	132.132	6.645	*S.D.* = 7.888
74	Control: Solid Beech	20 x 15	118.798	6.857	*CoV* =586.69
75	Control: Solid Beech	20 x 15	113.465	6.349	*t* = 5.53
76	Control: Solid Beech	20 x 15	110.789	7.215	*E: Mean* =

Table 24. Continued

Sample No.	*Materials:* Wood, adhesive, % fibre reinforcement	*Dimensions:* (mm) (w x d)	*∂: MoR* (MPa)	*E: MoE* (GPa)	*Mean & S.D. of group*
77	Control: Solid Beech	20 x 15	126.398	6.735	6.667 GPa
78	Control: Solid Beech	20 x 15	120.398	6.767	*S.D.* = 0.311
79	Control: Solid Beech	20 x 15	117.865	6.932	*CoV* = 33.33
80	Control: Solid Beech	20 x 15	117.732	6.665	*t* = 14.33
81	Control: Solid Pine	20 x 20	61.613	2.281	*∂: Mean* =
82	Control: Solid Pine	20 x 20	72.975	2.365	67.024 MPa
83	Control: Solid Pine	20 x 20	69.938	2.105	*S.D.* =3.972
84	Control: Solid Pine	20 x 20	73.201	2.401	*CoV* =15.97
85	Control: Solid Pine	20 x 20	63.563	2.106	*t* = 29.07
86	Control: Solid Pine	20 x 20	67.688	2.115	*E: Mean* =
87	Control: Solid Pine	20 x 20	63.975	2.306	2.255 GPa
88	Control: Solid Pine	20 x 20	65.888	2.404	*S.D.* = 0.123
89	Control: Solid Pine	20 x 20	64.238	2.345	*CoV* = 0.016
90	Control: Solid Pine	20 x 20	67.163	2.119	*t* = 77.2

Table 24. Continued

Mean ∂ (MOR, Modulus of Rupture) (MPa)	*Mean E* (MOE, Modulus of Elasticity) (GPa)	*Standard Deviation*	*Coefficient of Variation*	*Number of Samples n*
103.544	5.258	*∂*: 2.891 *E*: 25.867	*∂*: 8.359 *E*: 669.107	90

Table 25. Mean, S.D., CoV for Parent Group

3.1 Discussion of Results

The variability of the results is high, with high standard deviations in the laminated birch group (birch/UF) (14.36 MPa for MOR), beech/epoxy/30% carbon (14.72 MPa for MOR), and solid birch (9.954 MPa for MOR). Standard deviations for elastic modulus were of the same order, ranging from 0.077 GPa (7.7 MPa) for birch/UF/50% carbon to 1.042 GPa for solid birch.

3.1.1 Mean & S.D.

The 95% confidence limit lies at 2.33 x S.D. from the mean. Confidence limits for sample groups are: *birch/UF* ∂ = 84.267 MPa, E = 5.284 GPa; *birch/UF/50% carbon* ∂ = 100.896 MPa, E = 1.491 GPa; *beech/epoxy/30% carbon* ∂ = 104.904 MPa, E = 6.723 GPa; *oak/UF/50% glass* ∂ = 65.411 MPa, E = 1.160 GPa; *oak/UF/30% glass* ∂ = 47.427 MPa, E = 2.019 GPa; *oak/UF/25% carbon* ∂ = 77.911 MPa, E = 1.159 GPa; *solid birch* ∂ = 74.530 MPa, E = 6.907 GPa; *solid beech* ∂ = 98.960 MPa, E = 5.942 GPa; *solid pine* ∂ = 57.769 MPa, E = 1.968 GPa. The 95% confidence limit (*design limit*) is a much more accurate figure to use in assessing the samples, as it takes into account the level of variance from the mean (see especially beech/epoxy/30% carbon).

3.1.2 Coefficient of Variation

Coefficient of Variation is defined as 100 x S.D./mean and is expressed as a percentage. It is used here to compare the variability of the sample groups and the variability of the parent group. CoV was again much higher for modulus of rupture than modulus of elasticity values. For example laminated birch had a CoV of 588.6% for MOR values, and only 33.54% for MOE.

3.1.3 *t* Test

The assumption of the *t* test is that there is no significant difference between the mean of the sample group and the mean of the large parent group, and the probability of this being the case is determined by calculating the value of *t*, and referring to a *t* table. Data required is n (number of samples = 90); m = mean of samples; s = standard deviation of the samples; M = mean of the large parent group; then $t = \frac{\sqrt{n}(M-m)}{s}$. A *t* table is shown:

n	Probability of no significant difference between M and m			
	10%	5%	1%	0.2%
60-120	1.67	2.00	2.66	3.23

Table 26. t Table

(i) Any probability larger than 5% is considered insufficient to deny the assumption that the results have stemmed from the same source. This situation shows that *significant difference not proven.*

(ii) A probability of 5% is *probably significant.*

(iii) A probability of 1% shows that the likelihood is that the observed difference is due to the sample groups originating from different parent groups. The difference is therefore *significant.*

The results in Table 24 can be summarised:

(a) *Control: Birch/UF:* MoR (∂) is *probably* different from the mean (t = 3.08)
MoE (E) is *significantly* different from the mean (t = 7.50)

(b) *Birch/UF/50% Carbon:* MoR (∂) is *significantly* different from the mean (t =5.55)
MoE (E) is *significantly* different from the mean (t = 147)

(c) *Beech/Epoxy/30% Carbon:* MoR (∂) is *significantly* different from the mean (t = 7.65)
MoE (E) is *significantly* different from the mean (t = 17.27)

(d) *Oak/UF/50% Glass:* MoR (∂) is *significantly* different from the mean (t = 12.83)
MoE (E) is *significantly* different from the mean (t = 32.60)

(e) *Oak/UF/30% Glass:* MoR (∂) is *significantly* different from the mean (t = 20.52)
MoE (E) is *significantly* different from the mean (t =15.01)

(f) *Oak/UF/25% Carbon:* MoR (∂) is *significantly* different from the mean (t = 8.90)
MoE (E) is *significantly* different from the mean (t =32.89)

(g) *Control: Solid Birch:* MoR (∂) is *not proven* different from the mean (t = 1.85)
MoE (E) is *significantly* different from the mean (t = 12.00)

(h) *Control: Solid Beech:* MoR (∂) is *significantly* different from the mean (t = 5.53)
MoE (E) is *significantly* different from the mean (t =14.33)

3.1.3 Continued

(i) *Control: Solid Pine:* MoR (∂) is *significantly* different from the mean (t = 29.07)
MoE (E) is *significantly* different from the mean (t = 77.2)

A t test compares a random sample of at least 3 measurements with a large parent group whose mean is known. It is a modification of the *zM* test in which the S.D. of the samples is used instead of the S.D. of the large parent group. In making this substitution we are really using the S.D. of the samples as an estimate of the S.D. of the parent group. Accordingly, it is necessary to make allowance for the fact that, in the same way as the means or proportions of different samples drawn from the same parent group show variation from one another as a result of chance, so the S.D. of different sample groups from the same source will also vary from one sample to another. The solid birch therefore represents the approximate mean value of modulus of rupture, with the laminated birch having a higher mean value of MOR, but a higher S.D., giving it a t value low enough to make it very similar to the mean MOR of the parent group. These results must be put into context, as the highest value of MOR is 139.202 MPa for beech/UF/50% carbon, compared with 62.253 MPa for oak/UF/30% glass, a value which represents only 45% of the larger MOR value. With such a wide variation between groups, comparing samples with the parent group gives very misleading results. Figures 31 to 34 present data in chart form for MOR and MOE comparing only control samples and one type of fibre reinforcement. This makes for much easier comparison.

Sample No.	*Materials:* Wood, adhesive, % fibre reinforcement	*Impact Energy* (Nm)	*Impact Strength* (kJ/m^2)	*Mean & S.D. of group*
1	Control: Birch/UF	0.51	12.364	*Mean Impact*
2	Control: Birch/UF	0.54	13.091	*Strength =*
3	Control: Birch/UF	0.52	12.606	12.485 kJ/m^2
4	Control: Birch/UF	0.53	12.849	*S.D.* = 0.416
5	Control: Birch/UF	0.49	11.878	*CoV*= 0.173
6	Control: Birch/UF	0.52	12.606	*t* = 548.138
7	Control: Birch/UF	0.53	12.849	
8	Control: Birch/UF	0.50	12.121	
9	Control: Birch/UF	0.52	12.606	
10	Control: Birch/UF	0.49	11.878	
11	Birch/UF/50% Carbon	1.89	45.818	*Mean Impact*
12	Birch/UF/50% Carbon	1.57	38.061	*Strength =*
13	Birch/UF/50% Carbon	1.51	36.606	39.806 kJ/m^2
14	Birch/UF/50% Carbon	2.39	57.939	*S.D.* = 7.383
15	Birch/UF/50% Carbon	1.63	39.515	*CoV* = 54.51
16	Birch/UF/50% Carbon	1.41	34.182	*t* = 4.221
17	Birch/UF/50% Carbon	1.30	31.515	
18	Birch/UF/50% Carbon	1.57	38.061	
19	Birch/UF/50% Carbon	1.63	39.515	
20	Birch/UF/50% Carbon	1.52	36.848	
21	Beech/Epoxy/30% Carbon	2.83	68.606	*Mean Impact*
22	Beech/Epoxy/30% Carbon	2.67	64.727	*Strength =*
23	Beech/Epoxy/30% Carbon	2.76	66.909	66.594 kJ/m^2
24	Beech/Epoxy/30% Carbon	2.61	63.273	*S.D.* = 2.397
25	Beech/Epoxy/30% Carbon	2.63	63.758	*CoV* = 5.746
26	Beech/Epoxy/30% Carbon	2.72	65.939	*t* = 120.379
27	Beech/Epoxy/30% Carbon	2.88	69.818	
28	Beech/Epoxy/30% Carbon	2.72	65.939	
29	Beech/Epoxy/30% Carbon	2.90	70.303	
30	Beech/Epoxy/30% Carbon	2.75	66.667	
31	Oak/UF/50% E GlassFibre	2.22	53.818	*Mean Impact*
32	Oak/UF/50% E GlassFibre	2.16	52.364	*Strength =*
33	Oak/UF/50% E GlassFibre	2.44	59.152	53.576 kJ/m^2
34	Oak/UF/50% E GlassFibre	2.20	53.333	*S.D.* = 2.239
35	Oak/UF/50% E GlassFibre	2.12	51.394	*CoV* = 5.016
36	Oak/UF/50% E GlassFibre	2.17	52.606	*t* = 72.263
37	Oak/UF/50% E GlassFibre	2.28	55. 273	

Table 27. Results: Impact Strength

Sample No.	*Materials:* Wood, adhesive, % fibre reinforcement	*Impact Energy* (Nm)	*Impact Strength* (kJ/m^2)	*Mean & S.D. of group*
38	Oak/UF/50% E GlassFibre	2.20	53.333	
39	Oak/UF/50% E GlassFibre	2.14	51.879	
40	Oak/UF/50% E GlassFibre	2.17	52.606	
41	Oak/UF/30% E GlassFibre	1.76	42.667	*Mean Impact*
42	Oak/UF/30% E GlassFibre	1.46	35.394	*Strength =*
43	Oak/UF/30% E GlassFibre	1.76	42.667	40.655 kJ/m^2
44	Oak/UF/30% E GlassFibre	1.71	41.455	*S.D.* = 2.289
45	Oak/UF/30% E GlassFibre	1.65	40.000	*CoV* = 5.238
46	Oak/UF/30% E GlassFibre	1.60	38.788	*t* = 17.133
47	Oak/UF/30% E GlassFibre	1.68	40.727	
48	Oak/UF/30% E GlassFibre	1.74	42.182	
49	Oak/UF/30% E GlassFibre	1.76	42.667	
50	Oak/UF/30% E GlassFibre	1.65	40.000	
51	Oak/UF/25% Carbon Fibre	1.63	39.515	*Mean Impact*
52	Oak/UF/25% Carbon Fibre	1.59	38.545	*Strength =*
53	Oak/UF/25% Carbon Fibre	1.76	42.667	39.830 kJ/m^2
54	Oak/UF/25% Carbon Fibre	1.52	36.848	*S.D.* = 1.833
55	Oak/UF/25% Carbon Fibre	1.71	41.455	*CoV* = 3.358
56	Oak/UF/25% Carbon Fibre	1.66	40.242	*t* = 17.126
57	Oak/UF/25% Carbon Fibre	1.71	41.455	
58	Oak/UF/25% Carbon Fibre	1.69	40.970	
59	Oak/UF/25% Carbon Fibre	1.57	38.061	
60	Oak/UF/25% Carbon Fibre	1.59	38.545	
61	Control: Solid Birch	1.30	31.515	*Mean Impact*
62	Control: Solid Birch	1.33	32.242	*Strength =*
63	Control: Solid Birch	1.34	32.485	31.224 kJ/m^2
64	Control: Solid Birch	1.22	29.578	*S.D.* = 1.095
65	Control: Solid Birch	1.25	30.303	*CoV* = 1.198
66	Control: Solid Birch	1.33	32.242	*t* = 45.892
67	Control: Solid Birch	1.27	30.788	
68	Control: Solid Birch	1.34	32.485	
69	Control: Solid Birch	1.25	30.303	
70	Control: Solid Birch	1.25	30.303	
71	Control: Solid Beech	1.15	27.879	*Mean Impact*
72	Control: Solid Beech	1.18	28.606	*Strength =*
73	Control: Solid Beech	1.14	27.636	28.039 kJ/m^2
74	Control: Solid Beech	1.16	28.121	*S.D.* = 0.555

Table 27. Continued

Sample No.	*Dimensions:* Wood, adhesive, % fibre reinforcement	*Impact Energy* (Nm)	*Impact Strength* (kJ/m^2)	*Mean & S.D. of group*
75	Control: Solid Beech	1.13	27.394	*CoV* = 0.308
76	Control: Solid Beech	1.19	28.848	*t* = 144.986
77	Control: Solid Beech	1.12	27.152	
78	Control: Solid Beech	1.17	28.264	
79	Control: Solid Beech	1.15	27.879	
80	Control: Solid Beech	1.18	28.606	
81	Control: Solid Pine	0.73	17.697	*Mean Impact*
82	Control: Solid Pine	0.76	18.424	*Strength* =
83	Control: Solid Pine	0.67	16.242	16.485 kJ/m^2
84	Control: Solid Pine	0.63	15.273	*S.D.* = 1.262
85	Control: Solid Pine	0.65	15.756	*CoV* = 1.593
86	Control: Solid Pine	0.69	16.727	*t* = 150.616
87	Control: Solid Pine	0.71	17.212	
88	Control: Solid Pine	0.62	15030	
89	Control: Solid Pine	0.61	14.788	
90	Control: Solid Pine	0.73	17.697	

Table 27. Continued

Mean Impact Strength (kJ/m^2)	*Standard Deviation*	*Coefficient of Variation*	*No. of samples n*
36.521	16.362	267.719	90

Table 28. Mean Impact Strength, S.D., CoV for Parent Group

3.2 Discussion of Impact Results

The variability of the impact results is much smaller than those of the moduli. This was quite unexpected, as the very small sample dimensions (6.5mm x 3.5mm) meant that exact preparation of samples was difficult, as the outer (impact) surface had to be wood in order to give consistent results. It often fell on a glue line or fibre layer, so the wood layers on the sample had to be planed down until the desired thickness was met, or another sample made with slightly thicker veneers. The conclusion that can be drawn from this is that the wood veneers play only a minor role in the impact behaviour of the beams when compared with the fibre reinforcement, shown by the much higher impact strength of oak/UF/50% glass than birch/UF (53 and 12kJ/m^2).95% confidence limit for sample groups is (in kJ/m^2): *birch/UF* 11.516; *birch/UF/50% carbon* 22.604; *beech/epoxy/30% carbon* 61.009; *oak/UF/50% glass* 48.359; *oak/UF/30% glass* 35.321; *oak/UF/25% carbon* 35.559; *solid birch* 28.673; *solid beech* 26.746; *solid pine* 13.545.CoV is only of concern for sample 14, which had a very high reading, possibly a reading error. All sample groups have a mean impact strength *significantly different* from the mean of the parent group (t =4.221-548.138), so no sample groups represent a mean impact strength group.

Sample No.	*Materials:* Wood, adhesive, % fibre reinforcement	*MoE* (GPa)	*Mean & S.D. of sample group*	*Mean, S.D. and CoV of parent group*
1	Beech/UF/30% Glass Fibre	11.465	*Mean* = 12.084	
2	Beech/UF/30% Glass Fibre	12.229	*S.D.* = 0.627	
3	Beech/UF/30% Glass Fibre	11.744	*t* = 1.337	
4	Beech/UF/30% Glass Fibre	12.898		
5	Control: Beech/UF	9.626	*Mean* = 9.426	
6	Control: Beech/UF	8.885	*S.D.* = 0.473	
7	Control: Beech/UF	9.766	*t* = 8.19	
8	Beech/UF/50% Glass Fibre	12.468	*Mean* = 12.611	
9	Beech/UF/50% Glass Fibre	12.754	*S.D.* = 0.202	
10	2 Cross lams: Beech/UF	9.342	*Mean* = 11.023	
11	2 Cross lams: Beech/UF	11.012	*S.D.* = 1.687	
12	2 Cross lams: Beech/UF	12.717	*t* = 0.659	
13	Beech/UF/20% Glass Fibre	10.636	*Mean* = 13.355	*Mean* = 11.665
14	Beech/UF/20% Glass Fibre	16.287	*S.D.* = 2.831	*S.D.* = 1.904
15	Beech/UF/20% Glass Fibre	13.144	*t* = 1.034	*CoV* = 3.625

Table 29. Results of Curved RF-cured samples (Modulus of Elasticity, Mean, S.D., CoV, *t*)

3.3 Curved Samples

Modulus of elasticity of the curved samples was calculated using the formula derived in 2.6. Modulus of rupture could not be calculated as samples were not tested to failure due to the method of testing (see Figure 24), which only allowed for a small degree of sample curvature. MOE was calculated by testing with a 10mm extension of the tensometer head after taking out any twist in the laminate, or any play in the bearing plates (see Figure 23).

3.3.1 Mean & S.D.

95% confidence limit values for MOE of sample groups are (in GPa): *beech/UF/30% glass* 10.623; *beech/UF* 8.324; *beech/UF/50% glass*12.140; *beech/UF (with cross laminations)* 7.092; *beech/UF/20% glass* 6.759. The effect on stiffness of turning 2 laminations 90° to act as cross laminations is shown clearly here - a 17% reduction in stiffness. The beams with cross laminations were still stiffer than the samples with 20% glass fibre, due to poor bonding to the fibres and subsequent delamination. Samples containing 30% and 50% glass fibre performed much better, the reason for this is unknown as they were glued at the same time.The coefficient of variation of the sample groups against the parent group is low at 3.625%. This is probably due to the use of only one adhesive (urea formaldehyde), only one type of fibre reinforcement (glass), and one wood (beech) therefore the number of variables is reduced. *Beech/UF/30% glass* group, *beech/UF/50% glass, beech/UF (2 cross lams)* and *beech/UF/20% glass* are all not proven different from the mean; only *beech/UF* group is significantly different from the mean. Here, the greater stability offered by cross laminations has improved stiffness.

Sample No.	Materials: Wood, adhesive, % fibre reinforcement	Max Deviations of Cross Section (mm)	Description of Distortion faults	Deviation of Length (mm)
1	Beech/UF/30% Glassfibre	*+ve:* 1.50 *-ve:* 0.50	Slight twist, opens out	*+ve:* 0.25
2	Beech/UF/30% Glassfibre	*+ve:* 1.45 *-ve:* 0.47	Twisted at one end	*+ve:* 0.20
3	Beech/UF/30% Glassfibre	*+ve:* 1.45 *-ve:* 0.45	Lumpy at both ends	*+ve:* 0.20
4	Beech/UF/30% Glassfibre	*+ve:* 1.55 *-ve:* 0.52	Dry joint, delamination	*+ve:* 0.25
5	Control: Beech/UF	*+ve:* 2.50 *-ve:* 0.95	Twisted both ends	*+ve:* 0.55
6	Control: Beech/UF	*+ve:* 2.85 *-ve:* 1.20	Dry joint extreme end	*+ve:* 0.60
7	Control: Beech/UF	*+ve:* 2.65 *-ve:* 1.32	Cupped end, bad shape	*+ve:* 0.50
8	Beech/UF/50% Glassfibre	*+ve:* 1.05 *-ve:* 0.20	Lumpy, dropped end	*+ve:* 0.10
9	Beech/UF/50% Glassfibre	*+ve:* 1.20 *-ve:* 0.15	Wavy laminations	*+ve:* 0.15
10	2 Cross Lams: Beech/UF	*+ve:* 0.80 *-ve:* 0.10	Slight cup one end	*-ve:* 0.05
11	2 Cross Lams: Beech/UF	*+ve:* 0.95 *-ve:* 0.12	Cupped one end	*-ve:* 0.10
12	2 Cross Lams: Beech/UF	*+ve:* 1.00 *-ve:* 0.13	Cupped both ends	*-ve:* 0.10
13	Beech/UF/20% Glassfibre	*+ve:* 1.85 *-ve:* 0.36	Opened out both ends	*+ve:* 0.40
14	Beech/UF/20% Glassfibre	*+ve:* 1.95 *-ve:* 0.48	Cupped ends	*+ve:* 0.45
15	Beech/UF/20% Glassfibre	*+ve:* 1.90 *-ve:* 0.56	Cupped ends	*+ve:* 0.40

Table 30. Distortion Measurements of Radio Frequency Cured Samples (+ve indicates upwards or outwards, -ve indicates downwards or inwards, depending on context)

3.4 Distortion Measurements

BS4169:1980 (Manufacture of Glued Laminated Timber Members) states that:

(a) The maximum cup of individual laminations prior to gluing is 1.5mm for sections with a finished thickness up to 17mm, and a finished width of up to 600mm. For finished thicknesses of 17 to 30mm, the maximum cup falls to 1mm.

(b) The maximum deviation of cross section for widths up to 300mm is 3mm, for widths up to 600mm is 6mm.

(c) The maximum deviation in length is 1mm/m (up to a maximum of 15mm).

The measurements in Table 30 were measured at 8 points along the laminate, with the coordinates of each section being compared to the coordinates of the mould as a reference. The beech and urea formaldehyde control samples showed most distortion. This is to be expected as all the grain of the timber is in one direction, and there is little strength in the direction at 90° to the grain. Increasing levels of glass fibre reinforcement give greater strength in this direction, which reduces distortion. The least distorted samples were those with beech cross laminations, that is 2 laminates placed at 90° to the direction of the bend. The samples with cross laminations 'towed in' as the bend closed up slightly after moulding, with very slight cupping viewed across the laminate. For flat beams, the use of cross laminations was not deemed necessary as distortion is always more pronounced in curved sections. If they had been added, a 20-30% reduction in beam stiffness could be expected, due to the grain of 2 (out of 7) of the laminations being at 90° to the strain imposed by the 3-point test load (if wood at 90° to the load contributed

3.4 Continued

nothing to the stiffness, the reduction would be 28%). When the beam is curved however, the 2 cross laminations appear to make the beam stiffer, with a mean of 11.023 GPa against 9.426 GPa. When the standard deviation is taken into account by looking at the 95% confidence limit however, the beams with cross laminations were 17% less stiff than those with all laminations running along the length of the beam. Distortion was much higher when there was no restraint at 90° to the grain, either from woven mat or cross laminations.

3.5 Summary of Results

'Authors...have obscured their works in a cloud of figures and calculation: the reader must have no small portion of phlegm and resolution to follow them through with attention: they often tax the memory and patience with a numerical superfluity, even to a nuisance' (Black, 1973)

3.5.1 Modulus of Elasticity

The elastic modulus tabulated previously was calculated as shown in 2.4, using the general bending equation, therefore shear forces are assumed to be negligible. As discussed in 1.4.12 and 1.4.13, the shear contribution to the deflection of a wood/fibre composite beam could be quite considerable. In order to gain a fair understanding of the behaviour of these beams, a shear factor needs to be added, and the MOE recalculated. Without taking shear into account, the stiffness gain by incorporating fibre composites is small, and in some instances it may lower the stiffness, as the differences in moduli of the two materials appears to act as a trigger mechanism (see 1.3.12). The effect of poor adhesion can be seen by comparing MOE of birch/UF/50% carbon (1.670 GPa) and beech/epoxy/30% carbon (7.806 GPa). Epoxy is clearly bonding much better to the carbon fibre than the urea formaldehyde. This is more noticeable for the carbon fibre as the weave used was 8H satin, a closed weave with a weight of 400 g/m^2, therefore the fibre mat was quite impermeable for the urea formaldehyde. The twill weave glass fibre mat (270 g/m^2) was much easier for the UF to soak through, and therefore the wood laminates could be bonded together, even though the glass mat may well act as a stress raiser in the glue line in these cases.

