ABSTRACT

The Design for Manufacture of Continuous Fibre Reinforced Thermoplastic Products In Primary Aircraft Structures

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As the technology of composite structures matures, the use of thermoplastic composite materials in aircraft increases, offering reduced structural weight and improved payload. However, primary load bearing applications demand optimum structural integrity in harsh environmental conditions, and the total installed manufacturing cost has previously restricted the use of thermoplastic materials.

This paper describes a programme of work to develop a carbon fibre reinforced thermoplastic transverse floor beam for a commercial jet. Component selection, material selection, design optimisation, equipment, processing methods and testing are discussed. A cost model for the composite component is presented in comparison to that of the incumbent aluminium alloy beam. A key element of the work has been design for manufacture. The performance of the prototype sections is considered in terms of manufacture, structural integrity and mechanical properties.

INTRODUCTION

Over the last 15 years thermoplastic resins have been reinforced with fibres to provide a family of composite materials which can now compete with metals as materials for primary aircraft structure. In this family technologists bring together the skills of various disciplines to provide materials whose properties can be tailored to suit a specific need. Many of these new materials which offer improved performance in terms of high strength, low weight, good fatigue properties, corrosion resistance etc. Towards the end of the 80's researchers began heralding thermoplastic composites as the structural material of the 90's, predicting its replacement of graphite /epoxy and other thermoset composites[1] A 1987 report by the National Materials Advisory Board (NMAB), crystallized thinking within the aerospace industry, concluding that thermoplastic composites could be made tougher and more durable, and at significantly less cost than their thermoset counterparts[2].

Industry has been intent on reducing the manufacturing costs of thermoplastic composites. Some believe that the key lies in automation[3]. Many companies, including Nissan Aerospace, Thiokol Corp., Sikorsky Aircraft, General Electric, and Lockheed, have recently made large investments in automated thermoplastic processing equipment, locking them into this technology for years to come[4,5]. Others believe that the key lies in reducing high cost of raw composite material, and companies like Douglas have committed themselves over the last 15 years to producing their own high strength, damage tolerant raw materials and novel processing alternatives[6,7].

Boeing have illustrated the effectiveness of their "design for manufacture" philosophy with weight-savings of 25% being achieved through cost-effective design strategies, in the latest 777 widebody aircraft[8]. Throughout the programme, composite components were designed with efficient production in mind. Engineering design and manufacturing have been co-located throughout the program with designers actually sitting in the same office as manufacturing planners[9]. The success of this approach is more than obvious as cost-effective composite structures weighing 25% less than their Aluminium counterparts begin to roll off the production line.

In this programme a primary load bearing component is designed from thermoplastic composite material. In optimizing the design, the emphasis has focused on both efficient manufacture and maximised weight saving. The result of this exercise has been the production of cost-competitive components made from thermoplastic composite. Lessons were learned in many areas - component selection, material selection, design optimization, forming, consolidation, cost analysis - and it is hoped that further development of this work will lead to more cost-effective thermoplastic components being produced using a similar "design for manufacture" philosophy.

COMPONENT SELECTION

Selection of a suitable component was critical in this project. At the outset it was important to choose an existing structural element which could benefit from the known advantages of thermoplastic composites. More than this, it had also to enable a comprehensive assessment of issues such as the correct material selection, design optimisation, fibre lay-up, forming method, ease of manufacture and overall economies.

As composites prove to be cost-effective in many secondary structural applications, speculation now focuses on the ability of composites to be cost-effective in the primary structure. Many developments have been made in this area, with a variety of components having been selected for composite development programs both in military and commercial applications. In recent years, the composite floorbeam is a concept that has repeatedly attracted attention. Boeing Commercial Aircraft, Airbus, Westlands and Rockwell are among the many companies who have shown significant interest in this area.

Boeing's decision to use composite floor beams on the new 777 is significant since it will mark the debut of composite floor beams on large civil aircraft. It is expected that as the beam is granted FAA certification the demand for composite floor beams will increase. With the 777 order guaranteeing 500 shipsets of 74 beams per aircraft, and more cost-effective methods of manufacture being established, competition between companies for a share of the market is keen.

A C-section transverse floor beam for a commercial jet was selected to be the subject of this work. Single curvature C-Section components of this size can be manufactured relatively easily by a variety of production methods because the flow mechanisms involved are of low complexity. Thus the associated risk in designing and manufacturing the beam are relatively low.

MATERIAL SELECTION

The design specification for composite floor beams lists a wide range of requirements, some of which are primarily dependent on the material system used. The specification is particularly elaborate in outlining the thermal stability, chemical resistance, and flame resistance of the materials used. Factors such as flammability requirements and upper service temperature would reduce the list of candidate material systems to only the high performance thermoplastic composites.

