IIB CRIBS
2003

4C2 14p

ENGINEERING TRIPOS PART IIB
ELECTRICAL AND INFORMATION SCIENCES TRIPOS PART II

Wednesday 23 April 2003 9 to 10.30

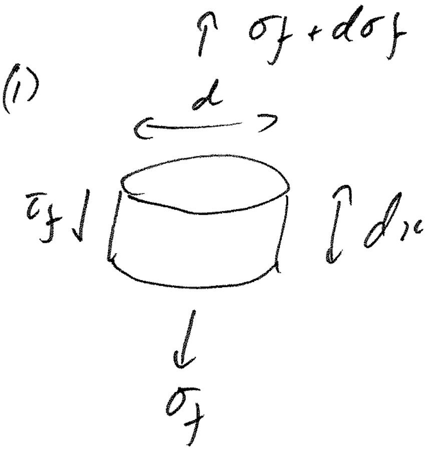
Module 4C2

DESIGNING WITH COMPOSITES

CRIB

1. (a) Use laminates with various ply directions so as to bridge potential splits. [10%]

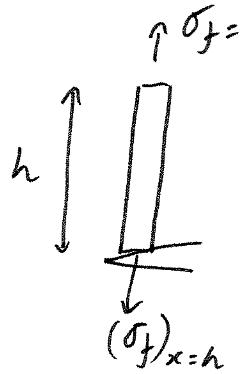
(b) (i)



Equilibrium

$$\frac{\pi d^2}{4} d\sigma_f = \pi d \, \tau_f \, dx \Rightarrow \frac{d\sigma_f}{dx} = \frac{4\tau_f}{d}$$

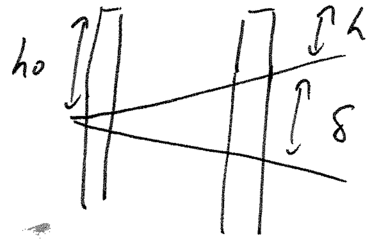
$$\Rightarrow (\sigma_f)_{h=x} = 4\tau_f \frac{h}{d}$$ using boundary condition $\sigma_f = 0$ at fibre break.



Now bridging stress is average across composite: $\sigma_b \cdot 1 = \sigma_f \cdot v_f = \frac{4\tau_f h v_f}{d}$

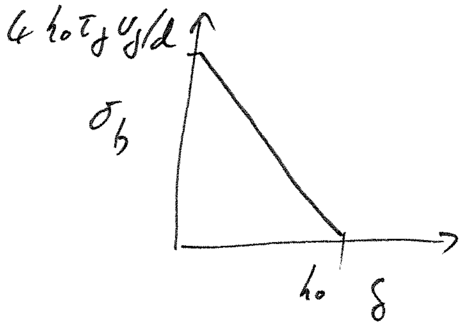
[25%]

(ii)



Assume that, as the crack opens, elastic extensions of the fibre are small, and that it is pulled out of the matrix by a distance δ.

Hence $\delta + h = h_0 \Rightarrow \sigma_b = 4(h_0 - \delta)\tau_f v_f / d$



Toughness G_{IC} is area under this curve:

$$G_{IC} = \frac{1}{2} \cdot h_0 \cdot 4h_0 \tau_f v_f / d$$

$$= \frac{2h_0^2 \tau_f v_f}{d}$$

[20%]

1. (cont) (iii) Assume $v_f = 0.6$ (typical for high performance CFRP)

and $\tau_f = 60$ MPa (typical of shear strength of composite, see data sheet, so typical of matrix strength).

and $d \approx 6\mu m$ (typical of carbon fibres)

Then $G_{Ic} = 2\left(\frac{h_0}{d}\right)^2 \tau_f v_f d = 2.100.60\times10^6 . 0.6\times6\times10^{-6}\ Nm^{-2}.m$

$= 43\ kJ/m^2$

(Right order of magnitude)

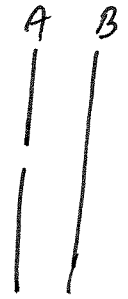
[15%]