3.5.2 Modulus of Rupture

Beech/epoxy/30% carbon is clearly the best combination for providing flexural strength. MOR is generally considered to be approximately twice the true tensile strength for timber. Here, the mean MOR of solid beech was 79.319 MPa with a S.D. of 5.969, while the beech/epoxy/30% carbon MOR was 139.202 with a S.D. of 14.72. The fibre reinforcement here gives a 57% improvement in MOR, while retaining a comparable standard deviation as a percentage of the MOR. For clear wood specimens, carefully selected, the MOR of beech is 118 MPa, with a

3.5.2 Continued

S.D. of 11 (n=183 wood specimens, Anon., 1989). Even when compared with this optimum value, the variability is comparable, and the modulus of rupture is 18% higher. The discrepancy between the experimental value and the published value for solid timber is due to natural faults in the timber. Laminated beech would have a higher MOR than solid beech, as the very act of laminating lessens the effects of flaws in the timber, and lowers variability as each laminate is graded before use. This can be seen in the birch results, where solid birch has a MOR of 97.723 (S.D. 9.954), whilst the laminated birch has a MOR of 117.726 MPa (S.D. 14.36). The glueline is assumed to have a negligible effect on strength (see 1.3.8), especially where urea formaldehyde adhesives are used.

3.5.3. Impact Strength

Solid birch had an impact strength 2.5 times higher than laminated birch (31.224 kJ/m^2, S.D. 1.095 against 12.485 kJ/m^2, S.D. 0.416). Even the pine samples had an impact strength 25% higher than the birch/UF. Beech/epoxy/30% carbon had an impact strength almost 2.5 times that of solid beech, with a comparable rise in S.D. (2.397 against 0.555). The urea formaldehyde glue lines act as stress raisers in the laminate, with the brittle resin being unable to withstand the high levels of impact energy in the same way as epoxy resin or indeed solid timber.

3.5.4 Distortion

The use of cross laminations is the best way tested for reducing distortion, with the maximum deviation of the cross section being 1mm. The inclusion of 50% glass fibre keeps the distortion to 1.2mm, 30% glass fibre to 1.55mm, 20% glass fibre gives a maximum distortion of 1.95mm. The laminated birch control sample had a maximum deviation of cross section of 2.85mm. The use of glass reinforcement could replace cross laminations in most cases where sections are not too large.

3.5.5 Failure

The inclusion of carbon fibre into wood laminates raises the modulus of rupture, modulus of elasticity and the impact strength of the laminated beam. A modulus of elasticity gain of just 25%, seen when reinforcing beech with epoxy bonded carbon fibre, could reduce the dimensions of a laminated section by between 10 and 18% in a beam of a size typical in the furniture industry. A great deal of research is currently being carried out in Sweden to reduce dimensions for furniture parts, so lessening the growing environmental burden on Scandinavian birch supplies. As an example, two of the sections of the armchair *Lamello* produced by Swedese Möbel in Vaggeryd, Sweden, were reduced in size from 53x28mm to 40x28mm by the inclusion of 4 layers of glass fibre into the twenty layers of timber laminates, a 25% reduction in thickness (Bäcklund, 1996). Also important for the safety of furniture is how the material

3.5.5 Continued

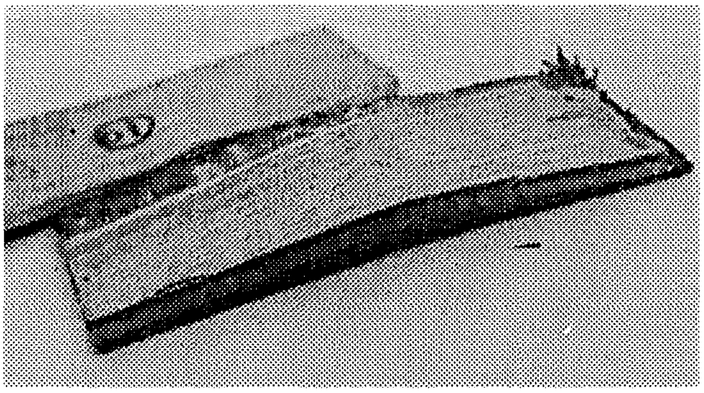

Figure 28. Failure of Carbon Reinforced Samples

fails. Many plastics fail suddenly and catastrophically as in the case of Panton's stacking chair when injection moulded in *Luran S* thermoplastic (see Figure 3). Laminated timber, when glued with brittle urea formaldehyde, has a very sudden failure, with a rough fracture surface as shown in Figure 30.

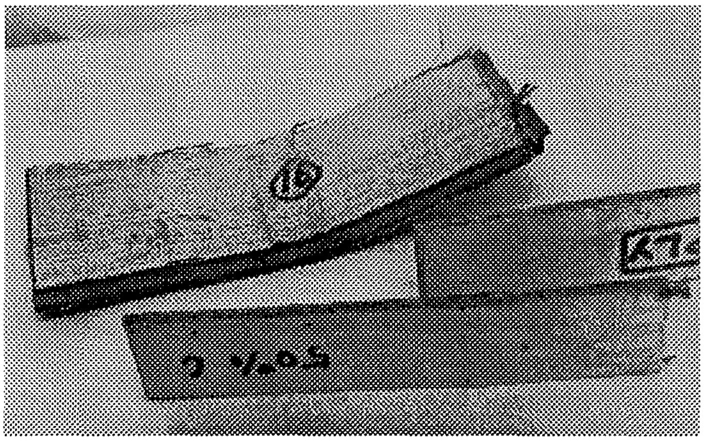

Figure 29. Failure of Carbon Reinforced Samples

If a large gain in mechanical properties could be gained by simply replacing brittle urea formaldehyde resins with tougher epoxy resins that would cut down the cost of improving the strength properties of timber laminates. Certainly epoxy resins ought to increase the impact strength and modulus of rupture significantly. It is the inclusion of fibres which greatly affects failure. The fibres act as crack stoppers, thus improving toughness and impact strength.

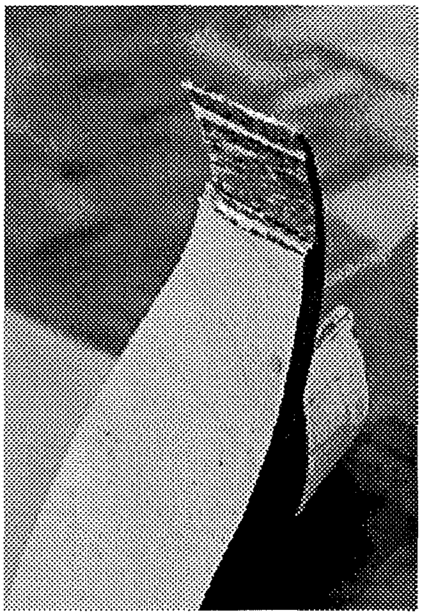

Figure 30. Failure of Unreinforced Sample

Whilst unreinforced wood samples fail suddenly by breaking in two, reinforced samples fail progressively and remain largely intact, with some delamination as the only clue to their failure, so that they can still carry a load, albeit with a larger deflection than before failure. Failure takes the form of shear failure in the glue line between the wood and fibre layers, where the large difference in the two moduli (for beech and glass fibre, the difference is around 70 GPa, or six times the MOE value of beech alone) causes a large stress gradient in the adhesive layer. Epoxy resin is able to withstand a higher level of this induced stress than brittle urea formaldehyde or phenol resorcinol formaldehyde adhesives (see Appendix 6).

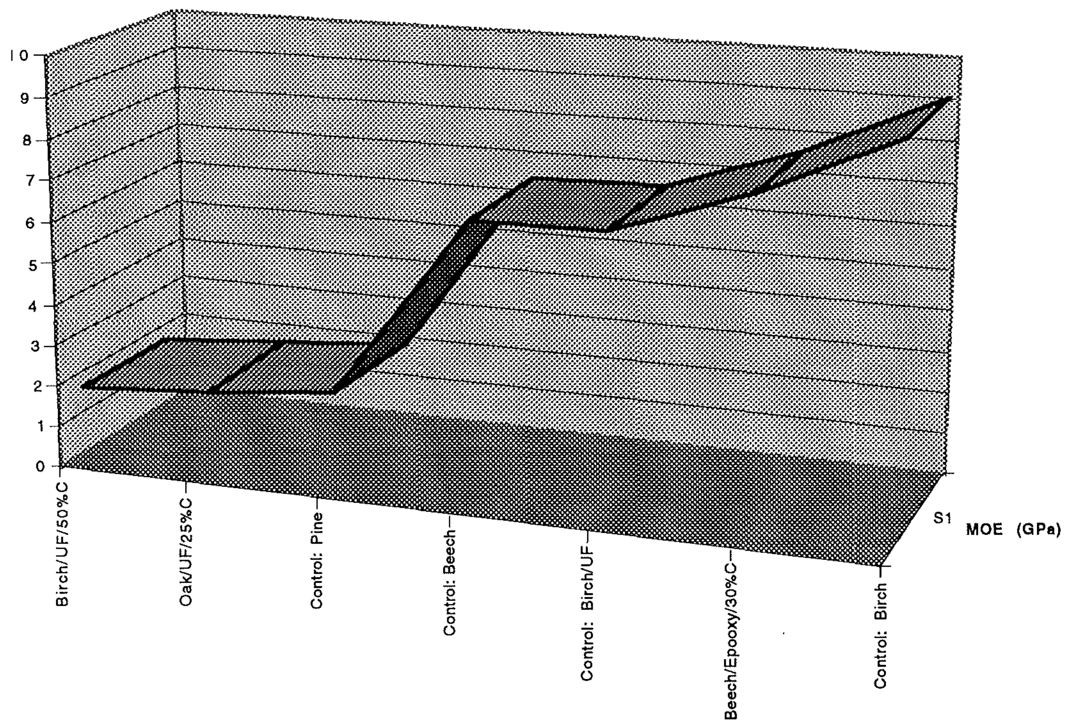

Figure 31. Chart of Modulus of Elasticity of Carbon Samples

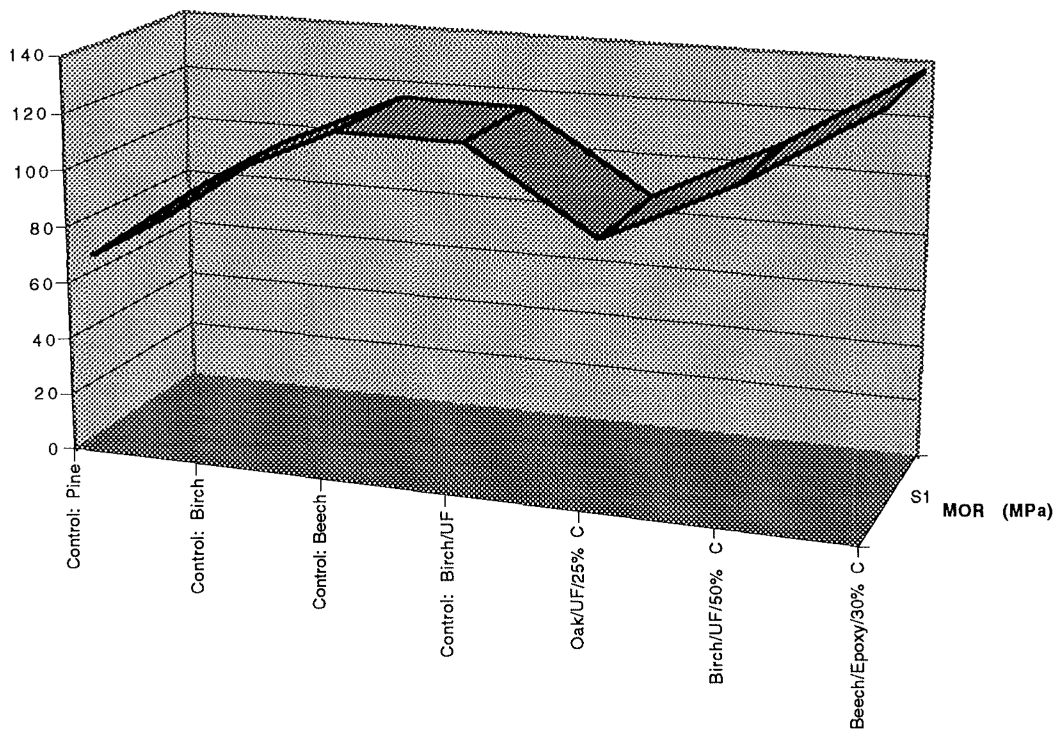

Figure 32. Chart of Modulus of Rupture of Carbon Samples

3.6 Discussion of Figures 31 and 32

The modulus of elastcity (MOE) values depicted in Figure 31 were calculated using the standard bending equation (see 1.3.2), and so do not include shear contributions to the beams deflection, with the result that the MOE values of the composite beams is much lower than the true stiffness. Figures 38 and 39 plot MOE and MOR values for glass, carbon and control samples, all including the shear contribution to the beam's deflection. Modulus of rupture (shown in Figure 32) was calculated from the formula shown in 2.3 and is a measure of the maximum transverse breaking stress that the sample can withstand before rupture. Without discepancies caused by shear contributions, the MOR figures begin to show the benefits offered by fibre composites. It is clear from the graph that carbon can be bonded effectively only with epoxy, as UF produces beams which have a lower MOR than the respective controls. Solid beech and laminated birch both had an MOR of 117 MPa, birch/UF/50% carbon 111 MPa, beech/epoxy/ 30% carbon 139.202 MPa. It is unlikely that there is a problem caused by shear forces in calculating MOR, if there is it is certainly less of a problem than for the modulus of elasticity.

3.7 Discussion of Figures 33 and 34

Solid birch has an MOE value of 9.335 GPa,whilst birch/UF (laminated birch) has an MOE of 6.708 GPa. The best glass sample before shear is taken into account is oak/UF/30% glass with an MOE of 3.084 GPa. When 50% glass is used, the MOE falls to 1.910 GPa. Without shear analysis, glass appears poor. The MOR of the laminated birch was the highest (117.7 MPa), slightly higher than beech (117.3 MPa). This is very close to the 'ideal' value for beech of 118 MPa as quoted in 3.5.2, showing that the beech control samples used were of a high quality. The MOR values shown are disappointing, although the beech control samples were much higher quality than the birch and oak veneers. The initial conclusion that can be drawn from these figures is that urea formaldehyde does not perform well with either fibre reinforcement, and only epoxy bonded fibres give a useful performance gain over solid or laminated timber. Samples bonded with UF showed extensive delamination after testing. The UF has poor bonding to the glass and carbon, with the effect that a crack develops in the glue line between the laminates, causing premature failure. Even pine had a higher value of MOR (67.024 MPa) than oak/UF/30% glass (62.253 MPa). The difference between oak/UF/30% glass and oak/UF/25% carbon is high, with carbon fibre giving a 43% better MOR (89.522 against 62.253). Carbon fibres generally have a tensile strength around 25% greater than glass, so the MOR of the carbon samples could be expected to give an equivalent gain over glass. Why the difference is 43% is unclear. As stated in 3.5.1, the carbon fibre cloth was thicker than the glass, so the urea formaldehyde could not soak through the weave. The bond between the wood laminates where carbon fibre was inserted was therefore compromised - the glue line effectively had a crack running through its middle. Why this did not dramatically lower the flexural strength is unclear.

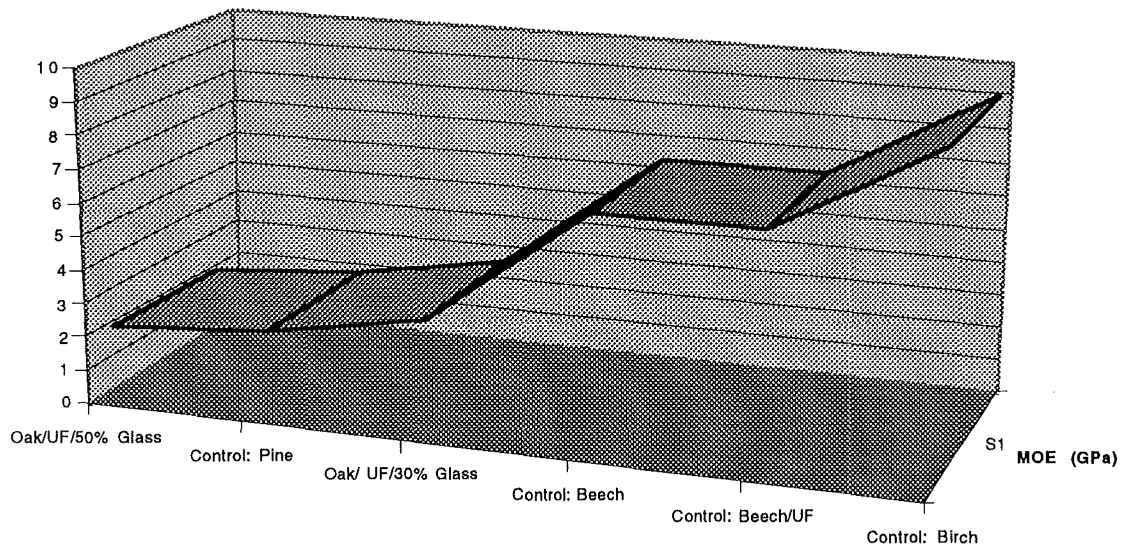

Figure 33. Chart of Modulus of Elasticity of Glass Samples

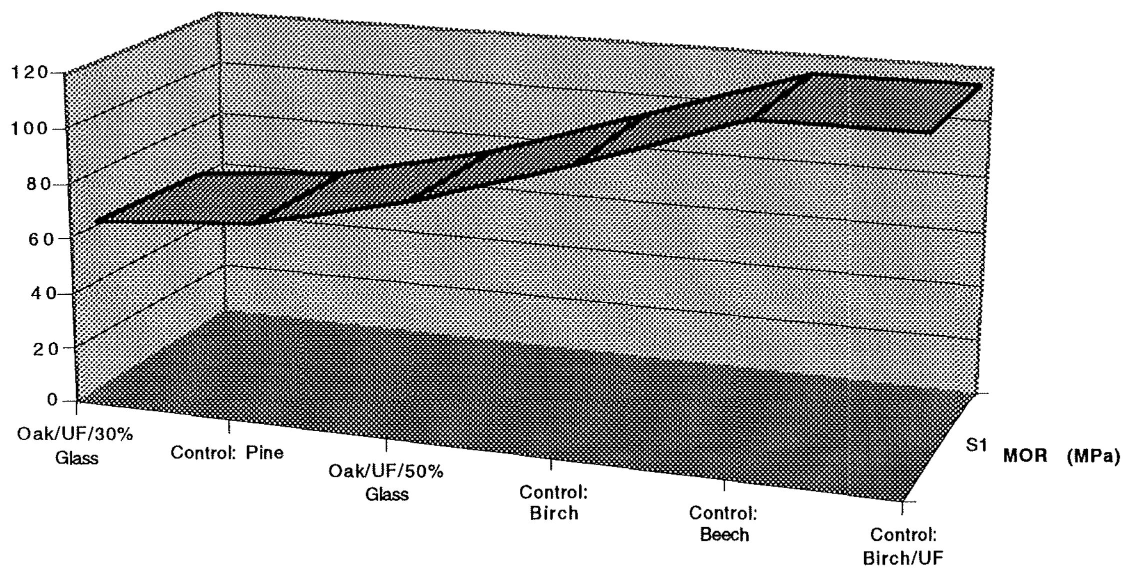

Figure 34. Chart of Modulus of Rupture of Glass Samples

3.8 Discussion of Figures 35 and 36

The improvement in impact strength of the carbon reinforced samples is obvious. The worst sample for withstanding impact was laminated birch, with a mean impact strength of 12.485 kJ/m^2. Beech had a value of 28.039 kJ/m^2 whilst birch/UF/50% carbon had a mean of 39.806 kJ/m^2, and beech/epoxy/30% carbon had the best value of 66.594 kJ/m^2 which is almost 2.5 times the value for the solid clear wood beech specimens. Epoxies, being tough, have a high impact strength so their contribution to the overall impact behaviour is high, as can be seen in Figure 35. Figure 36 shows that with urea formaldehyde there are few surprises. There is an almost linear relationship between the samples, ranging from laminated birch (12.485 kJ/m^2) through solid birch (31.224 kJ/m^2) to oak/UF/30% glass fibre (40.655 kJ/m^2) and oak/UF/50% glass fibre (53.576 kJ/m^2). If epoxy resin had been tested as an adhesive for glass, the impact strength of the glass fibre reinforced samples would no doubt have followed the same pattern as the carbon fibre reinforced samples.

3.9 Discussion of Figure 37

Series 1 (S1) depicts the maximum +ve (or upwards) deviation of the cross section in mm.
Series 2 (S2) depicts maximum -ve (or downwards) deviation of cross section in mm.
Series 3 (S3) depicts maximum deviation of length in mm. The samples with cross laminations showed the least distortion, whilst the laminated beech had the most. All figures are comparisons to the original mould form (see 3.4).