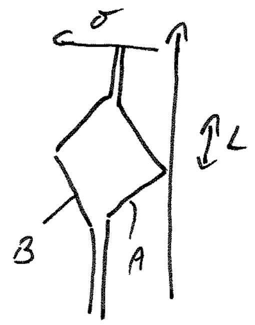
(iv) τ_f: Need to make sure that there is a good bond between fibre and matrix – use sizing.

v_f: Not sensitive to this. (relatively small variations in v_f practical)

h_0, d: h_0 depends on the way that fibres break.

This can be modelled using shear lag theory





to find the length L where the adjacent fibre is more highly loaded than normal. As per part (b i) L depends on τ_f and d, as well as the actual σ carried at failure. The relationship between L and h_0 depends on the statistics of fibre fracture, so that a fibre of uniform strength should, in theory, break next to that in A, while a distribution of strength along the fibre will cause a break somewhere within ±L of A.

[30%]

2 (a) We need to narrow down the design choices; this applies as much to material choice as geometry etc. For composites the wide choice of fibre/matrix combinations plus lay-ups makes ~~th~~ it important to have a system. In conceptual design very approximate material data for a wide variety of composites are used to estimate approximate lay-ups and perhaps two materials to take to preliminary design. Preliminary design uses more exact data to try to optimise ~~using~~ the lay-up and select a single material. In detailed design more sophisticated models and good materials data are used. Design calculations increase in complexity

Calc

Conceptual — Ply orientations act independently

↓

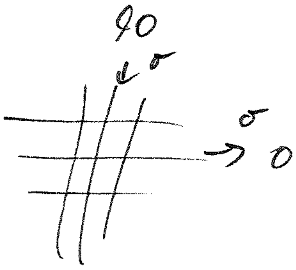
Preliminary — Strain allowables (approx method for failure analysis)

↓

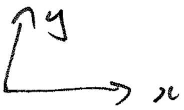
Detailed — Laminate plate theory.

[More detailed than expected]

2(b)



t: total thickness



Need <u>A matrix</u>:

$$[\bar{Q}]_0 = [Q] \; ; \; [\bar{Q}]_{90} = \begin{bmatrix} 8 & 2 & 0 \\ 2 & 40 & 0 \\ 0 & 0 & 4 \end{bmatrix}$$

No shear stresses applied – neglect third row & column.

½ thickness 0° plies

$$A = \sum \bar{Q}(z_k - z_{k-1}) = \frac{t}{2}\begin{bmatrix} 40 & 2 \\ 2 & 8 \end{bmatrix} + \frac{t}{2}\begin{bmatrix} 8 & 2 \\ 2 & 40 \end{bmatrix} = t\begin{bmatrix} 24 & 2 \\ 2 & 24 \end{bmatrix}$$

Now calculate <u>laminate</u> strains

$$\begin{bmatrix} N_x \\ N_y \end{bmatrix} = \begin{bmatrix} t\sigma \\ -t\sigma \end{bmatrix} = [A]\begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \end{bmatrix} \Rightarrow \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \end{bmatrix} = t\sigma[A]^{-1}\begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

$$\begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \end{bmatrix} = \cancel{t}\sigma \frac{1}{\cancel{t}} \begin{bmatrix} 24 & -2 \\ -2 & 24 \end{bmatrix} \frac{1}{24^2 - 4}\begin{bmatrix} 1 \\ -1 \end{bmatrix} = \frac{\sigma}{\underset{572}{\cancel{580}}}\begin{bmatrix} 26 \\ -26 \end{bmatrix} \text{GPa}^{-1}$$

<u>0° plies</u>

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \end{bmatrix} = Q\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \end{bmatrix} = \begin{bmatrix} 40 & 2 \\ 2 & 8 \end{bmatrix}\frac{\sigma}{\underset{572}{\cancel{580}}}\begin{bmatrix} 26 \\ -26 \end{bmatrix} = \frac{\sigma}{\underset{572}{\cancel{580}}}\begin{bmatrix} 988 \\ -156 \end{bmatrix}$$

← reverse ε's – or go via ~~[illegible]~~ $\bar{Q}$

<u>90° plies</u>

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \end{bmatrix} = Q\begin{bmatrix} \varepsilon_{22} \\ \varepsilon_{11} \end{bmatrix} = \begin{bmatrix} 40 & 2 \\ 2 & 8 \end{bmatrix}\frac{\sigma}{\underset{572}{\cancel{580}}}\begin{bmatrix} -26 \\ 26 \end{bmatrix} = \frac{\sigma}{\underset{572}{\cancel{580}}}\begin{bmatrix} -988 \\ 156 \end{bmatrix}$$

Check $\sigma_{xx} = \left[(\sigma_{11})_0 + (\sigma_{22})_{90}\right]/2 = \sigma$ ✓

. . .

2(b) Now apply Tsai-Hill
(cont)

$\underset{\sim}{0^\circ}$ $$\left(\frac{\sigma_1}{S_L^+}\right)^2 - \frac{\sigma_1\sigma_2}{S_L^{+2}} + \frac{\sigma_2^2}{(S_T^-)^2} = 1 \Rightarrow \left(\frac{988}{1103}\right)^2 + \frac{988.156}{1103^2} + \left(\frac{156}{138}\right)^2 = \left(\frac{572}{\sigma}\right)^2$$

$$\Rightarrow \sigma = 385 \text{ MPa}$$

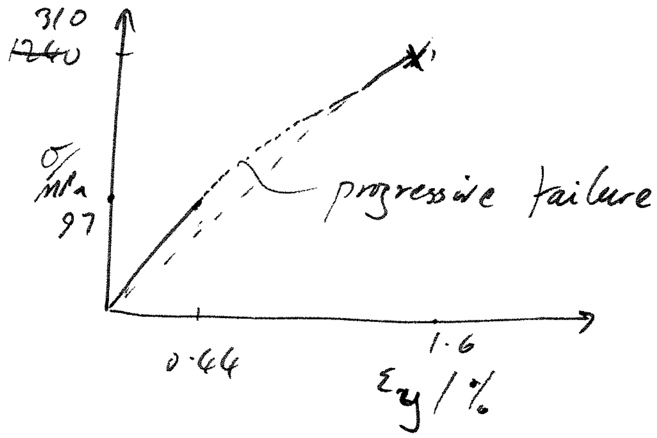
$\underset{\sim}{90^\circ}$ $$\left(\frac{\sigma_1}{S_L^-}\right)^2 - \frac{\sigma_1\sigma_2}{S_L^{-2}} + \frac{\sigma_2^2}{(S_T^+)^2} = 1 \Rightarrow + \left(\frac{988}{621}\right)^2 + \frac{988.156}{621^2} + \frac{156^2}{27.6^2} = \left(\frac{572}{\sigma}\right)^2$$

$$\sigma = 97 \text{ MPa}$$

90° ply fails first at $\sigma = 97$ MPa, probably by transverse tensile failure. ($\varepsilon_y = \frac{97.26}{572\times10^3} = 0.44\%$)
$\llcorner$ from previous calculation

(c) Expect the transverse failure mechanisms to take place first, slightly reducing the stiffness. Final failure when one set of fibres fail – in this case the material is weakest in compression so

$$\sigma_c \approx \underset{\substack{\uparrow\\ \text{only } \frac{1}{2} \text{ plies carry compression}}}{\frac{1}{2}} S_L^- = \overset{310}{\cancel{1240}} \text{ MPa} \qquad \varepsilon_c \approx \frac{S_L^-}{E_1} = \frac{621}{39000} = 1.6\%$$



3. (a) For 0° ply,
$$Q_{11} = E_1/(1-\nu_{12}\nu_{21})$$
$$Q_{22} = E_2/(1-\nu_{12}\nu_{21})$$
$$Q_{12} = \nu_{12}E_2/(1-\nu_{12}\nu_{21})$$
$$Q_{66} = G_{12}$$