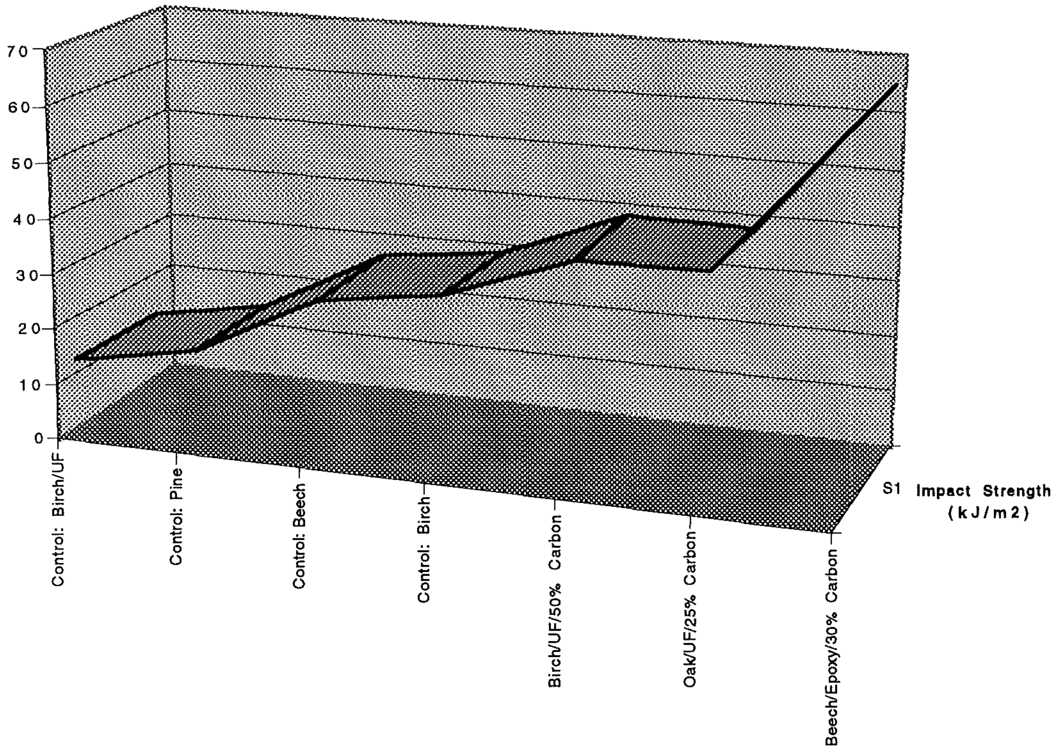

Figure 35. Impact Strength of Carbon Samples and Control Samples

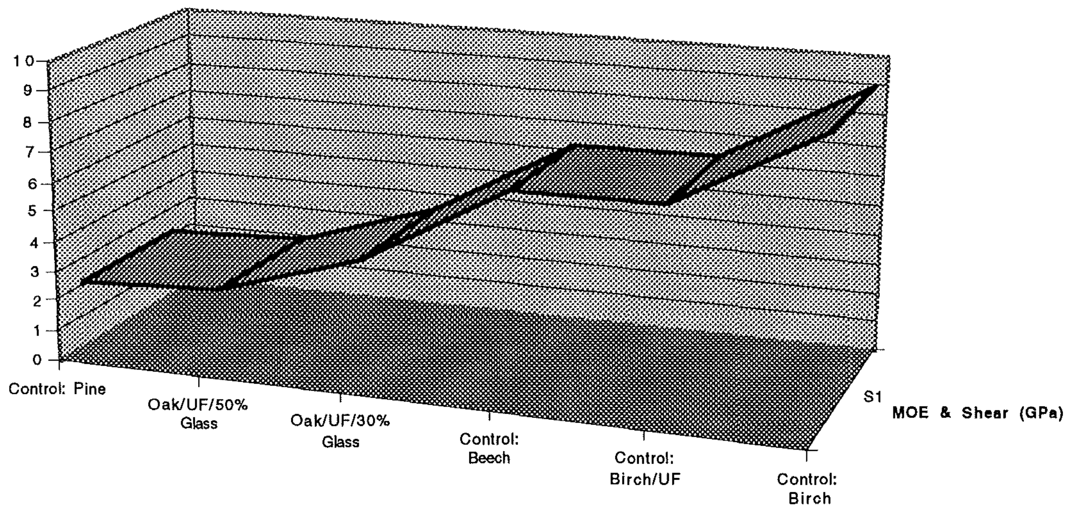

Figure 36. Impact Strength of Glass Samples and Control Samples

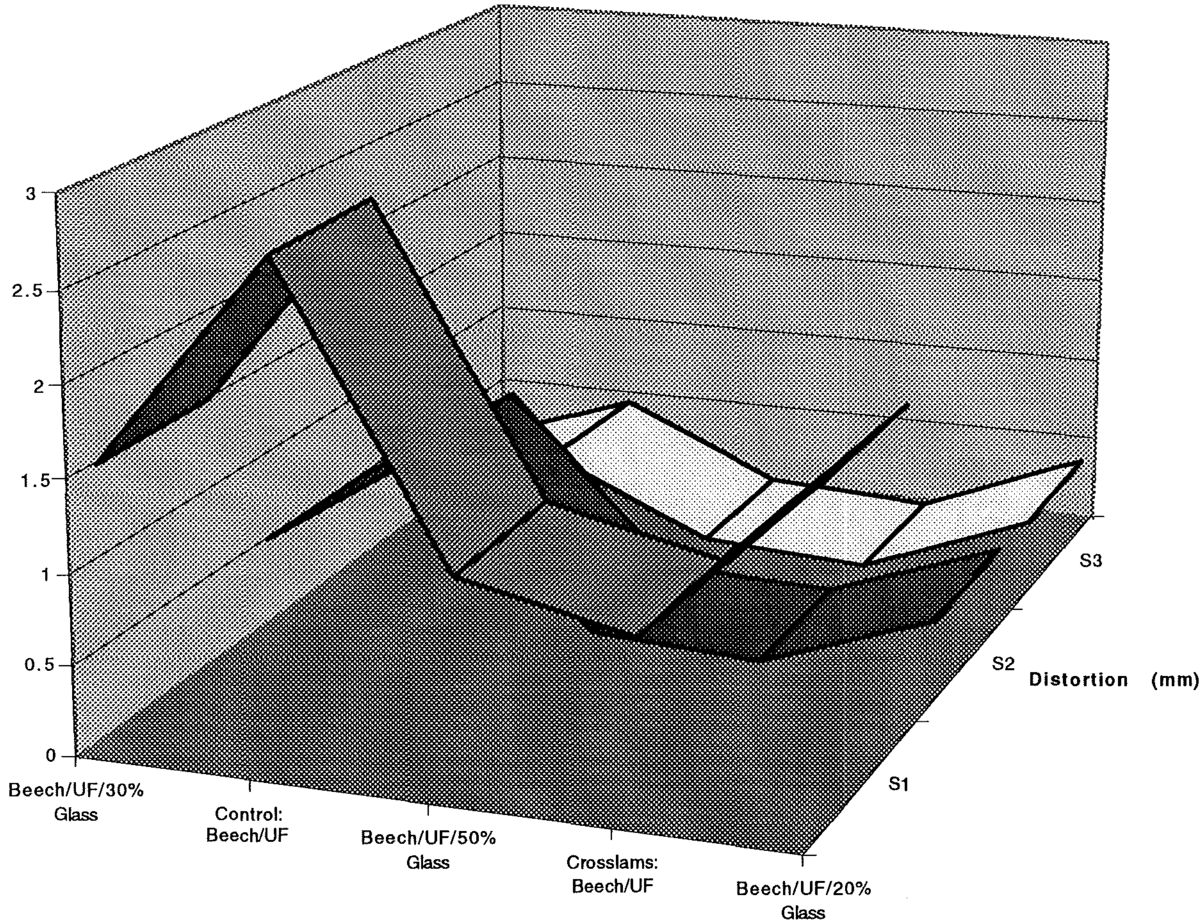

Figure 37. Chart of Distortion Measurements

3.10 Results - Conclusion

Variability of results is high, yet it must be stressed that timber was not specially selected for testing, but used as it came (although all veneers were previously selected structual grade rather than facing veneers) in order to give a more accurate picture of the feasibility of composite reinforcement in furniture (see 2.7). Selected timber would have lowered the variability by a fair margin, as although structural veneers are graded at source, their quality is still variable. The beech used was of a very good (previously selected) grade, and performed as well as reference sources who used graded clear (100% fault free) specimens for testing (Anon., 1974). Impact strength results for the fibre reinforced samples were much higher than solid timber, which in turn were higher than unreinforced laminated timber, with epoxy being better than UF resins. Distortion results were encouraging, as the inclusion of glass fibres cuts down the amount of distortion of the timber laminates to a point where the inclusion of cross laminations becomes useful only in extreme cases, where sections are large, or curves are very open, long curves where distortion is always difficult to control. Modulus of rupture results show clearly the effect that poor adhesion has on mechanical properties, with epoxy bonded beech and carbon fibre showing a 20% increase in MOR. In any case, the very act of laminating increases MOR by lessening the effect of natural defects. Modulus of elasticity results need to have the shear force contribution added. This is calculated by using the formula derived by Biblis (1965) and used by Rowlands *et al.,* (1986):

$$EI = \frac{Fl^3}{48Iy}\left(1 + \frac{1.2h^2}{l^2}\frac{E}{G}\right).$$

Since $E = \frac{Fl^3}{4ebd^3}$ and $I = \frac{bd^3}{12}$

as the beam is rectangular in section, the shear contribution is equal to the terms in brackets. The true value of E can be calculated by multiplying the experimental value of E by the terms in brackets, using the values relevant for the beam geometry and species (see 1.3.3 and 1.3.10 for explanation of this theory). Figures 38 and 39 show E values once shear force contribution has been taken into account. The differences can be large, and dramatically alter the effective E. Even after adding the shear contribution, glass fibre does not enhance stiffness if bonded with UF. The effective increase in E of including shear is 0.573 GPa for oak/UF/50% glass, and 0.925 GPa for oak/UF/30% glass. The epoxy bonded, carbon reinforced beech has an E value of 10.928 GPa when shear is added, making it clearly the stiffest material. Urea formaldehyde still performs badly. For carbon reinforced samples, the shear contribution adds approximately 40% to the modulus of elasticity, compared to approximately 30% for glass reinforced wood beams. Anon., (1989) recommends adding a 10% correction to account for shear deflection when testing using 3-point bending (simply supported, centre loaded beam). Woods with a low E/G should have only a 2% correction, for woods with a high E/G this can reach 24%.

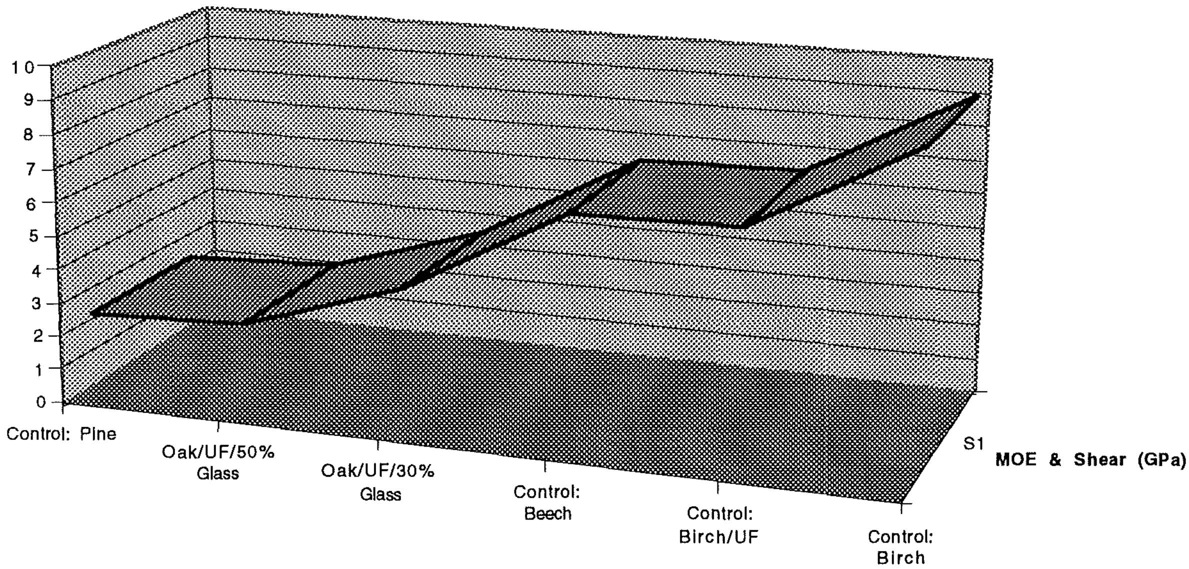

Figure 38. Chart of Modulus of Elasticity of Glass Samples, With Shear Contribution Added

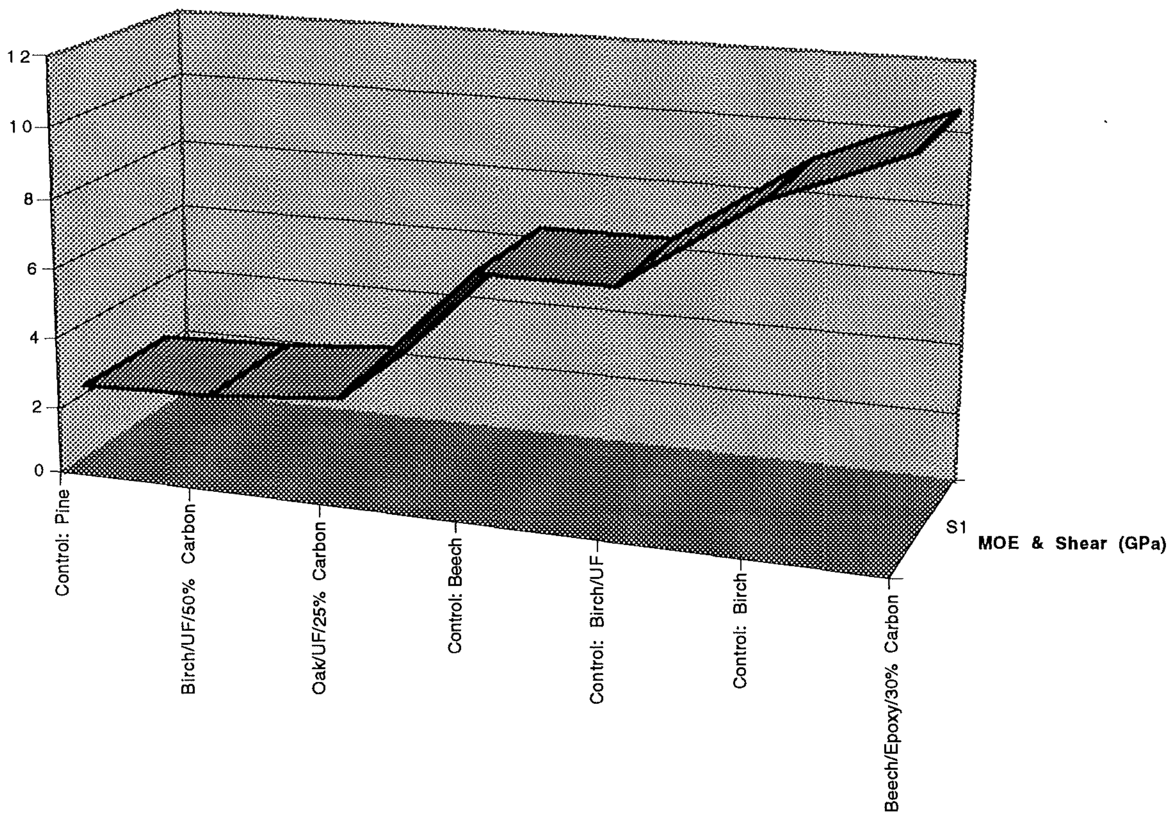

Figure 39. Chart of Modulus of Elasticity of Carbon Samples, With Shear Contribution Added

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4.1 Introduction

In order to demonstrate how composite materials can influence furniture design, a simple design will be produced. A one-piece chair will satisfy the requirements of demonstrating the enhanced performance of composite materials. It will be simple to create the mould, easy to form and test, yet involve complex forms dictated chiefly by anthropometric data and material properties.

4.2 Ergonomics

He who would do good to another must do it in Minute Particulars:
General Good is the plea of the scoundrel, hypocrite and flatterer,
For Art and Science cannot exist but in minutely organised Particulars,
And not in generalising Demonstrations of the Rational Power.

William Blake, *Jerusalem*, pl.55, 1.60-64

Ergonomics is the application of scientific information about humans to the problems of design. The purpose of a seat is to provide stable bodily support in a posture which is: (i) comfortable over a period of time; (ii) physiologically satisfactory; (iii) appropriate to the task or activity which is to be performed. It is likely that a seat which is comfortable in the long term is also physiologically satisfactory and vice versa. The extent to which a seat achieves these objectives is dependent on a number of anthropometric and biomechanical factors. The following data is for work chairs.

4.2.1 Seat Height

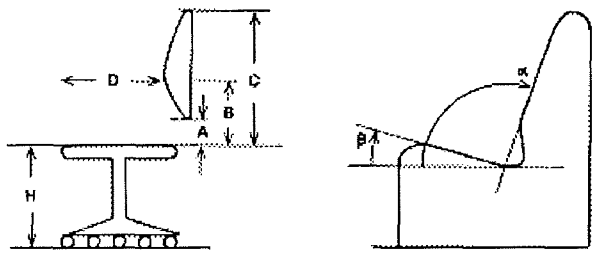
As the height of the seat increases, beyond the popliteal height of the user (the vertical distance from the floor to the popliteal angle at the underside of the knee where the tendon of the biceps femoris muscle inserts into the lower leg), pressure will be felt on the underside of the thighs, resulting in 'pins and needles'.The optimal seat height for many purposes is close to the popliteal height, and where this cannot be achieved a seat which is too low is preferable to one which is too high. For many purposes, the 5th %ile female popliteal height (400mm shod) represents the best compromise (see Appendix 2 for Anthropometric data).

4.2.2 Seat Depth

If the depth is increased beyond the buttock-popliteal length (5th %ile woman = 435mm) the user will not be able to engage the backrest effectively without unacceptable pressure on the backs of the knees. Furthermore, the deeper the seat the greater the problems of standing up and sitting down. The lower limit of seat depth is less easy to define. As little as 300mm will still support the ischial tuberosities (ligaments on the 3 bones of the pelvis) and may well be satisfactory.

4.2.3 Backrest

The higher the backrest the more effective it will be in supporting the weight of the trunk. Low-level backrests support the lumbar region only. The depth of the lumbar curve from front to back should be in the order of 15-20mm.



Dimension	*Fixed (mm)*
Seat to lower edge (A)	150
Seat to maximum convexity (B)	230
Seat to upper edge (C)	380
Width (for free movement of elbows)	330

Figure 40. Specimen dimensions for a low-level backrest (Pheasant, 1986)

4.2.4 Seat Width

For purposes of support a width of 25mm less on either side than the maximum hip breadth is all that is required. Clearance between armrests must be adequate for the largest user. The hip breadth of the 95th %ile woman unclothed is 435mm. In practice, allowing for clothing and leeway, a minimum of 500mm is required. Elbow-elbow breadth for 95th %ile clothed man is 550mm.

4.2.5 Backrest angle or 'rake' (α)

As the backrest angle increases, a greater proportion of the weight of the trunk is supported, hence the compressive force between the trunk and pelvis is reduced. However this will tend to drive the buttocks forward unless counteracted by (i) an adequate seat tilt, (ii) high friction upholstery or (iii) muscular effort from the user. Increased rake also leads to increased difficulty in sitting and standing. The interaction of these factors determines the optimal rake which is commonly 100 to 110°. A pronounced rake (greater than 110°) is not compatible with a low- or medium-level backrest since the upper parts of the body become unstable.

4.2.6 Seat angle or 'tilt' (β)

A positive seat angle helps the user to maintain good contact with the backrest and helps to counteract any tendency to slide out of the seat. Excessive tilt reduces hip/trunk angle and ease of sitting and standing. For most purposes 5-10° is a suitable compromise.

4.2.7 Armrests

Armrests may give additional postural support and can be an aid to standing and sitting, they must support the fleshy part of the forearm, but unless padded should not engage the bony parts of the elbow where the highly sensitive ulnar nerve is near the surface; a 100mm gap between

4.2.7 Continued

the armrest and the seat back is desirable. An elbow rest which is somewhat lower than sitting elbow height is preferable for comfort, this gives an elbow rest height of 200-250mm above the seat surface.

4.2.8 Seat Surface

The purpose of shaping or padding the seat surface is to provide an appropriate distribution of pressure beneath the buttocks. Also: (i) The seat surface should be more or less plane rather than shaped, although a rounded front edge is highly desirable; (ii) Upholstery should be 'firm'; (iii) Covering should be porous and rough to aid stability.

4.2.9 Easy chairs

An easy chair supports the body during periods of rest and relaxation. Grandjean (1973) recommends a seat tilt (β) of 20-26° and an angle between seat and backrest of 105-110°. This gives a backrest angle (α) of as much as 136°, which requires a degree of agility for standing and sitting. Le Carpentier (1969) found a tilt of 10° with a rake of 120° to be a good compromise, yet a rake of more than 110° is not suitable for elderly users. The most common failings in the easy chair are a seat which is too deep and a backrest which is too low. There is often an attempt to make the seat and back equal in length in the interests of visual symmetry (like Mies Van der Rohe's *Barcelona* chair, 1929), or to fit the chair into a cubic outline (like *Le Grand Confort* by Le Corbusier, Charlotte Perriaud and Pierre Jeanneret, 1928-1929) (see Figures 41 and 42). These modern classics show very little relationship between their form and that of the human body which it is their function to support. In fairness it should be stated that the Barcelona chair was designed for the German pavilion at the 1929 Exposición Internacional in Barcelona for the specific use of King Alfonso XIII and his queen at the opening ceremonies, and not for general, sustained use.

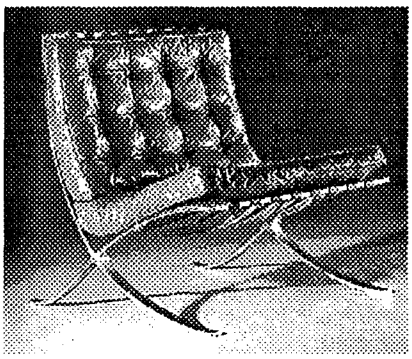


Figure 41. Barcelona chair, Mies van der Rohe (1929)

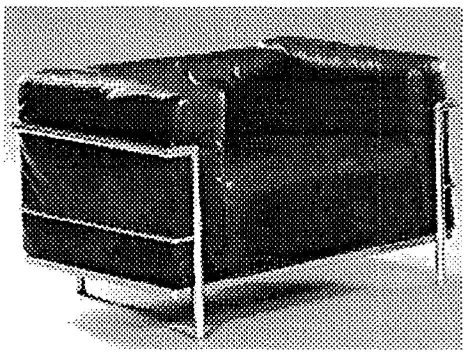


Figure 42. Le Grand Confort, Le Corbusier, Perriand, Jeanneret (1928-9)

4.3 Aesthetics

Well designed furniture should be structurally sound, functionally appropriate (convenient and safe to use) and aesthetically pleasing. The comfort of a chair is both a functional and an aesthetic characteristic if we assume 'aesthetic' applies to all of the senses rather than restricting it to vision alone. Neuroanatomists tell us that vision accounts for 40% of the incoming sensory input to the brain, tactile and kinaesthetic pleasure must therefore be comparable in effect to vision.

4.3.1 Modern Identity

The use of laminated wood and plywood in furniture dates from the 1930s, when its use in the aircraft industry lent it modern connotations. It was seen as the material of the future, yet more comfortable (and, by implication, more British) than the austere tubular steel furniture from the Continent. It still has a modern identity that endears it to today's designers. *'Plywood...is more domestic, more approachable than plastic; it has a clean, modern feel.'* (Hilton, 1993).

4.3.2 Beauty

Beauty in furniture is the result of a mental process which takes into account all the aspects of the problem and combines them into a harmonious whole. It is the result of a successful combination of form, colour and texture; but the right choice of materials and the economic use of machine and hand processes are almost as important. Whenever a new material is introduced some time is necessary before its possibilities can be fully realised. The mistake is often made of imitating the familiar forms of old materials. Since ply and laminated wood have different properties to solid wood, they quickly developed their own characteristic shapes. They can be bent into curved shapes with the minimum of joints and we therefore find continuous sweeps rather than right angles. Furniture can be directly moulded to the human shape, reducing the need for upholstery, and draw inspiration from organic forms rather than from classical architecture and motifs. *'What does 'beautiful' mean? It means that the thing makes me feel joyous, more rooted in the world, more whole as a person'* (Alexander, 1977).

4.4 Convenience

The convenience of a piece of furniture is possibly its most important quality to the user; how efficiently it does its job of being a useful chair; how much space it takes in the room; whether it fits in easily with other furniture; whether it can be moved about the room easily; whether it can be stacked to save storage space. Convenience is a quality one is apt to notice only in its absence.

'Nothing that is not practical can be beautiful' (Otto Wagner, 1896).

4.4.1 Stacking

A one-piece moulded chair, as discussed in 1.4.3 would be easily stackable if the back and the frame were cut from a single pre-formed sheet. The inspiration for such an organic form comes from a halved tennis ball and other natural forms.

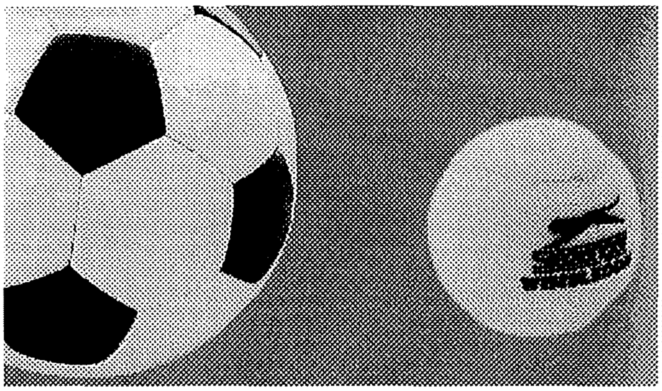


Figure 43. Organic forms 1

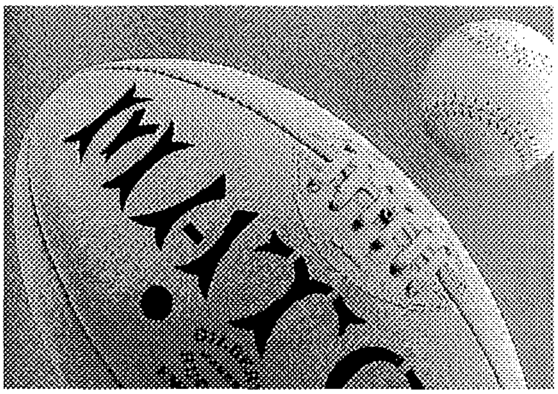


Figure 44. Organic forms 2

4.5 Durability

One of the commonest causes of failure in furniture is simply wear and tear. Projecting corners and edges are particularly vulnerable. Weak joints are another common cause of failure. One piece chairs avoid joints, and this method of construction favours composites, which are only strong when they exist in unbroken lengths along a member. Another cause of failure is under a sudden blow (impact). The high toughness and subsequent high impact strength of composites makes them ideal for strengthening furniture for tough contract use without making it bulky.

4.6 Form

'A chair is a stool with a backrest, and a stool is a board on four supports'' (Dresser, 1873). This definition seems simplistic today, for over the last century the chair has been subject to a succession of revolutionary transformations. The Modern chair is an industrial product which has an ancestry that can be traced to the second quarter of the nineteenth century. Modernism is not a style but a philosophical movement, the rational tenets of which are: the unification of the physical and the spiritual, the harmonising of functionalism and aesthetics, internationalism derived through abstraction for greater universality of appeal, innovation, social morality, truth to materials, revealed construction and the responsible use of technology. Within Modernism, there are two distinct approaches to design; geometric abstraction and organic abstraction. The former, widely promoted by the pioneers of the Modern Movement such as van der Rohe and Le Corbusier (Figs 41 and 42), though originally derived from the study of human anatomy, is extremely rigid, and are perceived as inhuman and alienating. Organic forms on the other hand are amorphous and flowing like living tissue.