Now, $\nu_{21} = \frac{E_2 \nu_{12}}{E_1}$

$$\Rightarrow \nu_{21} = \frac{10}{150} \times 0.3 = 0.02 \qquad \nu_{12} = 0.3$$

$$\Rightarrow \frac{1}{1-\nu_{12}\nu_{21}} = \frac{1}{1-0.3\times 0.02} = 1.006$$

$$\Rightarrow Q_{11} = 150.9 \text{ GPa} \qquad Q_{22} = 10.06 \text{ GPa} \qquad Q_{12} = 3.018 \text{ GP}$$
$$Q_{66} = G_{12} = 10 \text{ GPa}$$

$$\Rightarrow [Q]_{0^\circ ply} = \begin{bmatrix} 150.9 & 3.018 & 0 \\ 3.018 & 10.06 & 0 \\ 0 & 0 & 10 \end{bmatrix} \text{GPa}$$

$$[Q]_{30^\circ\ layer} = ? \qquad c = \cos 30^\circ = \sqrt{3}/2 \qquad S = \sin 30^\circ = \tfrac{1}{2}$$

From data sheet,
$$\bar{Q}_{11} = Q_{11}c^4 + Q_{22}S^4 + 2(Q_{12}+2Q_{66})S^2c^2 \text{, etc.}$$

$$\Rightarrow \bar{Q}_{11} = 150.9 \times \frac{9}{16} + 10.06 \times \frac{1}{16} + 2(3.018+20)\frac{3}{4}\cdot\frac{1}{4}$$

$$\Rightarrow \underline{\bar{Q}_{11} = 94.142 \text{ GPa}}$$

$$\bar{Q}_{12} = (150.9 + 10.06 - 40)\frac{1}{4}\frac{3}{4} + 3.018\left(\frac{1}{16}+\frac{9}{16}\right) = \underline{24.566 \text{ G}}$$

$$\bar{Q}_{22} = 150.9 \times \frac{1}{16} + 10.06 \times \frac{9}{16} + 2(23.018)\frac{3}{4}\frac{1}{4} = \underline{23.72 \text{ G}}$$

$$\bar{Q}_{16} = (150.9 - 3.018 - 20)\frac{3}{8}\frac{\sqrt{3}}{2} - (10.06 - 3.018 - 20)\frac{\sqrt{3}}{16}$$

$$\Rightarrow \bar{Q}_{16} = 41.53 + 1.4027 \text{ GPa} = \underline{42.933 \text{ GPa}}$$

$$\bar{Q}_{26} = (150.9 - 3.018 - 20)\,\frac{1}{8}\,\frac{\sqrt{3}}{2} - (10.06 - 3.018 - 20)\,\frac{1}{2}\,\frac{3\sqrt{3}}{8}$$

$$\Rightarrow \quad \bar{Q}_{26} = \underline{18.05 \text{ GPa}}$$

$$\bar{Q}_{66} = (150.9 + 10.06 - 6.036 - 20)\,\frac{3}{16} + 10\left(\frac{1}{16} + \frac{9}{16}\right)$$

$$\Rightarrow \quad \bar{Q}_{66} = \underline{31.550 \text{ GPa}}$$

$$[A] = 2t\,[Q]_{0^\circ} + 2t\,[Q]_{30^\circ}$$

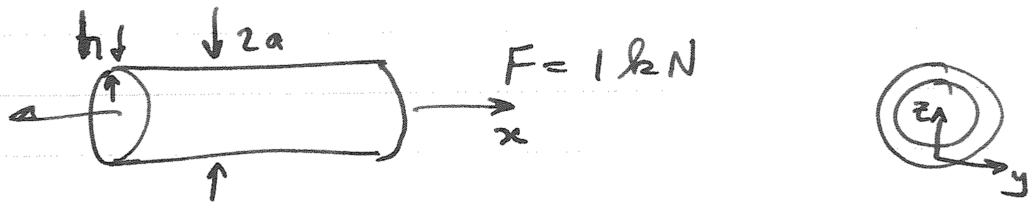
where thickness of each ply $t = 0.1$ mm