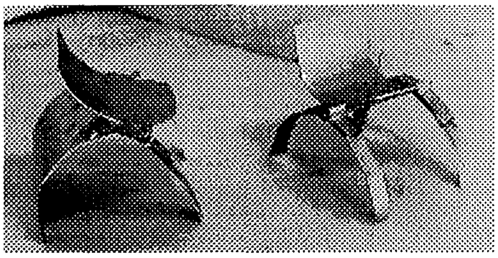
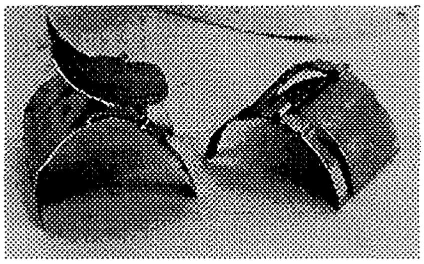
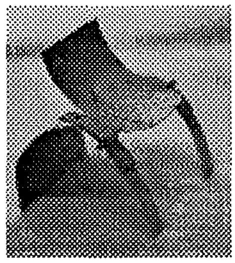




Figure 45. Models of Possible Forms

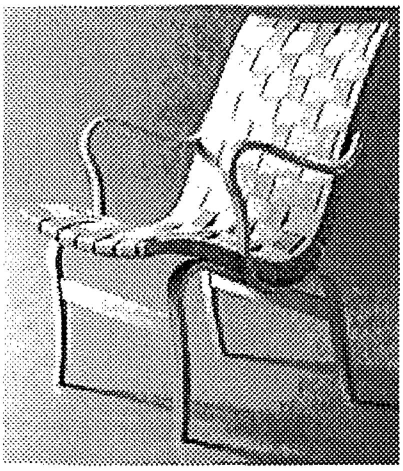


Figure 46. *Eva*, Bruno Mathsson (1934)

Bruno Mathsson (1907-88) was Sweden's pioneering modern furniture designer. He made analyses of proportion and weight bearing stresses, and found new ways of bending and laminating. His designs are distinguished by their lightness and simplicity and often include innovatory constructional features. Their exaggerated curves were a taste of things to come. Eva (1934) is constructed from bent plywood, laminated and bent birch and hemp webbing. Mathsson developed furniture to suit the human body. The furniture, which made a nervous impression with its unusual lines, was rendered calmer by means of traditional materials: blond wood and natural fabrics.

'The business of sitting never ceases to amaze me' (Mathsson, 1970)

'I should say that it would be greatly for our aesthetic good if we should refrain entirely from the use of ornament for a period of years, in order that our thought might concentrate acutely upon the production of objects well formed and comely in the nude. We should thus eschew many undesirable things, and learn by contrast how effective it is to think in a natural, favorous and wholesome way...We shall have learned, however, that ornament is mentally a luxury, not a necessity, for we shall have discerned the limitations as well as the great value of unadorned masses.' (Louis Sullivan, 1892)

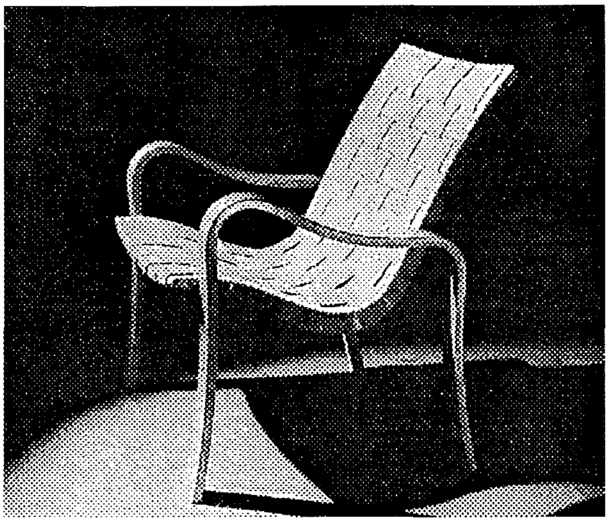


Figure 47. Laminated armchair with jute seat , Ewart Holt Kamp, Artek (1935)

For the sanatorium in Paimio (Figure 11), Alvar Aalto at first experimented with tubular steel frames, but he later wrote *'we soon changed over to wood, because steel furniture seems too harsh, psychologically, for the environment of sick people. And so we began to work with wood, using this warmer and more pliant material as a basis to construct a functional style of furniture .'* In the 1930s, Aalto founded Artek, and from experiments with birch, which is very elastic, and was used in Finnish industry exclusively for skis at the time, he developed a new process for the manufacture of solid wood constructions: plywood sheets glued in layers on top of each other were bent and pressed using steam and pressure, and then cut into strips, as in Figure 47.

4.7 Silhouette

The silhouette of the chair will be formed by the curve of the back of the chair, which in turn is the result of ergonomic considerations. The form will be similar to that of Figure 47, although this is not a one piece chair. The back will be cut from this single sheet form, reversed and inserted back into the sheet. The chair could be stacked by reversing and inserting the back into the cut out.

4.8 Environmental Considerations

The 1990s has seen a shift of attitude in the approach of some designers and manufacturers towards the production of environmentally sound furniture design. Philippe Starck's *Louis 20 chair* (see Figure 48) for instance, is an innovative construction of recyclable materials. For recycling purposes the *Louis 20* is constructed in two sections which are joined with screws rather than glue so the materials remain unsullied by additives. The voluminous hollow front legs, seat and springy back section are blown from a single piece of polypropylene. The aluminium frame of the back is joined with an oversized fixing plate to the hollow body so the chair can be tilted on its back legs without any damage. The organic form is continued in the way that the chairs stack, as shown in Figures 49 and 50.

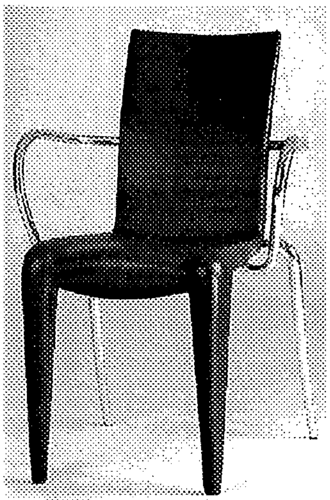


Figure 48. Louis 20 chair, Philippe Starck (1992)

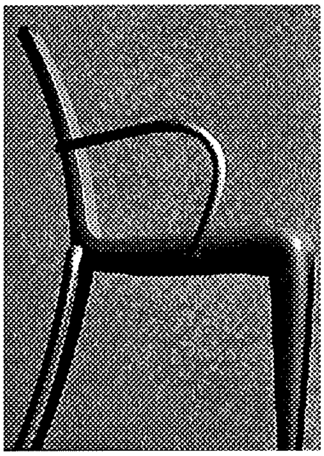


Figure 49. Louis 20, side view

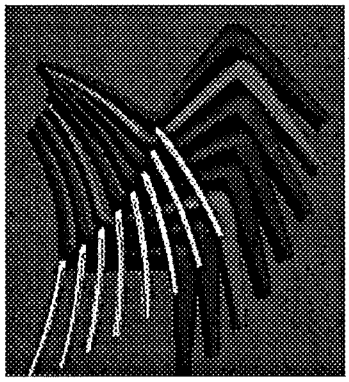


Figure 50. Stacking sequence of Louis 20

Admirable as many new designs are in addressing the environmental concerns of today, 1% of all industrial, ozone-depleting VOC (volatile organic compound) emissions in the United States still come from furniture manufacturing (Johnson-Gross *et al.*, 1995). The most effective guiding principle in confronting the longer term ecological requirement would be to simply make less last longer. The use of simple, organically derived forms and natural materials makes objects less likely to be associated with any particular period, and their life will therefore be extended (see Figure 46).

'A piece of furniture (and above all the chair), is not an arbitrary component of our environment... the outward expression of our everyday needs; it must be able to serve both the needs that remain constant and those which vary. This variation is possible only if the very simplest and most straightforward pieces are used; otherwise changing will mean buying new pieces. Let our dwelling have no particular 'style', but only the imprint of the owner's character.' (Breuer, 1965)

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5.1 Introduction

'One of the most promising new alternative technologies is reinforced composite fabrics.... which show significant advantages and benefits for the furniture industry. Designers and manufacturers of furniture (office seating, domestic seating, contract seating and tables), could use this new technology to produce moulded items in small batches using very low cost tooling. This would be a positive advantage and benefit especially when prototypes or pre-production batches are required. Costly tool investment costs can be postponed or reserved for high volume production. The process therefore offers manufacturers added flexibility to cope with variability in customer/ delivery requirements without large or costly stocks of finished goods. Composites have been shown to offer the following significant advantages: inert and cost competitive material, easily stored and handled; low labour requirement; improved mechanical performance, notably toughness and impact resistance; no fume emissions during processing.'

Furniture Industry Research Association Draft Press Release:
The Transfer of Composites Technology from the Aerospace, Defence and Automotive Industries to the Furniture Industry
(Courtesy of FIRA, April 1997)

5.1.1 Composite Reinforcement

Composite is the buzzword among new designers, who are creating their own formulae to strengthen, lighten, colour or texturise base materials. Strangely, it was partly the recession of the early Nineties which gave British designers the lead in creating objects from unlikely materials. Without factories making new products, they took skills from other industries, learning from the aviation industry, sports goods manufacturers and resin moulders. This cross-pollination of skills has produced new ways of working with materials and created some radical ideas. It has meant that furniture designers have become more practical, while still having fun.

'Don't make something unless it is both necessary and useful;
but if it is both necessary and useful, don't hesitate to make it beautiful.' (Shaker Hands)

5.1.2 Woven Fabric Reinforcement

Because of their unique combination of light weight, flexibility, strength and toughness, textile materials have long been recognised as an attractive reinforcement for composites. The recent revival of interest in woven fabric composites is a result of the need for significant improvements in intra- and inter-laminar strength and damage tolerance for structural composite applications. Two dimensional woven fabrics exhibit good stability in the mutually orthogonal warp and fill directions: they provide more balanced properties in the fabric plane than unidirectional laminae. The bidirectional reinforcement in a single layer of fabric enhances impact resistance. The ease of handling and low fabrication costs have made fabrics attractive for structural applications.

5.1.2 Continued

Triaxially woven fabrics, made from three sets of yarns which interlace at 60° offer improved isotropy and in-plane shear rigidity.

5.1.3 Weave Geometry

An orthogonal woven fabric consists of two sets of interlaced yarns. The length direction of the fabric is known as the warp, and the width direction is the weft. The various types of fabrics can be identified by the pattern of repeat of the interlaced regions. Two basic geometrical parameters can be defined to characterise a fabric; n_{fg} denotes that a fill yarn is interlaced with every n_{fg}th fill yarn and n_{wg} denotes that a fill yarn is interlaced with every n_{wg}th warp yarn. Fabrics with $n_g \geq 4$ are known as satin weaves. Plain weave has $n_g = 2$, twill weave $n_g = 3$, 4-harness satin $n_g = 4$, and 8-harness satin $n_g = 8$. One side of the fabric will be dominated by the fill yarns, whereas the other side is dominated by the weft yarns. These weaves are illustrated below.

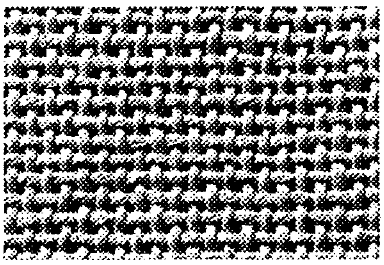


Figure 51. Plain Weave

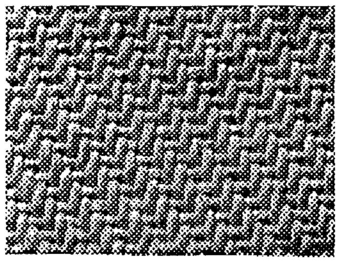


Figure 52. Twill Weave

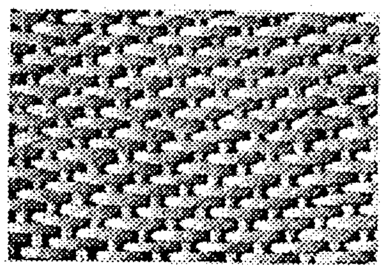


Figure 53. Satin Weave (n_g=8)

Plain weave is the simplest form of construction and also the stiffest and most stable, therefore it can be difficult to drape around compound curves or complex shapes. The plain weave imparts a high level of crimp to the fibres which gives them the relatively lower properties of the various weave styles. Twill weave has superior resin wet-out and drapability over plain weave, with little reduction in stability. In addition, the reduced crimp gives slightly higher mechanical properties and a smoother surface. Twill weave is characterised visually by a diagonal rib produced by the progression of the warp/weft intersection across the fabric. Satin (or crowsfoot) weaves are fundamentally twill weaves modified to produce fewer intersections of warp/weft. They are very flat, have good wet-out and drape, and the low crimp gives excellent mechanical characteristics. They are ideal for the production of thin, smooth surface finish laminates. These excellent properties are compromised by lack of stability. Since the chair form involves no compound curves and large flat sheets are being used, satin weave was chosen for the woven glass reinforcement, with a weight of $190 g/m^2$, a light weight weave to allow easy resin impregnation.

5.1.4 Design Philosophy

'Style is to see beauty in modest things' (Putman, 1992). A simple, pure shape for the chair section, which happens to look like the silhouette of a mammoth, has been created purely from anthropometric data, making it comfortable, easy and cheap to make, if a little unusual.

5.1.5 Lightness

'If the world's lightest - and most expensive - chair in carbon fibre can be blown over by a puff of wind, who needs it ?' (Dixon, 1997). The role of fibre reinforcement in furniture should be seen as being a 20-30% reduction in depth of wood sections, rather than paper-thin constructions.

5.1.6 Joints

'It is a curiosity of engineering design that it is impossible to fashion a simple tension member without first devising some end fitting through which the load may be applied; and whether the material be wrought iron or liana, wire rope or string, the stress system in the end fitting is a great deal more complicated than simple tension. There is plenty of scope for theory in the design of tension end fittings, but there is also a great deal of experience; and whether the competition is from the ancient pygmies' mastery of the craft of making knots in lianas, or from Brunel's development of efficient eye bars, experience will often dictate the design. Still the theorist has the final word.' (Cox, 1965). The absence of joints in plywood structures eliminates one of the main causes of failure in furniture. Loose joints cause excessive movement in furniture frames, a main cause of fatigue failure. Joints are very complex engineering problems, and are extremely difficult to model accurately with finite element analysis. By eliminating joints, the chair has been greatly simplified in order to enable finite element modelling, to predict the behaviour of the frame. *'God is in the details'* (Mies van der Rohe)

5.2 Matrix Stiffness

The stiffness of fibre glass composites is due to the high modulus of the glass. Whether the stiffness of the fibre can be fully exploited depends on the stress-strain properties of the resin matrix. A tough extensible binder will make the composite strong, where a high fracture energy is needed to produce failure, but the laminate will be too pliant. A very hard binder, with a modulus similar to that of glass is likely to be brittle; such a composite will fail before the glass has been loaded to the limit, even if high quality fibres are used. High modulus binders with little tendency to creep develop cracks at moderate (2-3%) elongations (Houwink *et al.*, 1967).

5.3 Fatigue

Fatigue of metals has been studied for over a century and despite significant advances it remains

5.3 Continued

a major cause of catastrophic failure of structures. Composites, on the other hand, have high potential for fatigue resistance and can, in certain cases, be designed to eliminate the fatigue problem. The fatigue properties of composite are anisotropic, or directionally dependent, and can be dangerously low in some directions. This warrants careful use of composites based on understanding of the mechanisms that govern the fatigue behaviour.

5.3.1 Fatigue of Unidirectional Composites

Mechanisms of fatigue damage in unidirectional composites depend on the loading mode, for example tensile or compressive, and on whether the loading is parallel to or inclined to the fibre direction.

(a) Loading Parallel to Fibres The mechanisms may be divided into 3 types: *(i) Fibre breakage* occurs at a local stress exceeding the strength of the weakest fibre of the composite. An isolated fibre break causes shear stress concentration at the fibre-matrix interface near the broken fibre tip. The interface may then fail, leading to debonding of the fibre from the surrounding matrix. The debond length depends on the shear strength of the interface and is usually small, of the order of a few fibre diameters. The debonded area acts as a stress concentration site for the longitudinal tensile stress. The magnified tensile stress may exceed the fracture stress of the matrix, leading to a transverse crack in the matrix. The matrix undergoes a fatigue process of crack initiation and crack propagation and generates cracks normal to the longitudinal tensile stress. This *(ii) Matrix cracking* is randomly distributed and initially restricted by the fibres. When the local strains are higher than a certain threshold, the cracks break the fibres and propagate. In this progressive crack-growth mechanism the fibre-matrix interface will also fail due to severe shear stresses generated at the crack tip, known as *(iii) Interfacial shear failure.* Final failure results when the progressive crack-growth mechanism has generated a sufficiently large crack (which may be only of the order of a few millimetres for brittle composites). The fracture surface of a specimen looks messy if the fibre-matrix interface is weak and increasingly neat for stronger interfaces (see Figures 53-57).

The mechanisms of damage described above may operate simultaneously. However, observations indicate that the predominant mechanism leading to failure may be effective in a limited range of the applied cyclic strain. The *lower* limit is given by the fatigue limit of the matrix, the threshold strain below which the matrix cracks remain arrested by the fibres. This strain is observed to be approximately the fatigue strain limit of the unreinforced matrix material. The *upper* limit is given by the strain to failure of the composite, which is also the strain to failure of fibres in a composite reinforced by stiff fibres.

(b) Effect of Fibre Stiffness Consider two unidirectional composites with the same matrix and different fibres. The fatigue limit of the two composites will be the same and given by the

5.3.1 Continued

fatigue limit of the matrix. The upper limit, given by the composite failure strain, which is equal to the fibre failure strain, will be different for the two composites. In a particular case where the composite failure strain strain and the fatigue limit strain are equal, the range of strain with progressive fatigue damage will be zero. In such a case fatigue damage will be absent and only static failure will be possible. This can be shown by comparing 2 composites of unidirectionally reinforced epoxy with either glass fibres or carbon fibres. The fatigue limit strain in both composites is 0.6% while the mean failure strains are 2.20% for glass-epoxy and 0.48% for carbon-epoxy. The glass-epoxy has a wide range of strain with progressive fatigue damage while the carbon-epoxy composite of highly stiff fibres has its fatigue damage totally suppressed. Other carbon-epoxy composites with less stiff fibres and having failure strain of about 1% show some progressive fatigue damage.

(c) Loading Inclined to Fibres When the cyclic loading axis is inclined at angles of more than a few degrees to the fibre axis, the predominant damage mechanism is matrix cracking along the fibre-matrix interface. The lowest fatigue limit is given by the strain for transverse fibre debonding, that is failure of the fibre-matrix interface by growth of an interfacial crack. This occurs at the off-axis angle of 90°, that is when loading is transverse to the fibre direction. The anistropy of unidirectional composites means that the fatigue limit strain decreases with the off-axis angle. The strain below which a composite is safe against fatigue failure when loaded normal to fibres is only 0.1% for glass-epoxy composites. This is one-sixth of the same strain for loading along the fibres. However, the ratio of the allowable stresses in the two directions is 1:24, when the elastic moduli in the two directions differ by a factor of 4, a typical value for glass-epoxy composites.

5.3.2 Fatigue of Bidirectional Composites

The inferior fatigue properties of unidirectional composites in the direction normal to fibres can be improved by building up laminates with woven composites. When loaded in a direction bisecting the angle between fibres, they suffer damage similar to that in a unidirectional composite loaded inclined to the fibres. However, the rate of progression of damage is reduced due to the constraint provided by plies of one orientation to cracking of plies of the other orientation. The constraint is highly effective at low angles between fibres but loses effect increasingly with increasing angle.With woven fabrics, the fibres are in two orthogonal directions. When loaded along one fibre direction a cross-plied laminate develops cracks along fibres that are loaded transversely. These transverse cracks are now constrained by plies with fibres normal to the crack planes, and the degree of the constraint depends on the thickness of the cracked ply (equal to the cracked length) and the stiffness properties of the constraining plies. The load shed by a cracked ply is carried by the constraining plies over a distance

5.3.2 Continued

determined by the constraint conditions. This distance determines the position of another transverse crack. Thus a crack-density progression process occurs, leading to a saturation crack density. Load cycling beyond attainment of the transverse crack saturation may lead to diversion of the transverse crack tips into the interfaces between plies. An interlaminar crack may thus form and grow causing an eventual delamination.

5.4 Finite Element Analysis

'Those who study the mechanics of laminated composites are quickly introduced to the fact that the large majority of analytical models are not readily suited to hand calculation, but must be computerised.' (Griffin, 1990) The first analytical model for laminated composites, which evolved into the Classical Lamination Theory, was actually developed for use in designing plywood structural components. Even this relatively simple model requires computerisation for effective analysis of realistic laminates. In addition, the simplifying assumptions lead to a model which ignores shear (see 5.4.2). The inherent complexity of the stress state in laminated components has meant that even more sophisticated analysis techniques are required in order to adequately predict the response of even simple parts. As discussed on Page 97 and shown in Figures 38 and 39, the effect of shear is too large to be ignored with composites.

5.4.1 Limitations of Finite Element Analysis

To analyse general problems, many structural analysts have turned to the finite element method, while others have approached the problem using elasticity solutions, perturbation methods, and a variety of other solutions. These solutions, although they may yield predictions of three dimensional stress states in laminates, are not in fact three dimensional models, but rather two dimensional models enriched with the appropriate terms to yield predictions of the stress components. The initial finite element approach was to use the computationally least demanding means possible: two dimensional elements. These analyses included models based on the assumptions of plane stress and plane strain, and ignore plane shear, which is often responsible for failure initiation. For problems which are two dimensional, application of two dimensional finite elements can yield accurate results. However, when the material properties or loading are not truly two dimensional, the two dimensional solution may not capture all the necessary information. As limitations of the two dimensional technique became known and more powerful computers became available, three dimensional finite elements saw an increasing amount of use.

5.4.2 Simplifying Assumptions of FEA

Most of the work in the area of three dimensional finite element analysis of laminated composites has been performed under a standard set of simplifying assumptions. The individual laminae are

5.4.2 Continued
assumed to be unidirectional, homogeneous, either orthotropic or transversely isotropic, and of constant thickness. Once some assumption has been made regarding the number of elements per ply or group of plies, the analysis is fairly straightforward. Understanding and presentation of the results has proven to be a much more difficult problem than actually making the runs.

5.5 Full Size Testing

'Not only is ornament produced by criminals, but also a crime is committed through the fact that ornament inflicts serious injury on people's health, on the national budget and hence on cultural evolution' (Loos, 1908)

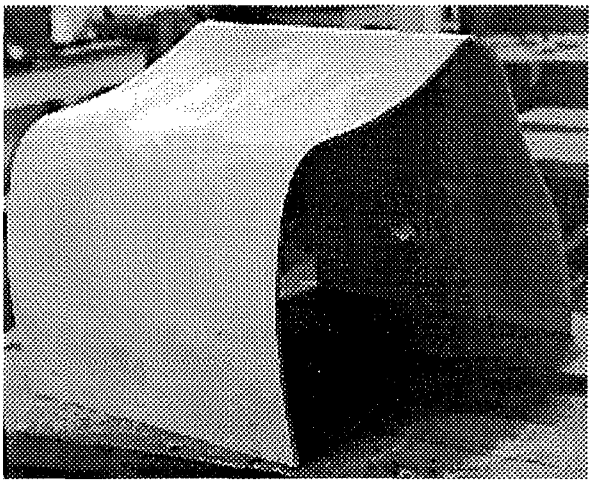


Figure 54. Glass Reinforced Chair Section

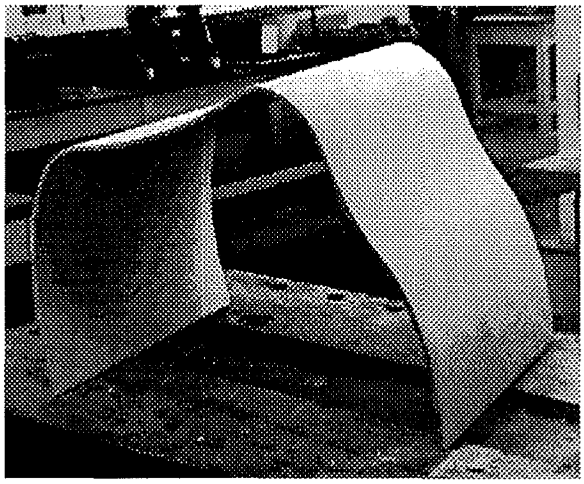


Figure 55. Glass Reinforced Chair Section

3 full size chair frames were made for testing. One of the epoxy bonded samples delaminated in the press due to a faulty vacuum pump, leaving 2 samples. One sample contained laminated timber bonded with urea formaldehyde, and was used as a control sample. The force used to simulate a design load was that imposed by a 90th %ile man. From Appendix 2, the mean body weight of men is 76.3kg with a standard deviation of 12.6kg. Therefore the 90th %ile = 76.3 + (12.6 x 1.28) = 92.5kg, where 1.28 is the z value at 90%, from standard statistical tables.The force applied was therefore chosen as 900 N. The ply sample, when loaded on the extended bed of the tensometer, failed at a peak load of 780N, with a vertical deflection of 22.76mm at failure. The glass reinforced frame had a vertical deflection of 9.45mm at 900N load, without failure.

5.5.1 Ply Sample

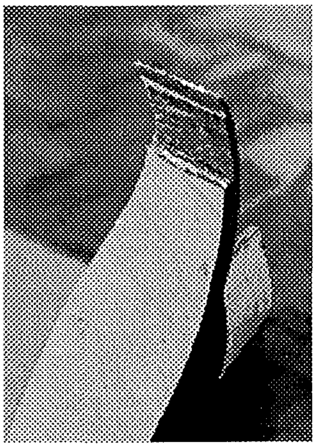


Figure 56. Fracture Surface

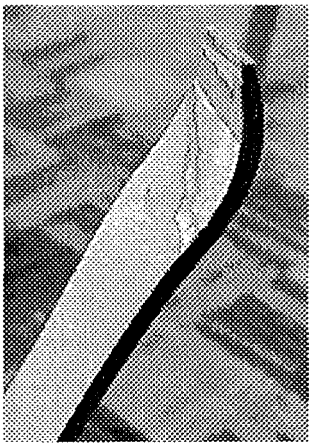


Figure 57. Tearing of Ply

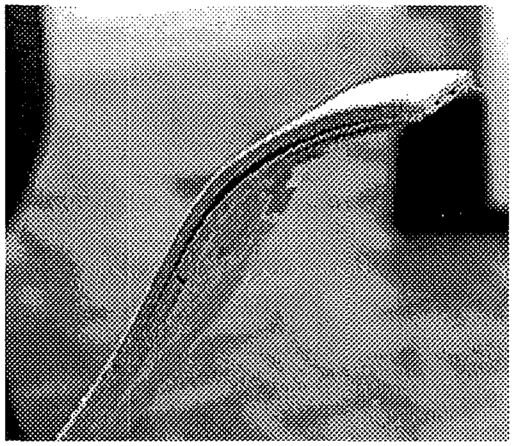


Figure 58. Delamination around Failure

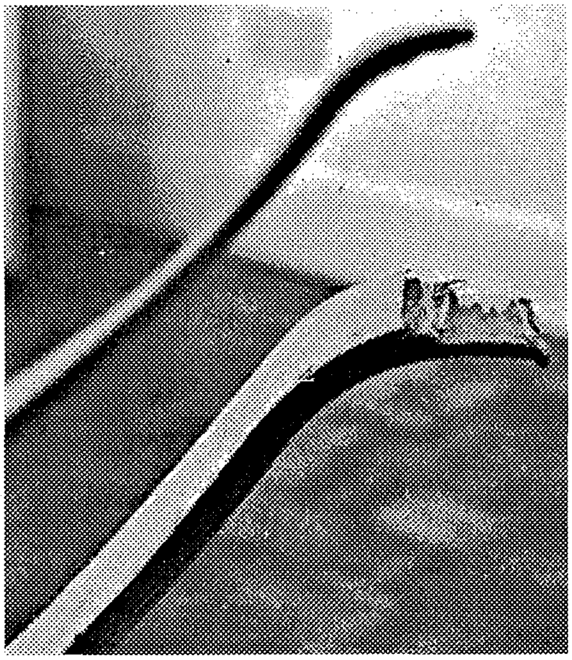


Figure 59. Rough Ply Failure Surface

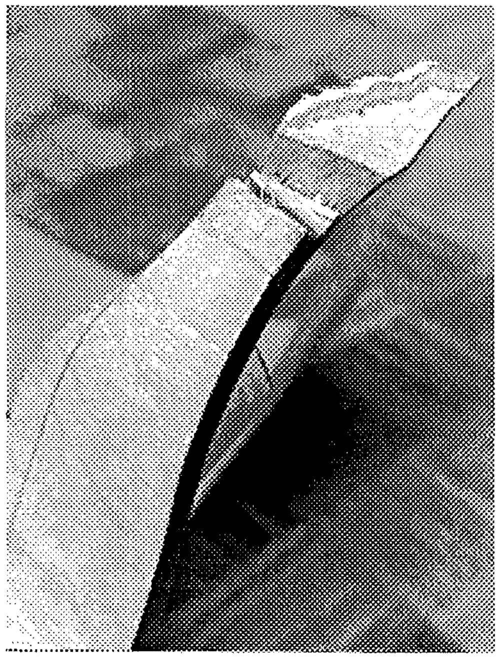


Figure 60. Rough Ply Failure Surface

5.6 Chair Design

'A house is a machine for living in;

An armchair is a machine for sitting in and so on.' (Le Corbusier, 1923)

Corbusier is clearly proposing above all that things should work, a chair should function as a place for sitting. This form is ergonomically correct and will withstand the dynamic force applied by a 90%ile man, yet it is first and foremost a large test piece to show the effects of fibre reinforcement.

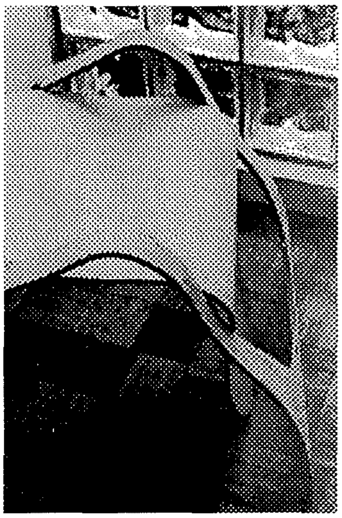


Figure 61. Chair When Flat

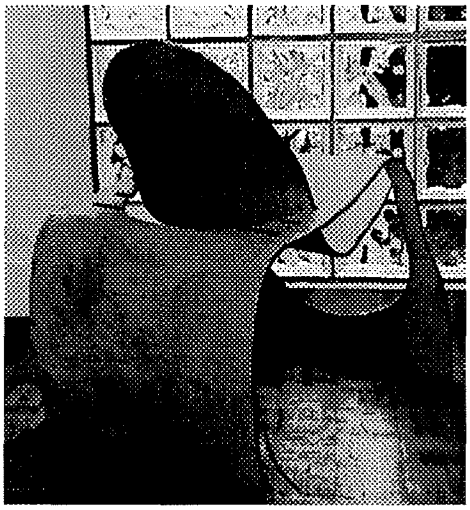


Figure 62. Chair (Rear View)

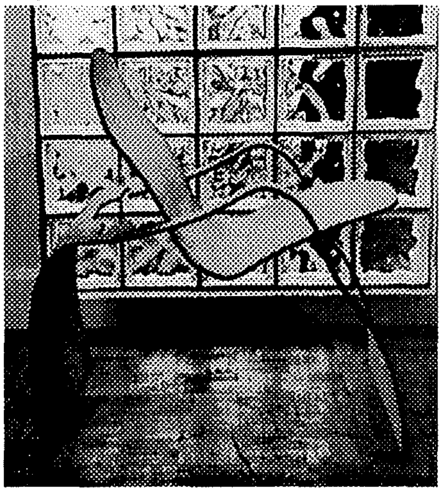
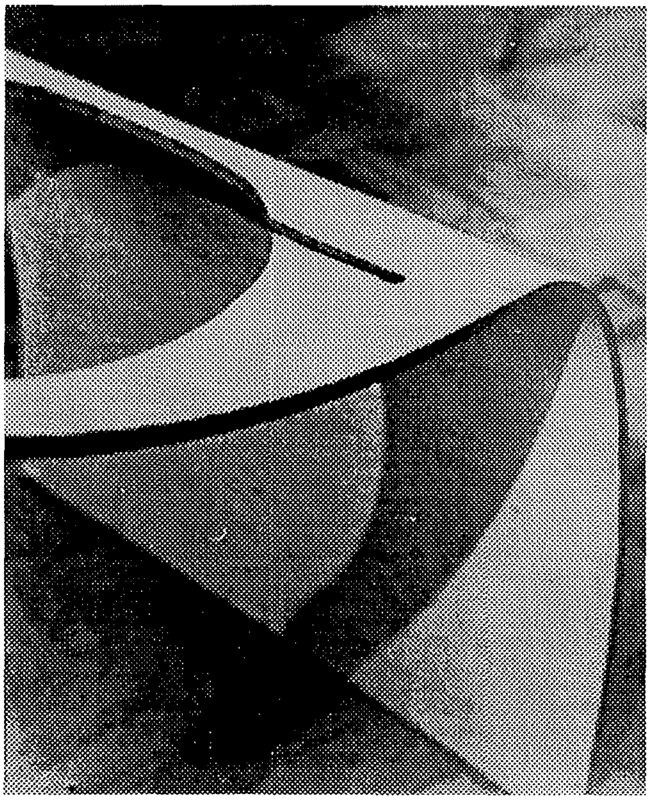


Figure 63. Chair (Side View, Detail)



'I can't think how many times I've wanted to leave a dinner table after spending too long in a designer chair' (Smith, 1995). The chair shape was derived from ergonomic data to ensure comfort. Cut outs in the frame allowed small alterations in seat positioning after testing to maximise seating comfort through angle adjustment of the seat back.

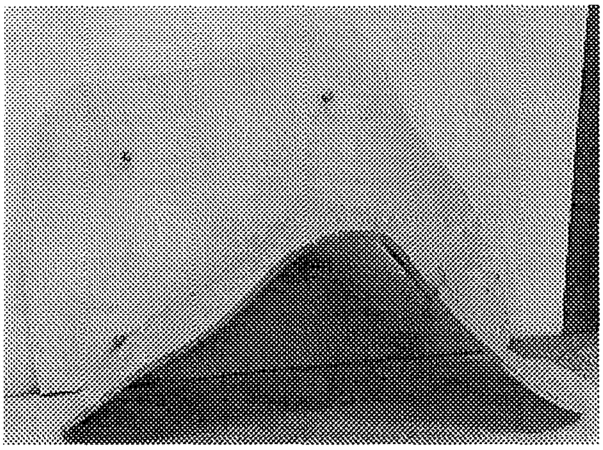


Figure 64. Moulder Template and Chair Back

Figure 64 shows the profile of the spindle moulder template, and the cut out profile of the chair back. The level of distortion on the glass reinforced sample was low, the laminate was checked against the template and the largest deviation from the mould dimension was a loss 'tow in' of 8mm over the whole length of the frame, which is much lower than the 33mm of the unreinforced sample. In the cross section, the reinforced sample had no noticeable twist, and deviations were no more than +/- 5mm. The unreinforced (birch) sample had a noticeable twist which would have caused rejection of the laminate. There were cross sectional deviations of +/- 12mm, mostly at areas of gentle curvature. Sharp curves showed more deviation from the profile, as the laminate retains some spring after moulding and always tries to level out bends after being removed from the mould. Figure 65 shows a profile of the chair design, showing how by lowering the seat back, the curve in the backrest forms an armrest section. Slots cut into the frame (see Figure 63) allowed testing of different angles for the backrest. The optimum angle between seat surface and backrest is between 100 and 110° for work chairs (see 4.2 Ergonomics). The angles chosen for test were 106°, 112° and 118°, with frame geometry dictating seat height.

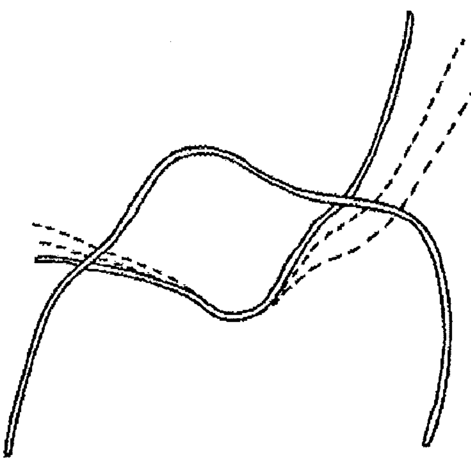


Figure 65. Schematic Chair Drawing

5.7 Discussion of Ansys Testing

Figure 66 shows an Ansys plot of the chair frame under loading. The loading diagram is shown in Appendix 7. The load applied to the frame is 900N at the nodes shown in Appndix 7 by 6 arrows, one on each of the 3 nodes on the armrest sections. The force is applied as a point load, and Figure 66, which is a plot of Von Mies' stress, shows an area of high stress around where the load is applied. Sharp radii also act as stress raisers, so this point is at a slightly higher stress than the surrounding areas anyway. Appndix 7 shows a plot of shear stress, which is similar in stress distribution, and a plot of the deformation of the chair frame profile when loaded. The maximum vertical deflection of the profile is 8.806mm. Ansys does not allow for the inclusion of friction forces in the x direction, so in order to give the model some stability the two ends of the frame have had to be restrained in the x direction by what amounts to a pair of pin joints.

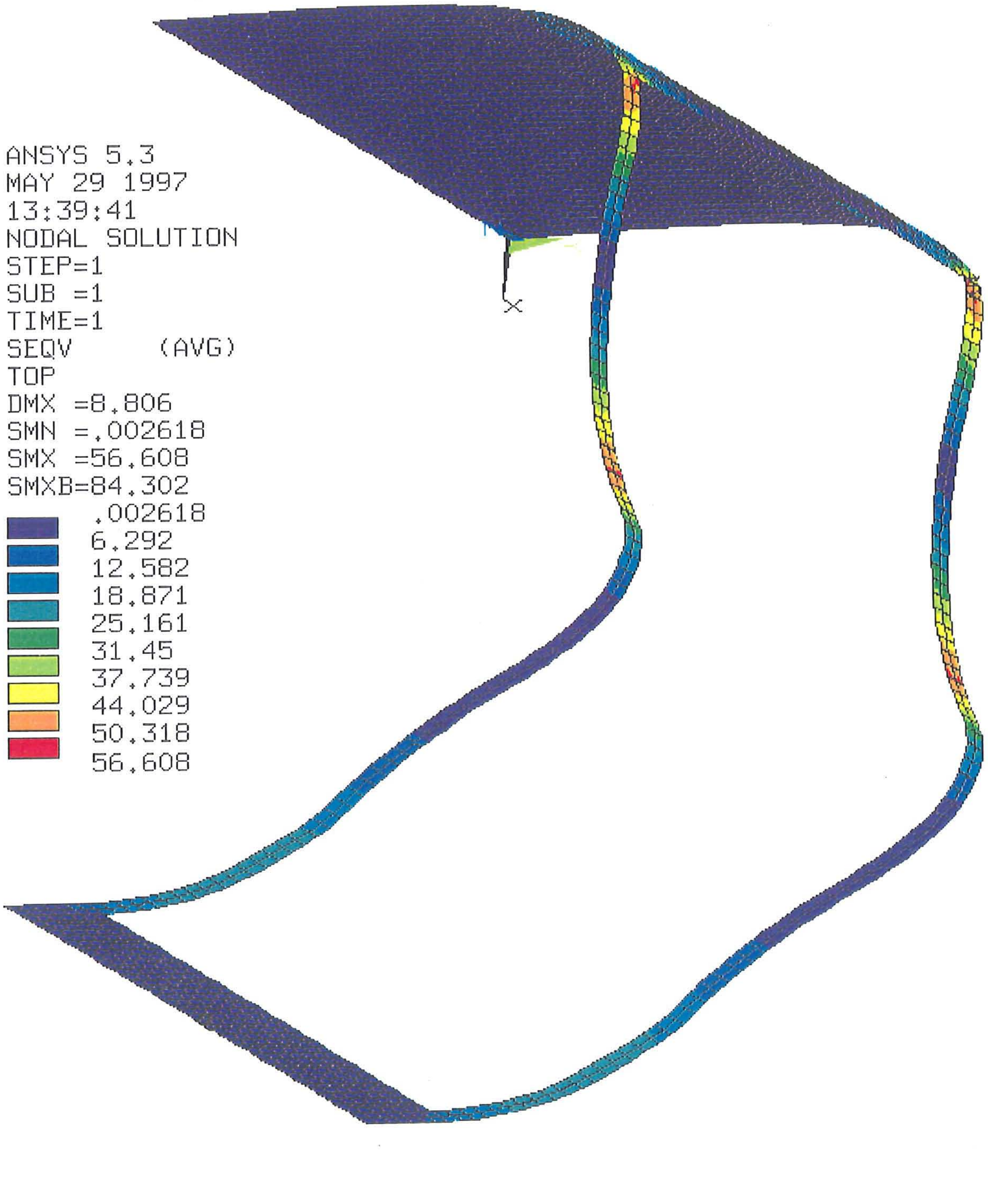


Figure 66. Finite Element Analysis of Chair (Von Mies' Stress)

5.8 Discussion of Chair Design

Fibre reinforcement allows the section of the chair to be around 25% thinner than a wood sample, and the improvement in distortion offered by the glass fibre satin weave mat means that no cross laminations need be inserted, so the difficulty of moulding such a shape is substantially reduced. The methods of calculating the stiffness of laminated sections meant the only way to accurately predict the behaviour under load of such a complex shape was through finite element analysis using Ansys. The profile of the shape was measured at 25 intervals, and the coordinates entered into the program, along with widths, MOE values, and the level of end restraint imposed to simulate friction between chair and floor. This method accurately predicts the behaviour, although the use of the program requires a great deal of experience and is time consuming. Results are however self explanatory and are presented in very helpful formats, especially when in colour.

The absence of joints in the chair helps the analysis, yet the design of the chair is severly limited by this simplification of construction. The majority of testing has been performed on the chair frame itself, as this is quite a representative shape for furniture, and shows the behaviour of fibre reinforced wood on a realistic scale. The chair back could however be tested separately, but the complete chair assembly could not be tested as it would not fit on the bed of the test machine. The chair form is thinner than would be possible with wood alone, yet is indistinguishable from a wooden laminate, even on close inspection. The public's resistance to cold, clinical materials is bypassed, and the form itself is organic and friendly, as well as being ergonomically correct so very comfortable and supportive, even without upholstery.

Although the inclusion of glass and carbon fibre reinforcement into wood laminates could bring exciting new forms into furniture, the most likely use would be to reduce dimensions of existing laminated sections, or to reduce distortion in sections where the introduction of cross laminations would make the laminate too difficult to mould. As with many new technologies and materials, the furniture industry has taken over 30 years to realise the potential offered by composites, and FIRA are currently instigating a large study into the subject area (see 5.1, page 105). The benefits to the furniture industry could be enormous, as here is a material which can be made with the same skills and machinery as normal laminated timber, with improved mechanical properties, and which is indistinguishable from laminated timber. The use of carbon fibre would raise both the cost and the performance, although not necessarily proportionally, but the reinforcement would be visible as thin black lines through the cross section. Far from being unsightly, these could become a sought after feature, in much the same way as visible carbon fibre has caught on in sports goods.

'Go to the woods and fields for colour schemes' (Wright, 1894)

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6.1 Introduction

'Fashions in furniture were very ephemeral. Every year the public taste was much better educated and it was more critical. To meet these contingencies it was absolutely necessary and imperative that every manufacturing firm should have its plant and facilities for manufacturing goods right up to date and fully abreast of the time' (Birch, 1912). The UK furniture industry has always been slow to embrace new technologies and materials. The public taste for reproduction furniture and rejection of modernist ideals has discouraged the introduction of new techniques. The constraints imposed by large scale industry do not allow for small scales batch production, which would bring more avant garde design to the marketplace at affordable prices. Laminating enables small batch runs as moulds are cheap to make and modify, so new forms can be created without the need for the costly tooling of moulded plastics or press tools for metals. If distortion can be kept to a minimum, laminate rejection rates could also be kept low.

6.2 New Materials

'Laminated bends presuppose new, and for this country, strange forms and these the trade has generally rejected in preference to forms derived from the more conventional methods of construction. The attitude of the trade towards the bending of laminated wood is disappointing, especially as it is merely one facet of the furniture manufacturer's deeply rooted antagonism to any change' (Farr, 1955). Charles Eames, in 1972, said of his early plywood work: *'The idea was to do a piece of furniture that would be simple and yet comfortable. It would be a chair on which mass production would not have anything but a positive influence; it would have in its appearance the essence of the method that produced it, an inherent rightness about it.'* There are few such examples. *'Unremittingly science enriches itself and life with newly discovered useful materials and natural powers that work miracles, with new methods and techniques, with new tools and machines. It is evident that inventions no longer are, as they had been in earlier times, means for warding off want and for helping consumption; instead, want and consumption are the means to market the inventions. The order of things has been reversed'* (Semper, 1852).

6.3 Low Voltage Heating

Low voltage heating as applied to the curing of glued joints utilises the principle of resistance heating in a simple and straightforward manner. The use of low voltage permits a cheap heating element to be used and makes for relatively safe handling. For efficient operation the heating element should be in direct contact with the work being glued, so that transfer of heat is by conduction. The only apparatus required is a step-down transformer with a capacity appropriate to the mass of the heating element and the temperature required. Transformers of 4, 6 or 12V capable of giving 500-1000A are commonly used. Galvanised steel or stainless steel are the metals generally used as elements; in most cases a thickness of 1-1.5mm is sufficient, and these can easily be shaped by bending. Low voltage heating is cheap to install in comparison with

6.3 Continued

dielectric heating (see 2.6.3), but it is not as efficient for gluing wood if the distance to the glueline is more than a few millimetres. With both forms of heating it is profitable to use glue formulations that give rapid curing, and to accept the inconvenience of short pot lives. The temperature of low volt heating elements may vary between 75° and 200°C. Although a period of a few seconds at the higher temperature does not char the wood, for prolonged contact a lower temperature such as 100-130°C is advisable (Houwink & Salomon), however it is often quite difficult to obtain a uniform temperature over a large heating element. The use of low voltage heating to cure epoxy resins would be an interesting development in fibre composites, allowing rapid curing of the resin in thin laminates, if temperatures of be maintained at around 80°C. *'If the artist is really to function in the modern world, he must feel himself a part of it, and to have this sense of social integration he must command the instruments and materials of that world'* (Moholy-Nagy, 1928).

6.4 Moulded Furniture

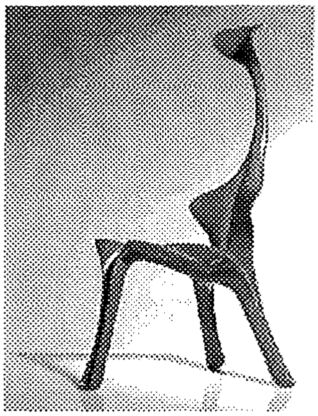

Figure 67. Floris chair, Günter Belzig (1967)

The extraordinary anthropomorphic Floris chair, produced by Günter, Berthold and Ernst Belzig, was first shown at the 1968 Cologne Fair. Intended as a totally weather resistant stacking chair, only 50 examples were originally manufactured, as its hand lay-up, 2 part construction in moulded fibreglass-reinforced polyester proved too complicated for efficient industrial production. It was subsequently reissued in limited numbers from 1992. In much the same way as Panton's stacking chair (Figure 3), the constraints imposed by the moulding of the plastic form raised the price to an unacceptable level, and the long term resilience of plastics has always been in doubt, not least in the eyes of the public.