$$\Rightarrow [A] = 0.2 \begin{bmatrix} 150.9 & 3.018 & 0 \\ 3.018 & 10.06 & 0 \\ 0 & 0 & 10 \end{bmatrix} + 0.2 \begin{bmatrix} 94.142 & 24.566 & 42.933 \\ 24.566 & 23.72 & 18.05 \\ 42.933 & 18.05 & 31.55 \end{bmatrix} \text{ MPa m}$$

$$\Rightarrow [A] = \begin{bmatrix} 49.01 & 5.517 & 8.587 \\ 5.517 & 6.756 & 3.61 \\ 8.587 & 3.61 & 8.31 \end{bmatrix} \text{ MPa m}$$

$$[B] \equiv 0$$

(b) (i)



$$N_x = \frac{F}{2\pi a} = \frac{10^3}{2\pi \times 0.1} = 1592 \text{ N m}^{-1}$$

$$N_y = N_{xy} = 0$$

(b) (ii) $\gamma = ?$

$$\begin{pmatrix} N_x \\ N_y \\ N_{xy} \end{pmatrix} = \left[A \right] \begin{pmatrix} \varepsilon_x^\circ \\ \varepsilon_y^\circ \\ \gamma_{xy}^\circ \end{pmatrix}$$

$$\Rightarrow \begin{pmatrix} \varepsilon_x^\circ \\ \varepsilon_y^\circ \\ \gamma_{xy}^\circ \end{pmatrix} = \left[\begin{matrix} & A^{-1} & \\ \otimes & & \end{matrix} \right] \begin{pmatrix} N_x \\ N_y \\ N_{xy} \end{pmatrix}$$

inverse of A

need this entry value only

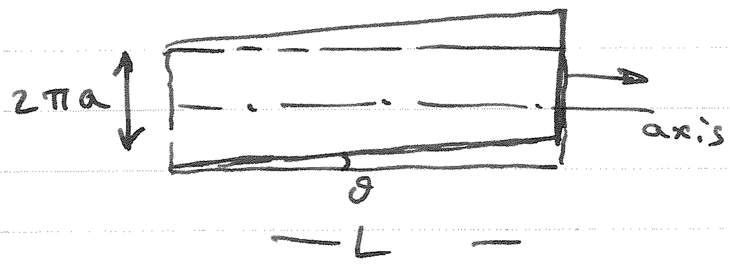
det A = ? $\quad \det A = 43.11 \times 49.01 - 5.517 \times 14.847 + 8.587 \times (-38.097) = \underline{\underline{1703.8 \times 10^{18}}}$ $(N\,m^{-1})^3$

$$\Rightarrow A^{-1}_{31} = \frac{1}{\det A} \left(5.517 \times 3.61 - 8.587 \times 6.756 \right) \times 10^{12} \, (N m^{-1})^2$$

$$= -0.02236 \times 10^{-6} \; N^{-1} m$$

$$\Rightarrow \gamma_{xy}^\circ = A^{-1}_{31} \, N_x = \underline{-35.6 \times 10^{-6}}$$

(iii) Show the developed view of the tube.



$$\frac{\theta}{L} = \frac{\gamma_{xy}^\circ}{\underset{\sim}{A}}$$

So twist per unit length $\frac{\theta}{L} = \frac{\gamma_{xy}^\circ}{\underset{\sim}{A}}$

(iv) Arrange for a balanced laminate such that $A_{16} = A_{26} = 0$. For example, try a laminate of geometry $[\pm 15]_s$ instead of $[0/30]_s$.

QUESTION 4

There is no single answer to this question and the students have some flexibility in formulating one. Nevertheless, each individual's answer should argue many of the points discussed below. The following discussion is based on many aspects of this Composite Design Module which the student should be familiar with. I would not expect the student to be able to produce such a comprehensive answer because of time constraints. I would expect the principal issues to be presented and argued.