'The chair remains unassimilable and in consequence it becomes very conspicuous...as much a piece of sculpture as an object of utility. The once humble chair has emerged as a thoroughly glamorous object.' (Nelson, 1960)

Eero Saarinen, a close collaborator of Charles Eames, strove for an organic unity of design. The *Pedestal* group, though visually unified, was a disappointment to Saarinen, as he was unable to achieve material unity - plastics technology did not allow for a single moulded pedestal chair form. Instead, a cast aluminium base had to be integrated with the fibreglass seat shell. The use of a pedestal base, however, did fulfil one of Saarinens's intentions - to clean up the *'slum of legs'*. He said *'Modern chairs, with shell shapes and cages of little sticks below, became a sort of metal plumbing.... I am looking forward to the point when the plastics industry will be*

6.4 Continued

Figure 68. Tulip chair, Eero Saarinen (1955-7)

capable of manufacturing the chair using just one material, the way I have designed it.' The Tulip chair is still produced today in its original form. In contrast to Eames, he was not particularly interested in technical problems. Harry Bertoia later said *'With chairs, functional problems need to be solved first...but, if you look carefully, chairs, too, are studies in space, form and metal.'*

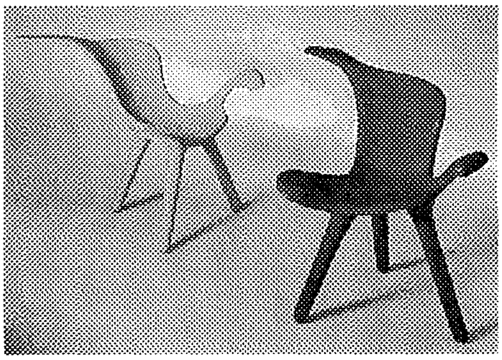

Figure 69. GRP chairs, Mark Robson (1989)

Mark Robson's 1989 moulded GRP (glass reinforced polyester) chairs have a vigorous asymmetry. The three legged form underlines an interest in pushing materials to their limits. With function strongly considered, the design takes advantage of the plasticity of GRP and allows its full potential to be realised in a fluid, organic shape. Apparently granting the medium a life of its own, the GRP chair literally grew around Robson as he constructed it while assuming different sitting positions within it. In this context, it could be seen as the beanbag for the 1990s, if only it could be efficiently produced.

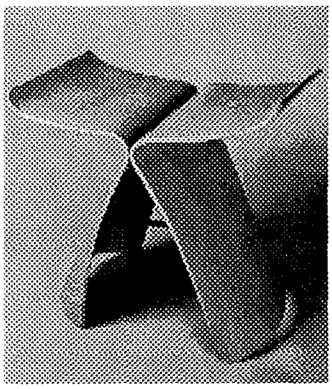

Figure 70. Butterfly stool, Sori Yanagi (1954)

The Butterfly stool is a delicate and harmonious synthesis of Eastern and Western culture. Consisting of 2 moulded plywood curves and a metal stretcher, it is extraordinary for several reasons. Yanagi uses no Western forms but based the highly organic form on the Japanese character for sky, and the wings of a butterfly. After meeting Charlotte Perriand in 1940 he developed an interest in seating, which did not exist in Japanese culture. Construction uses the plywood moulding techniques developed by Charles and Ray Eames. A 6mm thick sheet metal mould was used against which the wood was formed under pressure to achieve the compound curves.

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Figure 71. Japanese 'Sky'

6.4 Continued

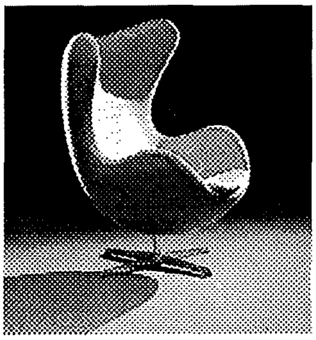

Figure 72. Egg chair, Arne Jacobsen (1957)

Jacobsen's Egg chair combines sculptural elegance with technical sophistication. The concave shape bestows a sense of power to the sitter. The problem lays in fitting the upholstery snugly to the latex foam padding over a fibreglass shell. Fibreglass is here used purely carcass material, and it would be impossible to guess the construction the chair form appearance alone. This organic form, characteristic of Jacobsen's work, would be difficult to make in any other material. *'A chair should not only look well as a piece of sculpture in a room when no one is in it, it should also be a flattering background when someone is in it.'* (Saarinen, 1960)

'Dear craftsmen friends! Throw away your artists' berets and bow ties and get into overalls. Down with artistic pretentiousness! Simply make things that are fit to use: that is enough to keep you busy, and you will sell vast quantities and make lots of money.' (Henningsen, 1957)

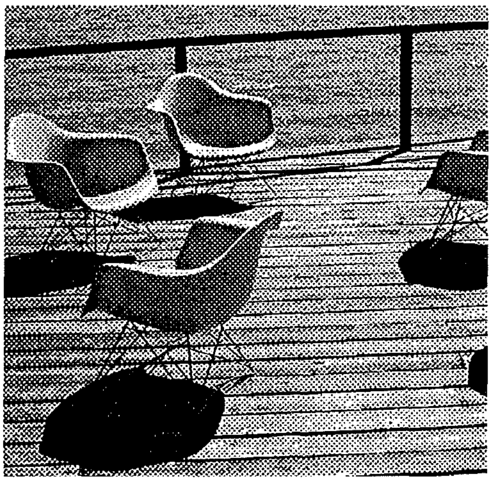

Figure 73. LAR Shell chairs , Charles and Ray Eames (1948-53)

The 1948 *International Competition for Low Cost Furniture Design* intended to find new designers who could fill the manufacturing gap left by the war years. In Venice, Charles and Ray Eames were experimenting with glass reinforced plastics. For the competition, Eames submitted a series of chair designs in stamped sheet metal. *'We were interested in a plastic chair, but technology at the time made that seem very difficult. We even made some drawings in aluminium, but finally chose sheet metal because of the highly advanced mass production techniques available for it, especially in stamped parts'.* Zenith Plastics had worked with Eames before, making his 1948 *La Chaise* by a slow, costly hand process: woven cloth with embedded fibres was immersed in a series of quick catalysing resins, laid up by hand and then sanded. Zenith said the job could be done with a matched metal mould for $5000. It finally cost four times that amount. Armchair shells like those shown cost $6.25 each based on an initial run of 10,000. Production was plagued by flying glass particles, and by devising a technique for letting the fibres show without being rough. Each of the early shells were practically handcrafted, and hand finished.

6.4 Continued

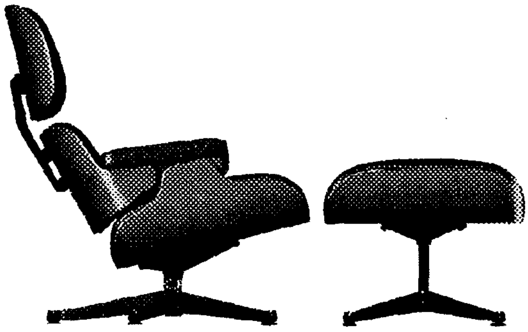

Figure 74. Lounge chair and ottoman, Charles & Ray Eames (1956)

Figure 75. Charles and Ray Eames (1947)

Although it can be dismantled using only a single spanner, the construction of the Eames Lounger is far more complex than any of his other pieces. The plywood shells, bent two dimensionally for the shoulders, back, seat and ottoman, have a unique method of connection to the rest of the structure. While both back sections are held together by two cast aluminium supports and hard rubber discs, the armrests provide the only connection of the back with the shell through neoprene washers. This division between the individual functions through segmentation of the structure and the use of different materials gives the chair a technical appearance. This linking of a technically mature modern structure with luxurious sitting comfort has ensured its status as one of the great design classics. Far more than 100,000 have been produced, despite the £3500 price (Anon., 1997). The Eameses' end view was always to create a product that could be mass produced with ease. Says Ray Eames: *'We wanted to get as much quality as possible into mass production so that more people could live with well made things.'* The many products of their philosophy - furniture wrought of heavy duty materials, and approached with an architect's concern for structure and spatial relations - had extraordinary impact not only on the look of the mid-century but on the decades beyond. *'I think of myself officially as an architect. I can't help but look at the problems of structure - and structure is architecture'* Charles Eames is the undisputed shining light of twentieth century American furniture design, yet it should be remembered that at the time Eames was working with Herman Miller he accounted for only around 2% of US furniture sales.

'The attitude that governs Herman Miller's behaviour, as far as I can make out, is compounded of the following set of principles: <u>What you make is important</u>.. Herman Miller, like all other companies, is governed by the rules of the (American) economy, but I have yet to see quality of construction or finish skimped to meet a popular price bracket, or for any other reason. <u>Design is an integral part of the business</u>. The designer's decisions are as important as those of the sales or production departments. If the design is changed, it is with the designer's participation and approval. There is no pressure on him to modify to meet the market. <u>The product must be</u>

6.4 Continued

honest.. Herman Miller discontinued production of period reproductions 12 years ago because its designer, Gilbert Rohde, had convinced the management that imitation of traditional designs was insincere aesthetically. You decide what you will make. Herman Miller has never done any market research or any testing of its products to determine what the market will accept. If designer and management like a solution to a particular furniture problem, it is put into production. There is no attempt to conform to the so-called norms of public taste, nor any special faith in the methods to evaluate the buying public. There is a market for good design. This assumption has been more than confirmed, but it took a great deal of courage to make it and stick to it.'

Forward to the Herman Miller catalogue, (Nelson, 1948)

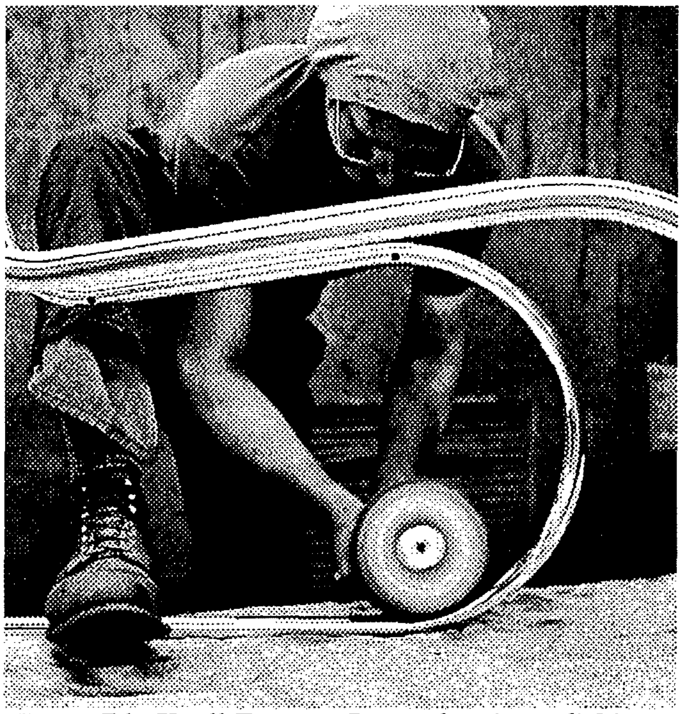

Figure 76. Knoll Factory, Pennsylvania: polishing one of the Breur Collection chairs (1995)

'Do all your work as if you have a thousand years to live or might die tomorrow.' (Lee, 1842). Forty years separate Figures 76 and 77, yet the level of hand finishing required on many furniture 'classics' remains high. The twentieth century furniture industry has only gradually made the transition from machine assisted craft to a full blown industry. *'The process of production in other non-heat using industries had the same characteristics as those making leather and wood products. Total output was increased more by adding men and machines than by continual technological and organisational innovation. For this reason the increased size of the enterprise brought few advantages in terms of increased productivity and decreased costs'* (Chandler, 1977). *'The furniture trade with its craft tradition has never acquired, so far as its cheap productions are concerned, the standards of precision and quality which are applied to mass produced articles in newer industries such as plastics, motor cars, and radio'* (Booth, 1935). As far as labour saving is concerned, amending the making process rather than introducing new machines may be an answer. The use of constructional features as part of the design could improve both. However much scientific research goes into furniture making, there

6.4 Continued

are many cases when it still has to be an integration of science and craft. The act of balancing two different cultures of production was noted by Trippe(1962): '*Furniture making is very much a traditional craft, and it has been essential to retain the craft element without losing it somewhere in the machinery of mechanisation. The planning policy thus provides an exceptional example of mass production of a craft product - almost a contradiction in terms.*' A revolutionary step was taken with the development of furniture factories working to strict engineering tolerances.

Figure 77. Herman Miller Factory, Michigan: fitting rubber mounts to Eames shell chairs (1955)

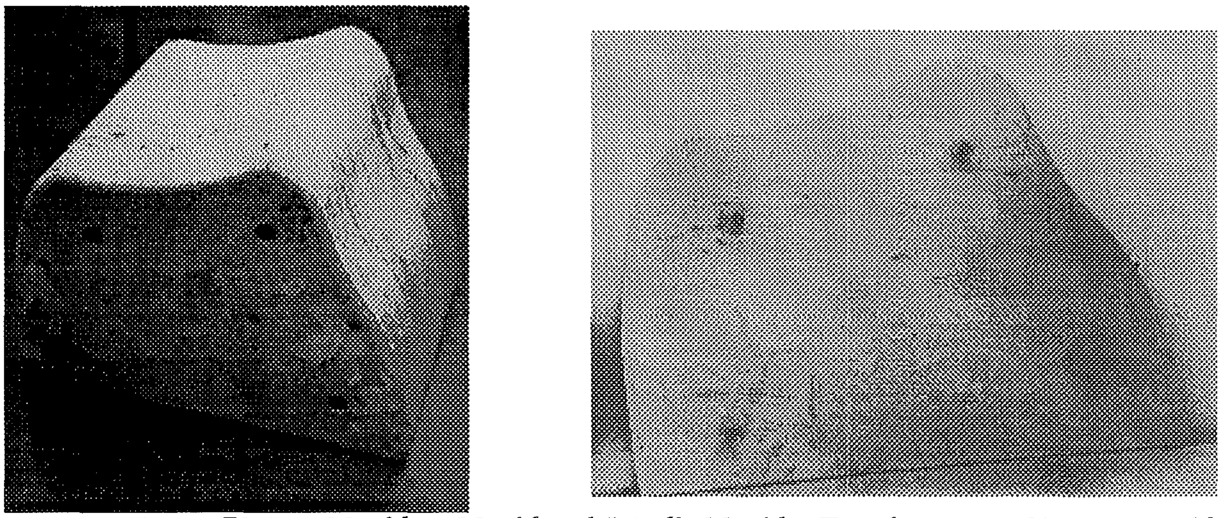

Figure 78. Bag Moulding Mould and Spindle Moulder Template for making the mould

6.5 Adhesives and Moulding Technology

It is clear from experiments performed with urea formaldehyde resins that they do not perform to their full potential with glass and carbon fibres. Bonding to the fibres does not appear to be too good, and their brittle nature does not allow them to withstand the high shear forces imposed by a wood/fibre composite, where the difference between the elastic moduli of the two materials is high. Delamination after testing exposed their useful limits. Epoxy resins are tough (elongation at break 5-10%, compared with 1-1.5% for urea formaldehyde), yet they are non-polar, so cannot be cured by radio frequency (dielectric) heating. The best compromise for performance and usability would appear to be a phenol resorcinol formaldehyde (PRF) resins, which have an elastic modulus of around 7000 MPa, a tensile strength of 55 MPa, and a compressive strength of 200 MPa. Processing data given in Appendix 6 shows that setting times at 100°C are as low as 90 seconds. Heat distortion temperature for PRF is around 115°C, so 100°C is about the maximum safe operating temperature, allowing for 10% error in thermostat performance on the press. Disadvantages of PRF include its high cost relative to UF, although it is comparable to epoxies. The brown colour can be a problem, although it is only noticeable with pale timbers such as birch and unstained beech. The relatively high viscosity is a problem shared with epoxies, and this can cause problems when trying to produce a thin, even glue line, especially over a glass fibre mat substrate. An application roller was used to ensure consistent coverage.

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7.1 Introduction

The next generation of composite materials will no doubt take their inspiration from natural materials. Nature makes the best use of easily available materials using the minimum amount of energy. The walls of wood cells are made from spirally wound cellulose fibres which are embedded in a matrix of lignin. This structure of the fibrous cell wall gives wood a very clever energy absorbing mechanism. When wood cells are loaded axially in tension they buckle inwards, developing spiral cracks between the fibres. If surrounded by identical cells, this causes the cells to pull away laterally from each other, retaining their longitudinal stiffness and strength because the cellulose fibres remain intact. It takes a great deal to improve on wood itself.*'Plastics are made by fools like me, but only God can make a tree.'* (Gordon, 1968)

7.1.1 Laminated Furniture

Charlotte Perriand, one of the foremost modernists, said in 1975: *'Metal plays the same part in furniture as cement has done in architecture'* . She used metal to make pure, simple yet cold and clinical, impersonal furniture. Compare this view with: *'Laminated wood has become not only a desirable but an essential and inescapable element in furniture construction. It gives to furniture the same character that the use of steel and concrete tends to produce in architecture. Thus at length we may confidently look forward to a genuine revitalisation of design and decoration proceeding not from successive waves of imitative fashion but from the truthful application of a material of which the practical and decorative possibilities seem to be endless.'* (Weaver, 1930)

7.2 Design History

'We are now predominantly a fashion industry and have learnt from experience in the past few years that public taste follows a strict pattern in which top design for a minority group soon flows into a majority market area' (Liley, 1969). The chair has been something of an icon for twentieth century designers. Mackintosh, Wright, Rietveld, Corbusier, Breur, Mies, Eames, Jacobsen, Aalto, Saarinen, Gehry - the list of architects who have seized the opportunity to express their theories in the design of a chair is seemingly endless. As architect Peter Smithson once proclaimed, *'When we design a chair, we make a society and a city in miniature.'* In describing the house and chair as a machine, Corbusier seems to suggest a denial of personality, character and individuality. On reflection, it seems clear he was proposing that things should work. Corbusier was writing at a time of great technological change. These developments offered the opportunity to design objects anew, free from historical precedents and tradition.

7.2.1 Modernism

'The demand for period furniture shows signs of giving place to a craving for ultra-modern forms of severe and simple type, which wholly ignore tradition and claim the fulfilment of function as their only object' (Anon., 1931). In common with many of the designers of the

7.2.1 Continued

Modern Movement, Corbusier's pronouncements had a distinctly moral tone. Adolf Loos famously stated that *'ornament is crime.'* The modernists aimed to redirect attention back to the functional, practical nature of things rather than the superficialities of appearance. *'Beauty rests on utility'* was the Shaker motto, later to be mirrored in the *'form follows function'* of the Bauhaus, which cited the Shakers as one of its inspirations. Modern design has often provided people with good reason to be fearful. *'Less is more'*, another modernist saying, was a heartfelt cry for purity and simplicity in design, for less applied decoration. But the conspicuous failures of post-war housing projects, and other attempts to put modernist ideals into practice, have left many with the conviction that less is sometimes merely less.

7.2.2 Acceptance of Technology

'Interesting experiments have been made in the use of plywood as a structural material, and in the future present techniques may be superseded by the increased use of ply shaped and bent to form carcasses' (Booth, 1935). Britain, of all Western countries, was slowest to adopt technological improvements in the home, reluctant to abandon open fires in favour of central heating, late to embrace modern conveniences like refrigerators, dishwashers and washing machines. Technology, when it arrived, was viewed with mixed feelings. Modernism never caught on in a big way, and furniture has always been seen as a keeper of traditional values.

7.2.3 Post War Furniture

'War makes fashions' (Stein, 1942). Many designers experimented with plywood after World War 1, but it was the work of Charles Eames which was the nucleus of further developments in the plywood moulding process. Interrupted but also aided by work on wartime plywood products and by the development of synthetic materials and new technologies, the chairs were pure expressions of the moulding process. Eames' moulded leg splint of 1942 took 5 hours to mould and needed hand trimming and finishing, yet by the end of the war 150,000 had been produced, with exterior veneers of birch and mahogany, and cores of Douglas fir. Without the vast amount of capital invested in the project by US navy, plywood moulding techniques would have developed at a much slower pace. His Plyformed Wood Company also produced ply aircraft seats, stabilisers, petrol tanks, hinges and structural angles. *'Design is not the abstract power exercised by a genius. It is simply arranging how work shall be done'* (Lethaby, 1882).

7.3 Why laminated timber?

The advantages of glued laminated timber structures are:

(a) Large structural elements can be produced from standard commercial sizes of lumber; off-grade or shorter pieces can often be used.

7.3 Continued

(b) Defects due to checks, knots, drying, or seasoning can either be eliminated or minimised by selection of the laminations or repairs of defects.

(c) Thoroughly seasoned laminae will undergo only a minimum of distortion and shrinkage after erection of the structure.

(d) Laminae can be positioned according to strength criteria as determined by species, defects and grades. Thus material of high strength can be placed where it is most needed, and one or more reinforcing material can easily be incorporated at any point in the laminate.

(e) Members can be varied in cross section and tapered in depth for a more pleasing appearance or to save material, whenever possible.

(f) Laminated timber structures are highly durable and, for more than half a century, have had a record of chemical and physical stability (minimum of swelling and shrinking with changes in moisture content, and no loss in bending strength with time), absence of corrosion (in atmospheres where metals fail), and resistance to biological attack.

(g) Curved members not obtainable from natural lumbar are possible with these structures.

(h) Improved mechanical properties, allowable stresses and modulus of elasticity often permit a saving in timber.

Laminated timbers have some disadvantages:

(a) Economic factors in the use of laminated members (wages, price of glue, capital investment in equipment, plant space) may influence the picture unfavourably when compared with solid timber, frame constructions or materials such as steel, aluminium and plastics for volume production.

(b) Special equipment and a skilled work force must be maintained.

(c) Gluing operations require rather sophisticated manufacturing procedures, while nailing, bolting, or use of other mechanical connectors are fool proof operations.

(d) Large members, especially curved ones, are awkward to handle and transport.

7.4 Problems

'Though human genius in its various inventions with various instruments may answer the same end, it will never find an invention more beautiful or direct than nature, as in her inventions nothing is lacking and nothing superfluous' (da Vinci, 1511). Although adding fibre composite reinforcement improves the mechanical performance of wood, this isn't always advantageous to the furniture producer. Tool wear for example is much higher than with unreinforced laminated timber, which in turn is higher than solid timber, due to the blunting effects of glue lines. The effect on tool wear would have to be studied in detail, as the cost of tools and machine down time whilst tools are changed would have to be accounted for when calculating the cost of fibre reinforcement. Machining of fibre composites also gives rise to a great deal of fine fibre dust,

7.4 Continued

which in the case of glass fibres is small enough to be drawn into the lungs, causing symptoms not unlike asbestosis. Thorough extraction is necessary to counter this problem but more study needs to be undertaken into the long term effects of working with glass fibre dust and the associated resins. Aramid fibre dust is already known to be particularly harmful when inhaled.
'The broader one's understanding of the human experience, the better designs we will have' (Jobs, 1996). The reticence among many consumers to buy modern furniture may be rooted deep in the British consciousness, or it may be due to a lack of well designed, affordable, easily available modern designs. Whether a 25% reduction in cross section is deemed worth a 50% increase in cost, which is a best guess of the actual figure involved, is uncertain. The fact that the reinforcement cannot be seen may be an advantage in some situations, for instance when reinforcing existing designs that are prone to failure, such as Gerald Summers' plywood armchair of 1933 (see Figure 10, page 20). For avant garde designs, the modern movement has taught us that laying open the construction of a piece of furniture is very important, and truth to materials is everything, so it may be good to face the uppermost face of the laminate with wood veneer to give a warm, smooth surface, whilst the underside could be left as fibreglass. The contrast between the pale woven fibreglass and the wood grain, or even better the shiny black fishscales of carbon fibre, could launch an exciting new aesthetic.
'Good design is 98% common sense and 2% aesthetics' (Edison, 1925). There is no doubt that there is a place for fibre composites in the improvement of wood laminates for furniture. It is up to designers and manufacturers to use them efficiently, and to design structures specifically for their unique properties, rather than just replace existing members with the new material, which would give small gains in performance but would not allow the composites to be used in an optimum manner, thus wasting money. The increasing sophistication and ease of use of finite element analysis packages will allow designers with little grasp of the complexities of stress calculations to produce accurate models of possible designs. The problem remains in translating these designs into workable, profitable pieces of furniture which will adequately withstand long term stress. Many theoretical models for laminated sections exist, due to the popularity of plywood structures, such as the classical lamination theory, on which many finite element models are based. When computerised, these allow for fast and accurate stress analyses. The method of laminating allows a great deal of control over the making process, albeit at the expense of semi-skilled manual labour for much of the process. Hand lay up is time consuming and labour intensive, but there is a level of consistent quality control not present in plastic moulding, where manufacturing faults can only be detected by X-radiography or more intrusive methods. The use of simple male moulds with bag presses or male and female moulds allows for easy mould alteration without the enormous cost of matched metal dies associated with plastic moulding, which thus necessitates very large production runs to repay capital investment.

7.5 Feasibility of Composite Reinforcement

Reinforcing glulam with glass fibre composites is very effective in structural elements where the strength of the wood, perpendicular to the grain, would otherwise become critical for the load bearing capacity. Wood is a natural composite with an integral structure that is anisotropic and heterogeneous. It is, from an engineering point of view, impaired by imperfections. Some of these imperfections are micro cracks distributed with a certain density in the wood. When a wooden structure is subjected to external loads the stress distribution around these cracks will determine when failure occurs, depending on how the cracks interact as they propagate. This is a model which supports the high scatter connected with mechanical testing of wood. Finite element computations suggest (Hallström *et al.*, 1997) that fibre reinforcement decreases the stress intensity at cracks in the wood and acts as a crack stopper by retarding crack propagation.

7.5.1 Performance Gains

The placement of a small amount of fibreglass, for example replacing 2 of 7 wood layers in a beam with glass fibre, will increase the second moment of area of the beam by 278% (see Appendix 5) when calculated theoretically using equivalent sections. This is by virtue of its modulus of elasticity being 7 times that of structural beech. Experimental results of the strength properties of laminated composites have been disappointing in the past, due to poor fibre bonding and glue starvation, with some tests resulting in a loss of mechanical properties (see 1.3.17). When fibreglass is placed at the outer layers of the beam, the maximum MOE will be obtained, but by placing the fibreglass under a facing veneer of the core timber, the gains in stiffness and strength are retained, while the laminate appears to be solid timber. Thus fibre reinforcement can give extra performance whilst retaining the appearance, warmth and finish of the timber. If the fibre reinforcement is placed at alternate layers throughout the whole laminate, an increase of at least 300% in the impact strength can be expected. Again, the most important areas for impact reinforcement will be the outer edges as they are most likely to be struck, yet the core must be reinforced in order to withstand compressive loads. The inclusion of glass fibre towards the centre of a beam will substantially increase the stability of the laminate, reducing distortion almost to the level given by cross laminations, but without altering the ease with which the laminate can be moulded, an important factor in manufacturing, hence cost.

7.5.2 Ease of Manufacturing

Eliminating cross laminations allows much tighter bends to be moulded before the minimum bending radius of the timber (see Table 21) comes into force. Holding laminations into the curves of the mould before closure is extremely difficult with cross laminations in place, and bends are likely to open up more on release from the mould due to internals stresses set up in the laminate. Epoxy resins are the ideal adhesive to use with composites, as the bond achieved

7.5.2 Continued
is good, and the tough nature of the resin allows the mechanical properties of the composite to be exploited to the full. The high (5%) elongation to failure allows some resistance to shear forces and impact which is lacking in urea formaldehyde and phenol formaldehyde, which have an elongation to failure of around 1%, making them 5 times more brittle than epoxies. The use of radio frequency heating to cure phenol formaldehyde resins could speed curing up to a level comparable to urea formaldehyde bonded wood laminates. Although the bond to fibres is much better than urea formaldehyde, PF resins are still brittle. Low voltage heating of epoxies for fast curing of relatively thin laminates could be a major development in the furniture industry, as this method is much safer than radio frequency heating, almost as fast, involves much less capital investment and is easily controllable.

7.5.3 Economics of Fibre Reinforced Timber
At present, the use of epoxy resins to bond fibre composite reinforcement to timber is the only reliable method of achieving strong bonds, yet the cost of epoxies and composites restrict their use. As the cost of composites fall, the ability to use poorer quality timber for the core of reinforced beams will make fibre reinforced timber very attractive in the near future. At present, the use of glassfibre and epoxy resin to reinforce laminates is only economic where the 25-30% reduction in section depth is important aesthetically, or where laminates need reinforcing due to poor design (see Figure 10). The actual increase in cost of adding composite reinforcement will depend on economics of scale, but also mould design, press times, labour costs and adhesives.

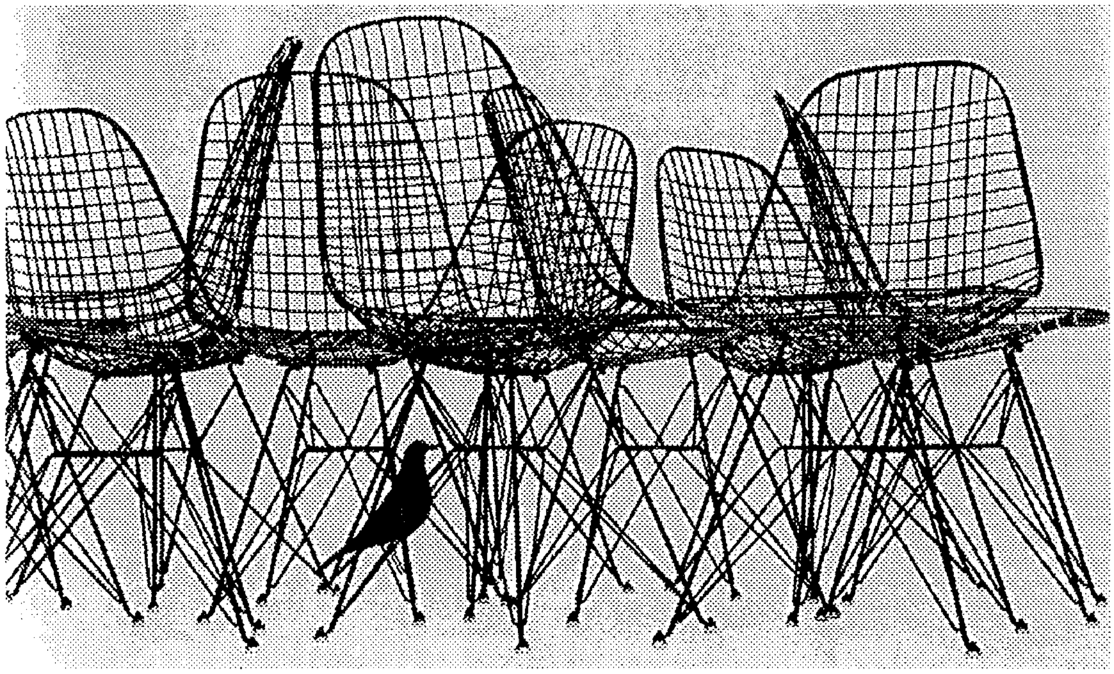

Figure 79. DKR chairs, Charles Eames (1951)

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'Technology is rooted in the past. It dominates the present and tends into the future. It is a real historic movement - one of the great movements which shape and represent their epoch. Technology is far more than a method, it is a world in itself. As a method it is superior in almost every respect. But only where it is left to itself, as in gigantic structures of engineering, there technology reveals its true nature.' (Mies van der Rohe, 1950)

'Technology is the knack of so ordering the world that we do not have to experience it.'

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APPENDIX 1 ***Mechanical Properties of Laminated and Clear Wood Specimens***

	Hungary		*Poland*		*Slovenia*	*United Kingdom*		
	Poplar	Turkey Oak	Alder	Birch	Beech	Poplar	Spruce: Sitka	Norway
MOR (MPa)	33.6 *72*	62.2 *130*	54.4 *80*	93.2 *123*	77 *108*	42.6 *72*	47.9 *67*	55.9 *66*
MOE (MPa)	7777 *8600*	12270 *11200*	12900 *8800*	18300 *13300*	15246 *10100*	9100 *8600*	12275 *8100*	13740 *8500*
Density (kg/m^3)	410 *433*	720 *785*	576 *450*	649 *600*	727 *600*	420 *433*	482	498
Compaction Ratio	0.95	0.92	1.28	1.08	1.21	0.97		

Table 31. Moduli of Laminated and Solid Poplar, Oak, Alder, Birch, Beech and Spruce (ELVE)

A summary of the strength results presented at the second progress meeting of the Copernicus ELVE (European Laminated Veneer Engineering) project, 1995. The figures in italics are the property values for small clear wood specimens. Each of the values given are the averages of either 10 or 15 replicants.

	Hickory *Carya spp.*	Pine, yellow *Pinus strobus*	Beech, European *Fagus sylvatica*	Birch, European *Betula spp.*
MOR (MPa)	132	53	118	123
MOE (MPa)	15100	5500	12600	13300
Shear strength (MPa)	16.5	8.9	15.9	16.2
Density (kg/m^3)	690 (@ 12%mc)	352 (@ 12%mc)	689 (@ 12%mc)	673 (@ 12%mc)

	Oak, European *Quercus spp.*	Balsa *Ochroma spp.*	Douglas Fir *Pseudotsuga menziesii*	Cedar, western *Thuja plicata*
MOR (MPa)	97	23	91	65
MOE (MPa)	10100	3200	10500	7000
Shear strength (MPa)	13.7	2.4	11.6	8.5
Density (kg/m^3)	689(@12%mc)	176 (@12%mc)	497 (@12%mc)	368 (@12%mc)

Table 32. Moduli of Hickory, Pine, Beech, Birch, Oak, Balsa, Cedar and Douglas Fir (BRE)

Results from Forest Products Research Laboratory *Bulletin 50* (Lavers, 1983).

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APPENDIX 2 ***Anthropometric Data***

Dimension	***Men*** 5th %ile	50th %ile	95th %ile	S.D.	***Women*** 5th %ile	50th %ile	95th %ile	S.D.
Stature	1625	1740	1855	70	1505	1610	1710	62
Elbow height	1005	1090	1180	52	930	1005	1085	46
Sitting height	850	910	965	36	795	850	910	35
Sitting shoulder height	540	595	645	32	505	555	610	31
Sitting elbow height	195	245	295	31	185	235	280	29
Buttock-knee length	540	595	645	31	520	570	620	30
Buttock-popliteal length	440	495	550	32	435	480	530	30
Popliteal height	395	440	490	29	355	400	445	27
Hip breadth	310	360	405	29	310	370	435	38
Shoulder breadth (max)	420	465	510	28	355	395	435	24
Abdominal depth	220	270	325	32	205	255	305	30
Shoulder-elbow length	330	365	395	20	300	330	360	17

Table 33. Anthropometric estimates for British adults aged 19-65 years (all dimensions in mm) (Pheasant, 1986)

Definitions

Stature: Vertical distance from floor to crown of head

Elbow height: Vertical distance from floor to the radiale (outer surface of elbow)

Sitting height: Vertical distance from sitting surface to crown of head (allow 10mm for clothing)

Sitting shoulder height: Vertical distance from seat surface to acromion (bony part of shoulder)

Sitting elbow height: Vertical distance from seat surface to underside of elbow

Buttock-knee length: Horizontal distance from back of the uncompressed buttock to front of knee

Buttock-popliteal length: Horizontal distance from the back of the uncompressed buttocks to the popliteal angle at the back of the knee

Popliteal height: Vertical distance from the floor to the popliteal angle at the underside of the knee where the tendon of the biceps femoris muscle inserts into the lower leg.

Hip breadth: Maximum horizontal distance across the hips in the sitting position (allow 10-25mm for clothing)

Shoulder breadth (bideltoid): Maximum horizontal breadth across the shoulders, measured to the protrusions of the deltoid muscles (allow 10mm for clothing)

Abdominal depth: Maximum horizontal distance from the vertical reference position (allow 10mm for clothing)

Shoulder-elbow length: Distance from the acromium (bony point) to the underside of the elbow in a standard sitting position

APPENDIX 2 Continued

Dimension	***Men*** Mean	S.D.	CoV (%)	***Women*** Mean	S.D.	CoV (%)	F/M (%)	R^2 (%)	%CE FEM
Body weight (kg)	76.3	12.6	16.5	64.5	12.6	19.5	92	50	8
Sitting height index	51.8	1.5	2.9	52.4	1.5	2.9	101	4	61
Biacromial breadth index	22.5	1.3	5.8	21.7	1.2	5.5	96	9	33

Table 34. Sex differences in body size & shape (F/M is female/male dimension) (Pheasant, 1986) (R^2 = between sex Ssq/total Ssq) (%CEFEM is % chance of female exceeding male)
Sitting height index: $\frac{\text{sitting height}}{\text{stature}}$ x 100% *Biacromial breadth index:* $\frac{\text{shoulder breadth}}{\text{stature}}$ x 100%

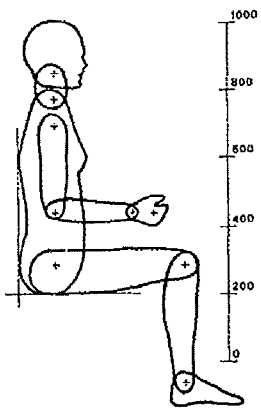

Figure 80. Mannikin - 5th %ile woman (scale 1:16)

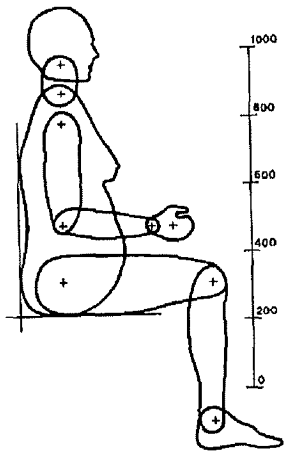

Figure 81. Mannikin - 95th %ile woman (scale 1:16)

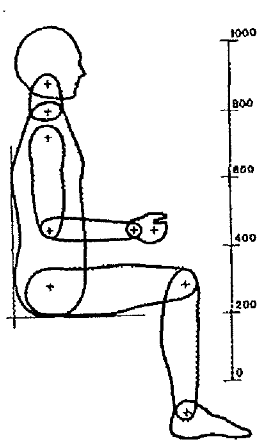

Figure 82. Mannikin - 5th %ile man (scale 1:16)

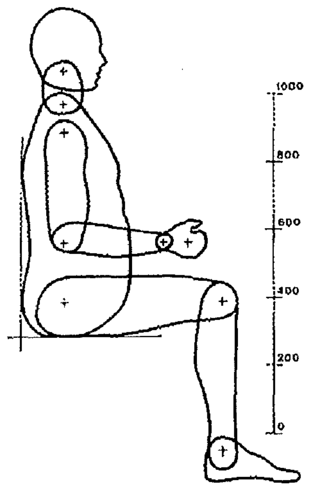

Figure 83. Mannikin - 95th %ile man (scale 1:16)

Note that, in theory at least, a 95th %ile mannikin is impossible since it is mathematically impossible for an individual to be, say, 95th %ile in all respects. Design methods which assume a '95th %ile person' or a '5th %ile person' are based on fictions. The designer should be aware of the limitations of such assumptions concerning percentiles and take care to ensure that these do not lead to major errors.

Reference

PHEASANT, S. 1986 *Bodyspace: Anthropometry, Ergonomics and Design* Taylor & Francis

APPENDIX 3 ***Epoxy Specifications***

SP110 Epoxy Laminating System

The minimum cure required before demoulding is 16 hours @ 20-25°C (standard hardener) but the laminate is not fully cured for a further 14 days at these temperatures. While a moulding will have adequate strength and stiffness after a room temperature cure, an elevated temperature post cure is necessary to fully stabilise the laminate and to give the finished composite maximum mechanical properties, particularly increased toughness. A typical post cure schedule is 5 hours @ 80°C.

Hardener	*Typical Uses*	*Laminate Working @ 20°C*
'Fast' 110FT	Core Bonding	0.3 - 0.5 hr
'Standard' 110SD	Laminating at Room Temperature	0.75 - 1.0 hr
'Slow' 110SW	Large Lay-up, Working at 25°C	1.5 - 2.0 hr
'Extra Slow' 110XS	High Ambient Temps, Large Components	3.0 - 4.0 hr

Table 35. SP110 - Working Properties with Different Hardeners

Property	*Room Temperature Cure:* 14 days @ 23°C	*Post Cured:* 16 hrs @ 23°C + 8 hrs @ 80°C
Tensile Strength	62.0 MPa	82.1 MPa
Tensile Modulus	3.35 GPa	3.34 GPa
Elongation at Break	2.85%	6.81%
Flexural Strength	101.2 MPa	122.6 MPa
Flexural Modulus	3.65 GPa	3.52 GPa
Compressive Strength	121.6 MPa	119.2 MPa
Compressive Modulus	4.7 GPa	3.92 GPa
Coefficient of Linear Thermal Expansion	56.7 x 10^{6}°C	52 x 10^{6}°C
Heat Deflection Temperature	55°C	78-80°C

Table 36. SP110 - Mechanical Properties (clear casting of SP110 resin & standard hardener)

Safety

Avoid skin contact, wash skin immediately if in contact with resin or hardener

Protect eyes

Avoid inhaling sanding dust

Reference

ANON. 1996 SP (Structural Polymer) Systems *SP110 Material Safety Data Sheet, SP110 Mechanical Property Guide* Montecatini Advanced Materials, Town Quay, Southampton SO1 1LX