In the aerospace industry high-value components and structures tolerate the higher cost of the materials, provided that the perceived performance and weight-saving benefits can be realised. Although the costs of composite replacements are higher than metal counterparts, with experience of rationalised design and manufacturing processes, the cost-benefit relationships have become attractive. Whilst value of aerospace-structures is high, the volume usage of materials in this industry is remarkably low.

The selection of a suitable process is influenced by various factors:

design of structure, materials selection, equipment availability,
component configuration, unit numbers.

The selection of a process is driven by certain considerations:

- Can previous designs and manufacturing experience be used to find a solution?
- Is there access to appropriate manufacturing facilities?
- Will the process allow an optimum fibre orientation and fibre volume fraction to be achieved?
- Will the process achieve the desired component shape and dimensional tolerances?
- What is the part count for the identified process route?
- Are there machining/finishing operations after processing?
- Can the process accommodate load introduction points in components?
- For design and quality control purposes, what material property data from the process route needs to be obtained.
- What are the cost implications with respect to man-hours, tooling, consumable materials and process times?

AUTOCLAVE MOULDING OF AN AIRCRAFT VERTICAL STABILISER

Consolidation of stacked thermosetting pre-pregs by autoclave curing is used for preparing high fibre volume fraction composites. With autoclave chambers available up to 4 m diameter, there are few size limitations on manufacturing composite sections. The capital investment in an autoclave is high and processing times are long. Access to an optimum-sized autoclave (from a cost perspective) can be a major criteria in the success of a project.

RESIN TRANSFER MOULDING OF AUTOMOTIVE PANEL PARTS

Resin transfer moulding (RTM) is a lower cost component production route than pre-preg lay-up and autoclave curing. Certain complex shapes can be more readily made by RTM than by other moulding routes. Car body shell parts can be moulded.
RTM is applied where component unit production is high, hundreds or thousands per year. The attraction of the process for aerospace applications is closely linked with the need for complicated component shapes: nose cones, radomes, integrally stiffened panels, complex shaped ducting, braided rings and tubes.

The characteristics of RTM include: preforms allow multidirectional reinforcement placement to improve damage tolerance. Good surface detail and accuracy. Complex shapes, with integral stiffening, can be made in a single moulding. Near net-shape parts can be produced, requiring minimum machining. Reinforcement lay-up is dry as opposed to tacky pre-preg. May remove need for refrigerated shipping and storage of pre-pregs. Close process control may avoid the need for non-destructive inspection. Variable thickness sections possible.

MANUFACTURE OF THERMOPLASTIC COMPOSITE PARTS

Any technique which melts the thermoplastic with instantaneous consolidation to component shape offers scope for exploitation. The rapidity of these processes is the largest difference between thermoplastic and thermosetting composites. The final choice of fabrication method depends on the size of the component and the availability of equipment for the higher processing temperatures required.

The attractive features of thermoplastic materials include: supplied in a ready to use form, either as pre-preg or laminate easy to store and do not need cold storage

MANUFACTURING ECONOMIC CONSIDERATIONS

Material costs

Historically, composites have been considered to be costly in comparison with established technologies based on light-alloys such as aluminium. The direct material purchase costs per kilogram may be very different, in some cases by orders of magnitude.

Manufacturing costs

The material costs are only part of the total manufacturing cost, typically falling in the range 10 to 25 % of the total. In order to control the "total manufactured cost" of a component or assembly, advantages which must be properly exploited include:

- a lower part count compared with metallic designs,
- fewer fasteners compared with metallic designs,
- lower material wastage compared with machined metal designs,
- reduced machining costs by net-shape forming,
- co-curing of parts,
- use of preforms instead of UD prepregs.

Note: The reduction and control of labour costs during the fabrication stages must also be addressed.