APPENDIX 4 ***Ansys Plot - Nodal Solution***

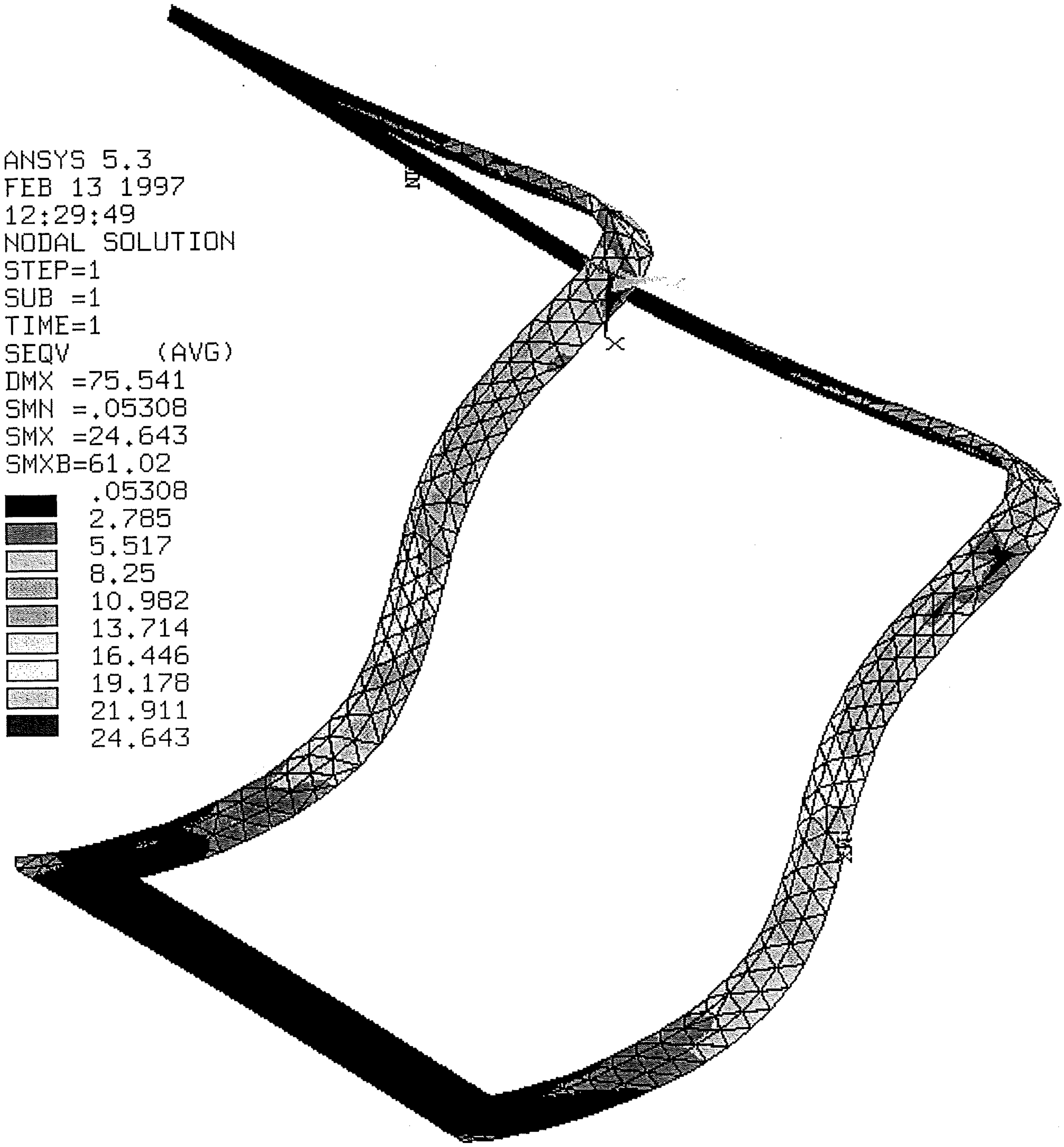

Figure 84. Ansys Plot

APPENDIX 4 Continued ***Ansys Plot - Nodal Solution (Von Mies' Stress)***

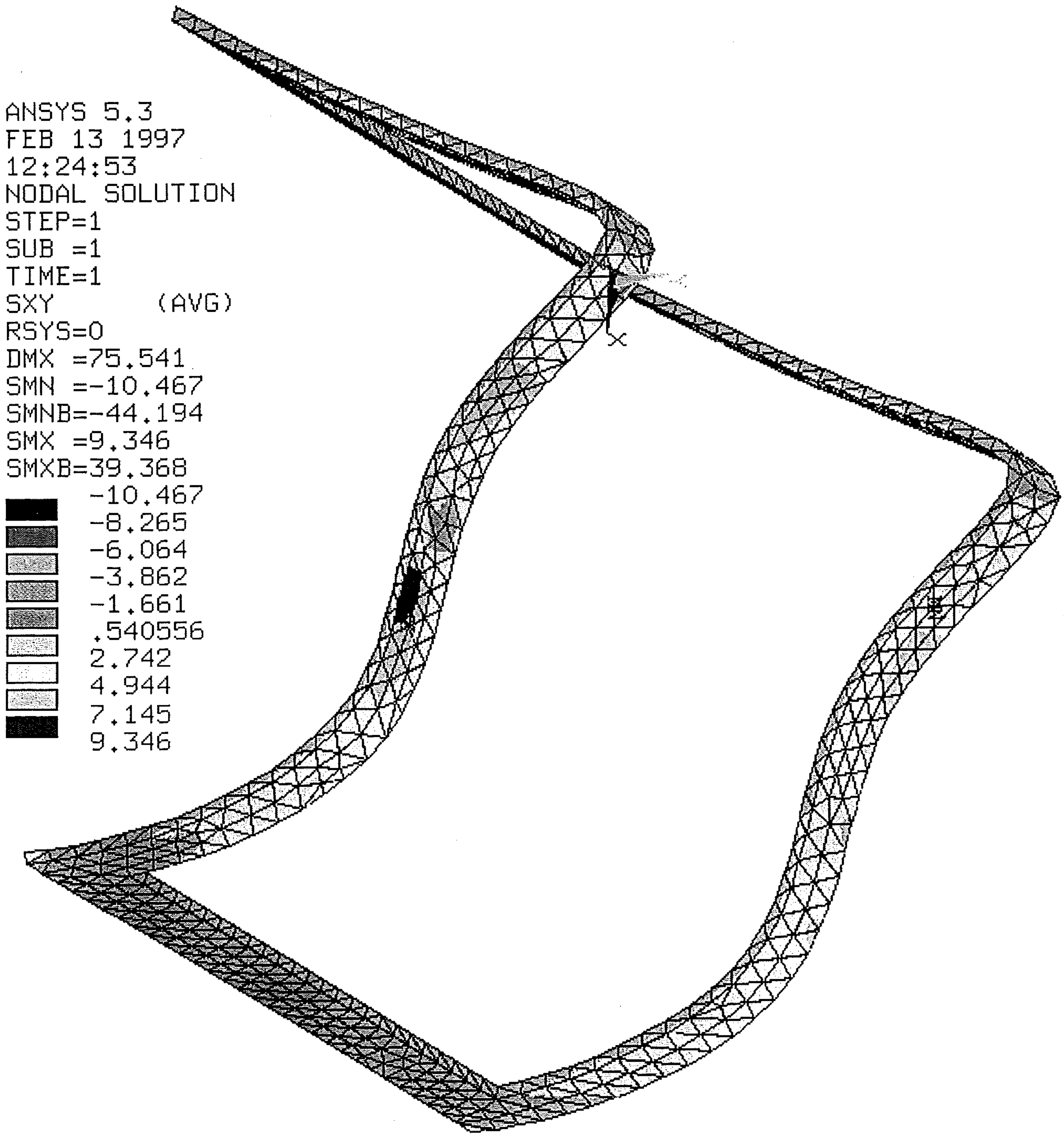

Figure 85. Ansys Plot

APPENDIX 4 Continued ***Ansys Plot - Displacement***

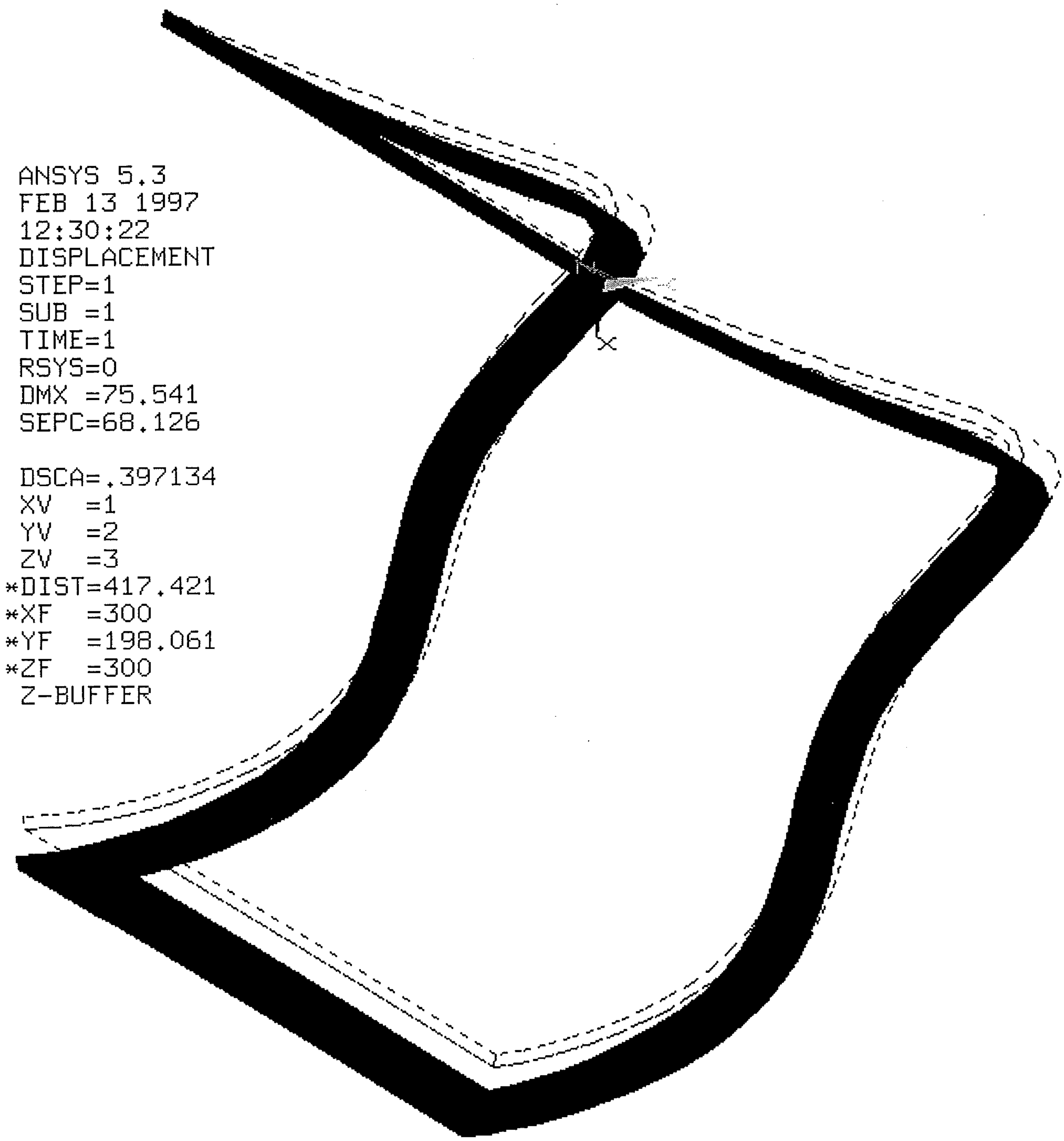

Figure 86. Ansys Plot

APPENDIX 5 *Beam Theory*

The basic formula for the stress ∂ at a point a distance y from the neutral axis (x-x) of a beam is $\frac{\partial}{y} = \frac{M}{I} = \frac{E}{R}$ *so* $\partial = \frac{My}{I}$ *where* ∂ = tensile or compressive stress (Nm^{-2}), y = distance from neutral axis (m), I = second moment of area of cross section about the neutral axis (m^4), E = Young's Modulus (Elastic Modulus) (Nm^{-2}), R = radius of curvature of the beam at the section under consideration due to the elastic deflections set up by the bending moment M (Nm). The neutral axis will always pass through the centroid (centre of gravity) of the cross section. For symmetrical sections such as the 'I' beam shown, the centroid will be in the centre of symmetry. The second moment of area of a cross section, I, is often (though incorrectly) called the 'moment of inertia'. If an element at a distance y from the neutral axis has a cross sectional area a then the second moment of area of this element about the neutral axis will be ay^2. Thus the *total I* or second moment of area of the cross section is the *sum* of all such elements, $I = \sum_{bottom}^{top} ay^2$. For irregular sections this can be calculated by arithmetic, or using a version of *Simpson's Rule.* For simple symmetrical sections: *Rectangle:* $I_{xx} = \frac{bd^3}{12}$

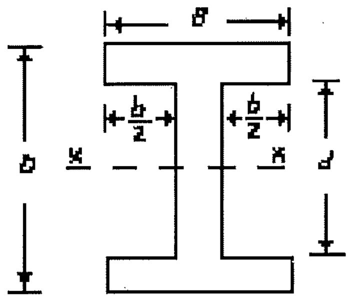

Figure 87. Beam Diagram 1

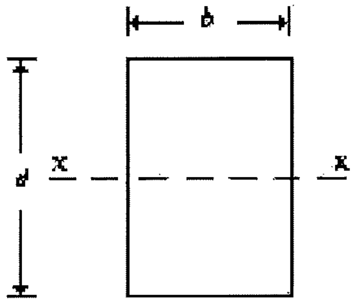

Figure 88. Beam Diagram 2

For beams of more than one material, the method of *equivalent sections* can be used. If a beam has a width of 100mm, and a depth of 15mm, $I = 2.813 \times 10^{-8}$. If the beam is made up of 8 wood laminations of known MOE, the MOE of the beam can be easily calculated. If a stiffer material such as glass fibre is inserted into the laminate in place of the second and seventh laminate, the stiffness of the beam will be improved. How much the MOE will increase will depend on the ratio of MOE of the two materials, and where in the beam the reinforcement is placed. In the case of glass and beech glass fibre is 7 times stiffer than beech, so the method of equivalent sections makes these laminations 7 times wider. The second moment of area of the beam can then be calculated as above, with the distance from the neutral axis being the only variable. If each laminate is taken as being a nominal 2mm, the calculation would be as follows:

$$I_e = \left(\frac{0.1 \times 0.002^3}{12} \times 2 \times 0.007^2\right) + \left(\frac{0.7 \times 0.002^3}{12} \times 2 \times 0.005^2\right) + \left(\frac{0.1 \times 0.002^3}{12} \times 2 \times .003^2\right) + \left(\frac{0.1 \times 0.002^3}{12} \times 2 \times 0.001^2\right) = 3.119 \times 10^{-14}$$

which is 2.785 times greater than I of the normal beam, therefore the composite beam could be expected to have an MOE 2.785 greater than the plain laminated timber beam.

APPENDIX 6 ***Phenol Resorcinol Formaldehyde Specifications***

Aerodux 500 and Hardener 501 PRF Adhesive.

Aerodux 500 is supplied in 3 grades: 500 F (Fast), 500 M (Medium) and 500 S (Slow); 501 hardener is used with all grades. Viscosity at 25°C is 0.35 - 11.3 Pa (3.5 - 3 poises). Resorcinol adhesives heat up more slowly under glue line or stray field heating than Urea Formaldehyde adhesives but curing may be accelerated by the addition of sodium chloride at a rate of 1-2 parts by weight of salt to 100 parts by weight of resin. Precautions should be taken against arcing which may lead to tracking and burning in the glue line. Arcing can be avoided by low spread, low moisture content and good jig design to ensure no air gaps between the electrode and glue line and sufficient and even pressure on the joint during curing. Accelerator XDF 694 is available which can accelerate the rate of cure with radio frequency or warm pressing.

RESIN	*Glueline Temperature*						
(time in hours)	10°C	15°C	20°C	25°C	30°C	35°C	40°C
500 F (Fast)	14	4	3	1.5	1	0.75	0.5
500 M (Medium)		8.5	5	4	2	1.25	0.75
500 S (Slow)			10	5.5	4	3	2

Table 37. Aerodux 500/501 - Cold Pressing Times (Hours)

RESIN	*Glueline Temperature*					
(time in minutes)	50°C	60°C	70°C	80°C	90°C	100°C
500 M (Medium)	30	12	6	3	2	1.5
500 S (Slow)	50	25	12	7	4	2.5

Table 38. Aerodux 500/501 - Hot Pressing Times (Minutes)

Minimum pressing or clamping times stated are those required to give 1.33kN dry falling load on close contact joints conforming to BS1204: Part 2. For dense or high moisture content timbers or where a component is impermeable (such as glass fibre), or if the joint is liable to be strained immediately after removal of pressure (as in the manufacture of laminated bends) the above times should be increased. Aerodux glues will continue to gain strength but full water resistant properties are developed only after several days.

Safety

Avoid breathing vapour from resin and hardener, Avoid skin contact (pH 6.7-7.8)
Flammable - Aerodux 500 flash point 31°C, Aerodux 501 flash point 38°C

Reference

ANON. 1995 *Aerodux 500 with Hardener 501 Data Sheet (GW.10R)* Dynochem UK Ltd, Duxford, CambridgeCB2 4QB *Contact:* Dr E. Van der Straaten (01223) 837370

APPENDIX 7 ***Ansys Plot - Shear Stress***

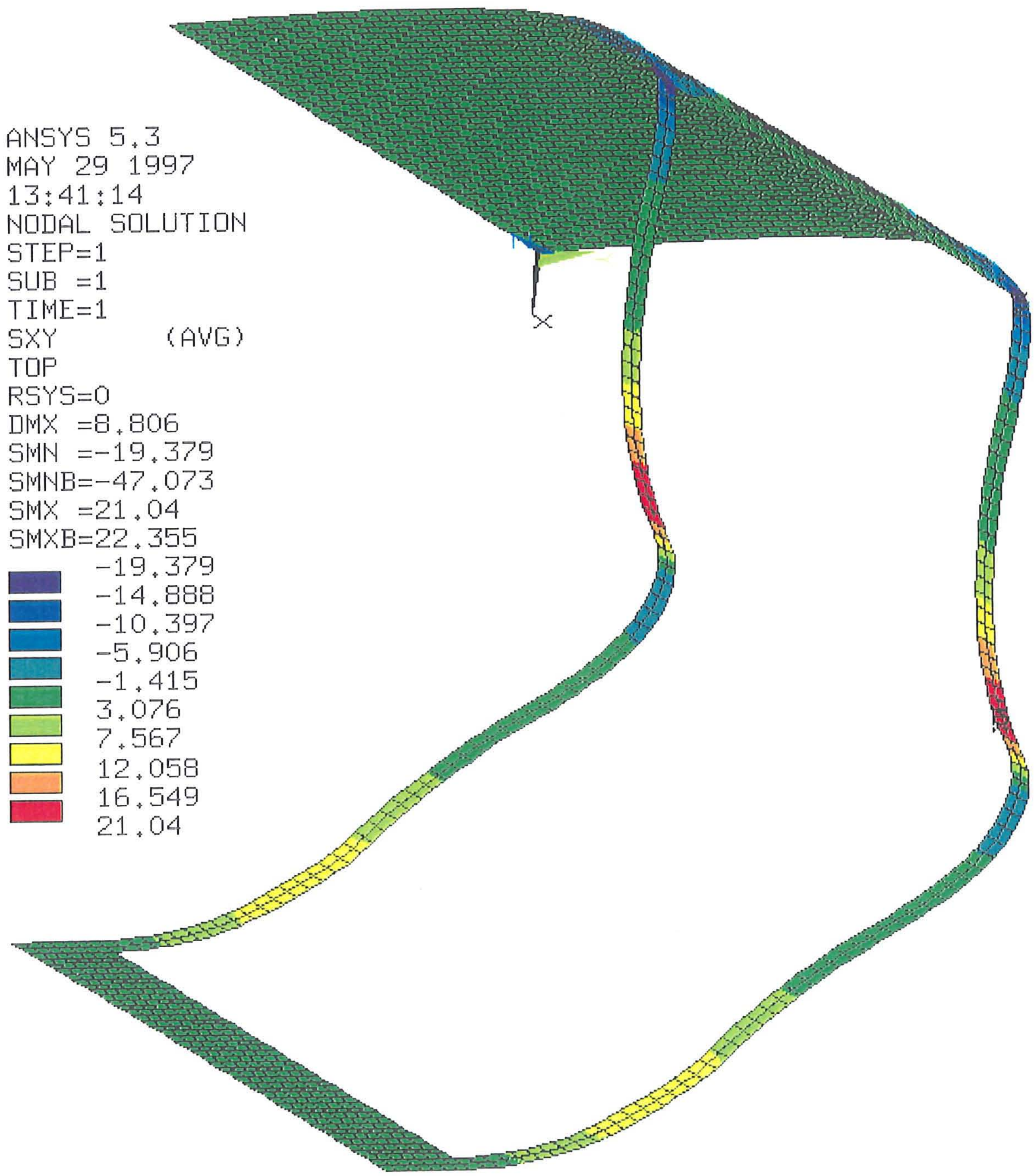

Figure 89. Ansys Plot

APPENDIX 7 - ***Ansys Plot - Displacement***

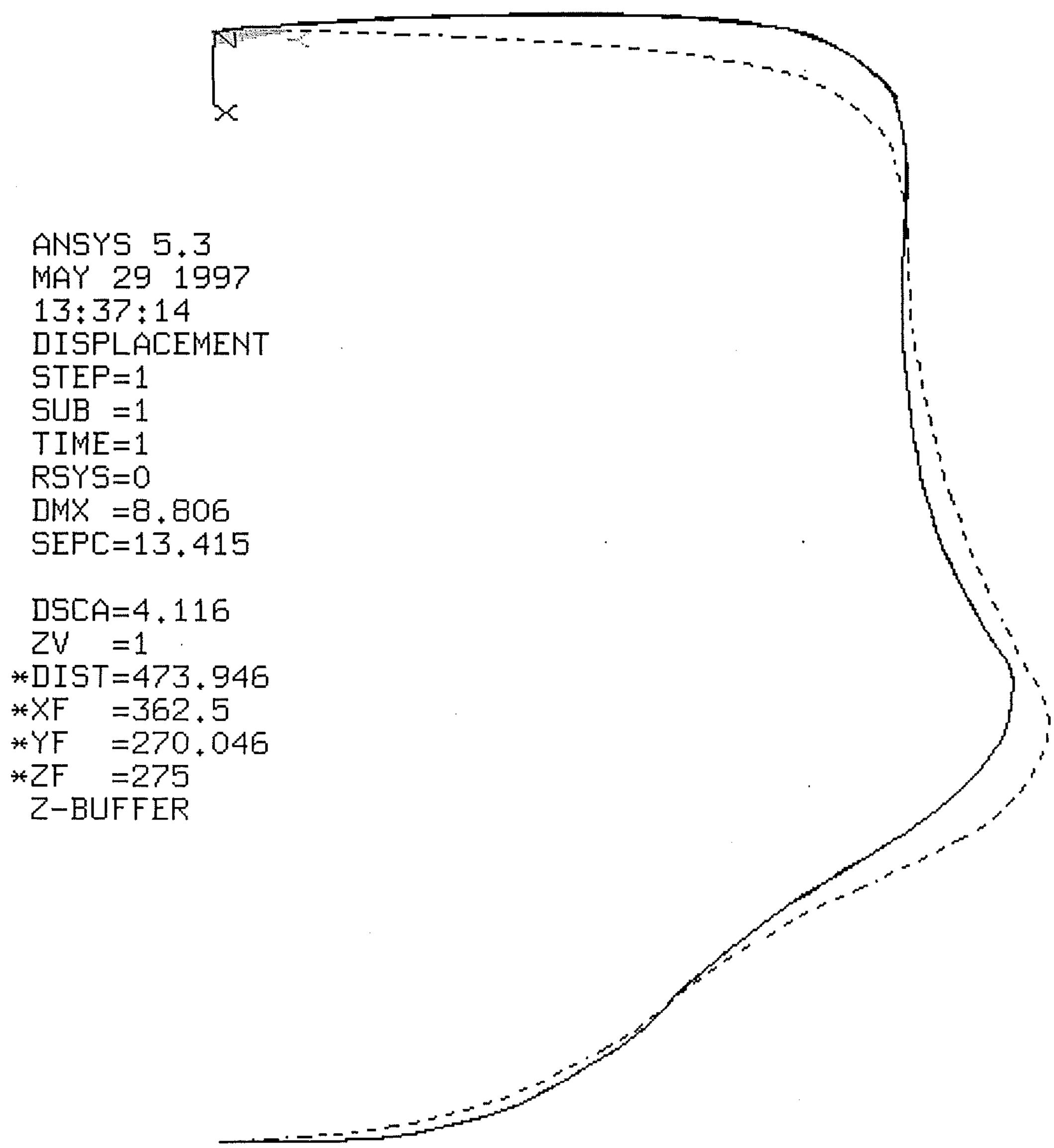

Figure 90. Ansys Plot

APPENDIX 7 ***Ansys Plot - Node Loading Pattern***

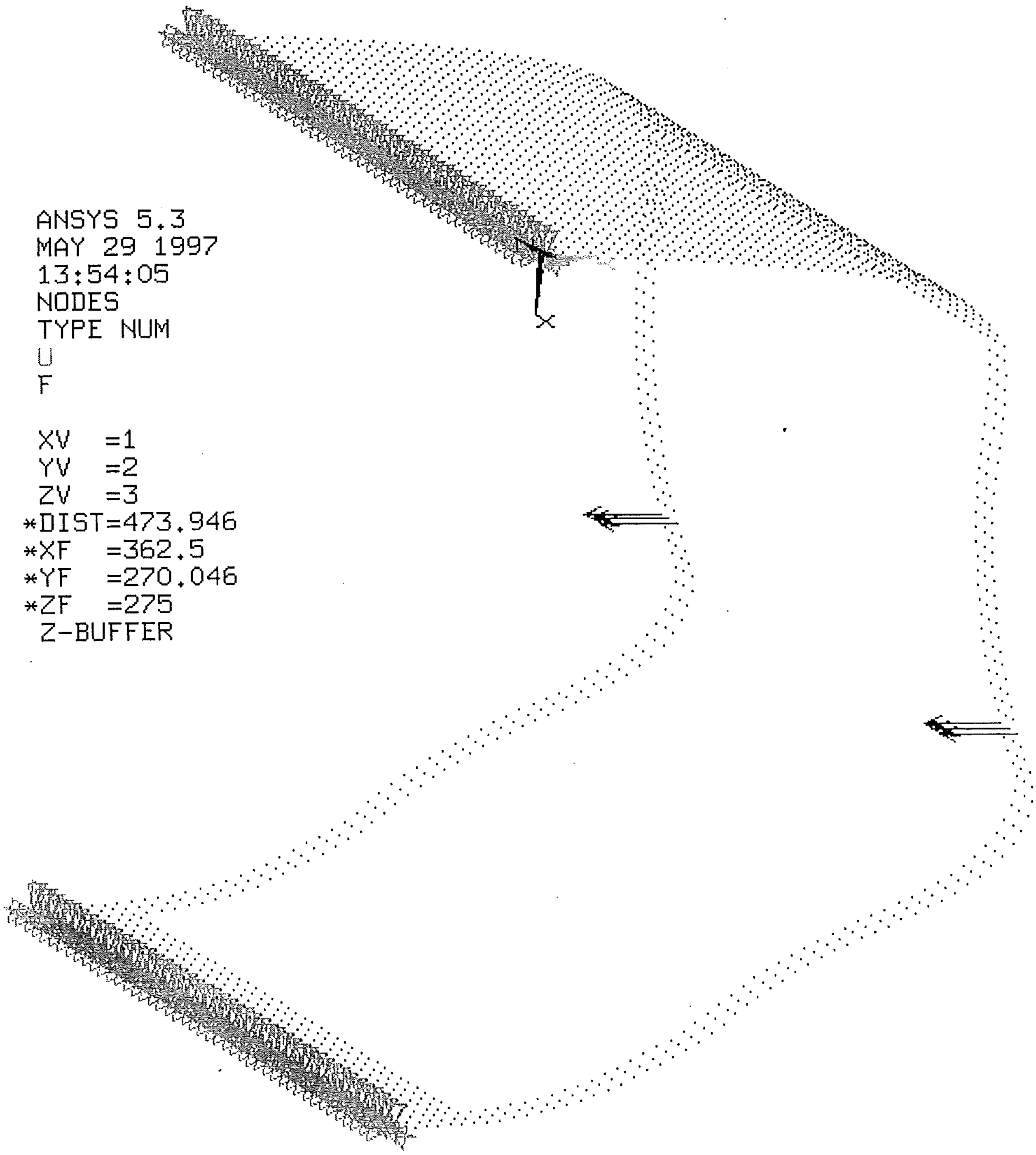

Figure 91. Ansys Plot

APPENDIX 8 ***Drawing of Chair Mould Form*** *(overleaf)*

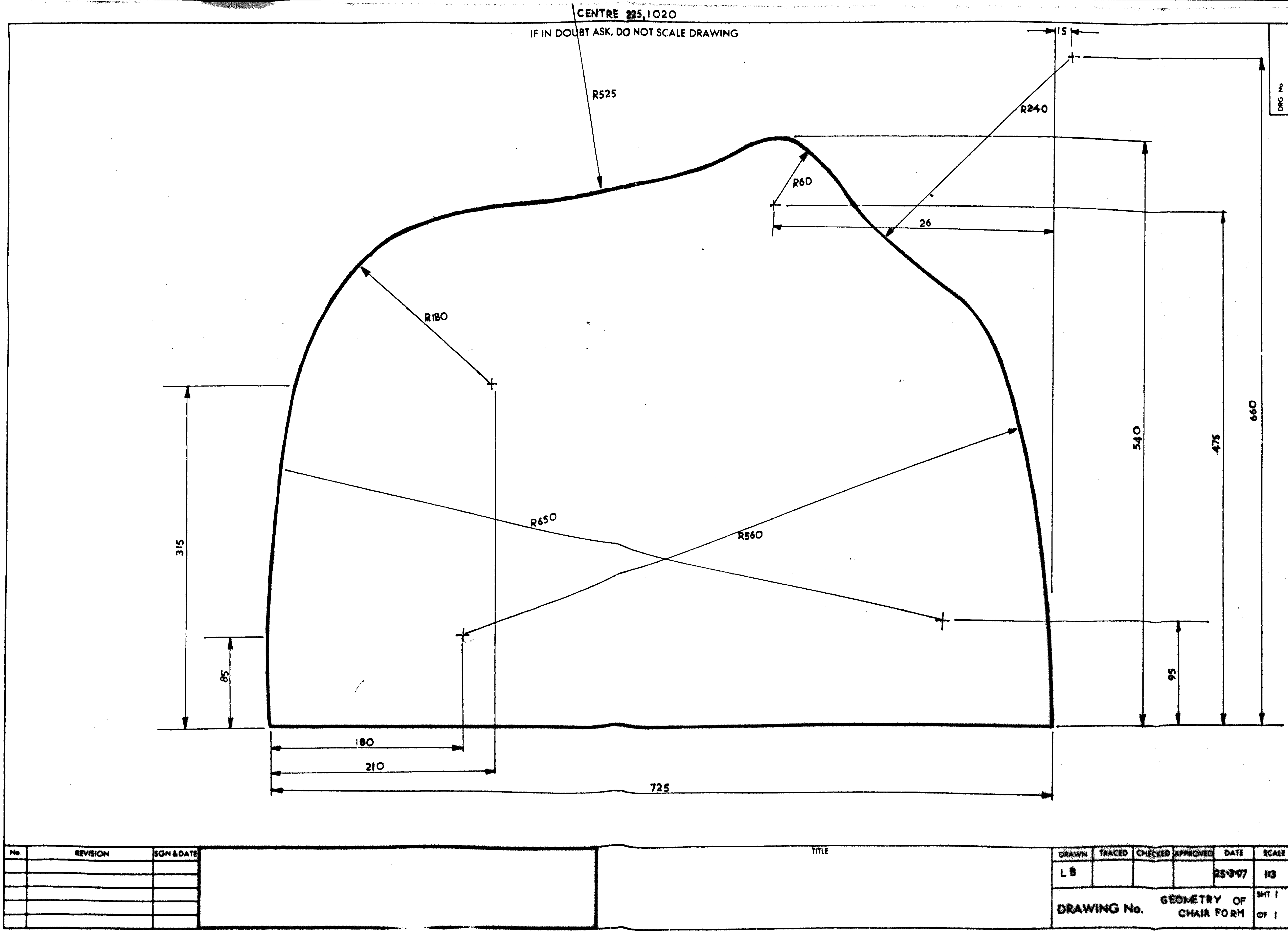
CENTRE 225,1020
IF IN DOUBT ASK, DO NOT SCALE DRAWING
R525
15
R240
DRG No
R60
26
R180
540
475
660
315
R650
R560
85
95
180
210
725
No
REVISION
SGN & DATE
TITLE
DRAWN
TRACED
CHECKED
APPROVED
DATE
SCALE
L B
25·3·97
1:3
DRAWING No.
GEOMETRY OF
CHAIR FORM
SHT 1
OF 1

Figure 92. Drawing of Chair Form