MATERIALS SELECTION AND MANUFACTURING ROUTES

A part of all design selection processes is to establish an acceptable balance between the total cost of manufacture, and efficiency of the structure (to meet functional requirements).

Construction

Is the structure manufactured by a "one shot" technique, whenever possible? Is maximum automation used?

Fabrication

Is the number of components at a minimum? Has composite adequate design been taken care of? Choose optimum processing techniques to reduce waste! Are assembly costs at minimum? Use as few joints as possible?

The manufacturing and fabrication factors affecting costs of structures include:
Materials, Consumables, Process times, Capital equipment, Labour.

Quantifying and allocating manufacturing costs to, for example, individual space composite structures and components is difficult because:

- Design and process development costs are very high,

- Unit production is often very low, typically no more than five for satellites, and
- Structural verification and qualification costs are high.

There is always a strong incentive to retain proven materials/manufacturing technologies because development and verification activities usually represent a large part of the costs.

Tooling and consumables
For limited production runs, cost of tooling is a very significant contributory factor to unit costs. Tooling is generally a one off, non- recurring cost. Some processes, such as autoclaving, require large quantities of consumables, such as:

- bagging materials,
- breather plies,
- peel plies,
- release films.

These are recurring costs as the materials cannot be reused. Other manufacturing routes, such as filament winding, use very few consumables.

Processing times
Short processing times are always desirable, but not necessarily essential. Large complex assemblies: a long cure schedule need not be a significant cost factor if only a few units are being manufactured. Smaller components (produced in larger numbers): reduction of process times is a major cost driver.

Labour costs
This remains one of the most difficult items to quantify, as organisations have different means of calculating it.

Direct Costs
For the actual manufacture of components, the direct costs include:

- material and tool preparation,
- lay-up,
- equipment operation,
- demoulding,
- machining and trimming, and
- inspection.

The cost of design and testing may be added to these.

Part count
It is important that composite designs offer a reduction in the part count compared with metallic solutions. The aim is for small number of components for subsequent assembly. A single part may be feasible, e.g. by co-curing. The material/consumable costs may therefore be high, but subsequent fabrication costs can be reduced. As more components of the same design are made, their unit cost is reduced. This is because of non-recurring costs over a greater numbers of units. The costs are mainly design costs, and tooling.

Capital cost and running cost
The net cost of a part (£ per kg) is given by

$$\frac{\text{Capital cost of equipment (£) \{+ running cost (£/kg)\}}}{\text{Total production mass, kg}}$$

The running cost is made up of the raw material cost (£/kg) and running cost of the process (£/kg). With increasing batch size, the net cost of the part decreases from the capital cost of the equipment to the running cost. Thus, the capital cost is the upper asymptote of the production cost for the case of a very small batch size, and the running costs the lower asymptote for the case of a very large batch size.

The cheapest processes have a low capital cost and running cost: hand lay-up for the case of composites. However, the hand lay-up method is suitable for only small production sizes and small production rates. Also, it can only be used to produce parts of medium quality, (autoclaving is used almost exclusively in aerospace to obviate delamination, and it is expensive).

Total production quantity versus the production rate

The hot press method (closed die pressing of "bulk moulding compound" (BMC) or of "sheet moulding compound" (SMC)) and the continuous pultrusion method are capable of high production rates and large production sizes. Despite being an automatic process, filament winding is slow because the fibres are laid down tow by tow. The other processes, RTM, autoclave and hand lay-up are slow and labour intensive.

Mass and the leading dimension of the part

The manual methods (hand lay-up, autoclave) are extremely versatile and can be used to produce both large and small part. Filament winding can also be used to make a wide range of size. The closed die processes of RTM, Hot Press and Pultrusion are suited to smaller parts and smaller part dimensions.

Section thickness and tolerance

The current production methods are unable to produce composite parts to a high tolerance, and over a wide range of section thickness. The design strategy is to make the component from a few composite parts to final shape rather than join together many smaller composite parts: joining required close tolerances. There are advantages in making components in a single step:

- the cost is less, and
- the final structural properties are enhanced, e.g.,
- monocoque construction is used to make the cfrp safety shell in racing cars: such monoque shells have high energy absorption.

Fabrication of Automotive Components

There is a fundamental difference in the strategy of application of composites between the aerospace industry and the automobile industry. primarily due to the volume requirements of the two businesses: aerospace and defence, where design is optimised to provide the required functionality and performance; the manufacturing process (and associated cost) is subsequently selected on the basis that the process is capable of achieving the desired design. High-volume consumer production industries (e.g., automotive industry), where the rate of manufacture is critical to satisfy the economics. An example is the use of pre-preg materials and hand lay-up procedures, common in aerospace and amenable to optimal design, but unacceptable in an industry requiring high manufacturing output *and* same quality level.

Sheet-moulding composite (SMC) materials are the highest performance composites in general automotive use today (25 wt% chopped glass fibres in a polyester matrix): grille opening panels and closures panels (bonnets, boot lids and doors). A characteristic moulding time for SMC is of the order of two minutes, The next major step for composites is the extension of structural applications, e.g., primary body structure and chassis/suspension systems.

These structures have to sustain the major road load inputs and crash loads and must deliver an acceptable level of vehicle dynamics so that passengers enjoy a comfortable ride. Composite fabrication procedures must be applied which satisfy high production rates and maintain the critical control of fibre placement. Unfortunately, carbon fibres cost £20 or more per kg at 1988 prices. Intensive research efforts are being devoted to reducing these but the most optimistic cost predictions are around £10 per kg, which would severely limit the potential of these fibres for use in consumer-oriented industries.

The fibre with the greatest potential for automobile structural applications, based on optimal combination of cost and performance, is E-glass fibre (costing £1 per kg at 1988 prices). Likewise, the resin systems likely to dominate are polyester and vinylester resins based on a cost-processibility trade-off.

It is expected that most of the structural applications involving significant load inputs will utilise a combination of both chopped and continuous glass fibre with the particular proportions of each depending on the component or structure. For example, unidirectional glass FRP materials typically have a well-defined fatigue limit of the order of 35-40% of the ultimate strength. By contrast the chopped-glass composite would have a fatigue limit closer to 25% of the ultimate strength and would exhibit much greater scatter in properties. There is evidence that glass fibre-reinforced composites can be designed to withstand the rigorous fatigue loads experienced under vehicle operating conditions. Fibre-reinforced plastic composites can be efficient energy absorbing materials.

The flexibility of composite fabrication processes allows the thickening of local areas as is required to optimise properties. Since the composite has a density approximately one-third that of steel, a significant increase in thickness can be achieved while maintaining an appreciable weight reduction, and the additional stiffness attained in composite structures by virtue of part integration. This integration leads directly to the elimination of joints, which results in a significant increase in effective stiffness.

As a rule of thumb, a glass FRP structure with significant part integration relative to the steel structure being replaced can be designed for a nominal stiffness of 50-60% of that of the steel structure. Such a design procedure should lead to adequate stiffness and typical weight reductions of 30-50%.

The successful application of structural composites to large integrated automotive structures is more dependent on the ability to use rapid and economic fabrication processes than on any other single factor. The fabrication process must also be capable of close control of composite properties to achieve lightweight, efficient structures.

Currently, the only commercial process which comes close to satisfying these requirements is compression moulding of sheet moulding compounds (SMC) or some variant of the process. There are, however, processes still at the development stage which hold distinct potential for the future in terms of: combining high production rates, precise fibre control and high degrees of part integration. In particular, high speed resin-transfer moulding (RTM). In terms of reduction in parts, the moulded SMC body structure could consist of some where between 10 and 20 major parts (compared to approximately 300 major steel parts) and the RTM structure could be composed of somewhere between: and 10 major parts. Note that the degree of integration is higher for RTM reflecting the greater versatility of this procedure. However, the high volume, high performance manufacturing techniques still need development and improved SMC materials and processes, and the RTM process holds promise in these areas.