While the mechanical property values of high performance thermoplastics are on par with those of thermosets, the former have a much greater tolerance to moisture uptake and subsequent ageing by hygrothermally induced degradation. Semi-crystalline thermoplastics exhibit better resistance to solvents than amorphous polymers and have been employed successfully in very harsh environments[10]. Research published by the E.S.A. indicates that PEEK retains higher tensile and compressive strength than epoxy after impact[11]. All these qualities combine to make thermoplastics a more desirable choice for the design of primary aircraft components. Thus PEEK, PEKK and PPS would be the most feasible matrix systems for this application.

DESIGN OPTIMIZATION

In optimizing the design of the composite beam, a balance must be struck between many variables. It is intended that the new design would be such that a variety of manufacturing routes could be used, while the possible combination of novel fibre orientations etc. should be explored. The weight of the beam must be minimised, yet ease of manufacture must always be borne in mind. The dimensions of the beam may be modified yet sensitivity to the structural relationship of the beam must be considered. At the outset of the project there was no stated bias towards being manufacturing critical or design critical, however, the ultimate success of the program would be the establishment of a cost-effective method of producing floor beams which offer significant weight-savings and perform as well as the incumbent components.

In redesigning the transverse floor beam, care should be taken to ensure that design modifications have no knock-on effects, ie. the composite floor beam must be able to be incorporated into the original subfloor assembly with a minimum redesign of other parts. This ruled out the use of other standard structural cross-sections such as T's, J's, Z's and boxes. Similarly, the general dimensions of the given C-section are also limited. However, the width of the flange can be varied to increase the buckling strength of the beam while having little knock-on effect on the rest of the assembly. The service holes and similar features must be retained in the composite beam.

In optimizing the strenth of the floor beam, the layer configurations in the web and flange will be the prime variables. The layer configuration in the web and flange of the component must allow maximum strength and minimum weight, yet be conducive manufacture from a variety of methods. Localised ply buildups and dropoffs should be employed wherever possible to improve weight savings, but not so much as to hinder fabrication.

Uni-directional tape allows the designer more freedom in choosing different layer orientations. Numerous configurations can be designed with UD tape that could not be realized with other product forms. UD tape is also preferred by manufacturers for its ability to form rapidly at relatively low pressures into both single and double curvatures[10].

When designing with UD tape, shear strength of can be directly increased by adding more layers of ±45°. The use of 0° layers was minimal, but some layers were retained to provide structural integrity at the web/flange interface.

After many ply combinations were analyzed, it was decided that the layer configuration for the portion of the web subjected to maximum stress levels should be $[\pm/\pm/0/\pm/0]_s$. Other portions of the beam subjected to considerably lower shear stress levels could provide acceptable shear strength with the configuration $[\pm/0/\pm/0]_s$.

The flange is subjected to the boom end loads as the beam bends. The strength of the flange can be increase by adding more 0° layers. The ideal flange design would incorporate continuous ply dropoffs. This flange would not be easy to manufacture and would involve a long and lengthy layup phase. Consequently, to make the manufacturing of the beam more straightforward, the flange shall have constant thickness. The flange width was decreased to improve buckling strength and a variety of layups were assessed. The optimized flange was 22 layers thick and of configuration $[\pm/0_4/\pm/0_3]$s.

The layer configurations of the flange and web can be blended together in such a way to provide the optimized interface below, where most of the layers in both the flange and the web run though the interface.

Figure 1 Schematic arrangement of optimized flange-web interface

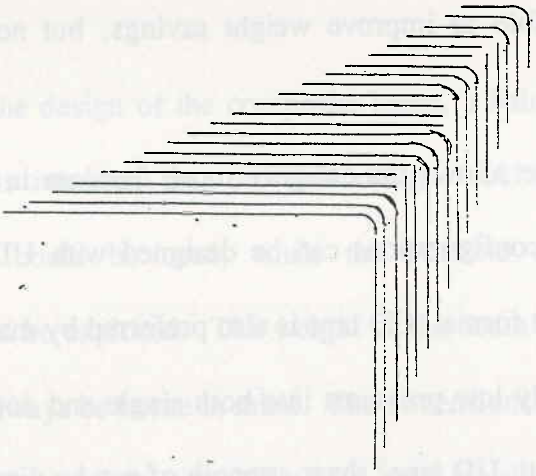


Table 1 Percentage of layers running through interface

	% of layers running through interface
16 layer web	75.0
12 layer web	100.0
22 layer flange	54.5

A comparison is made between the composite design with ply dropoffs and one of constant section 16 layer web. The weight saved by utilising these designs is shown in table 2.

Table 2 Weight comparison

	APC2 w/o dropoffs	APC2 w/ dropoffs	TA7075
Mass of Flange (kg)	0.228	0.228	0.265
Mass of Web (kg)	0.796	0.662	1.060
Total (kg)	1.251	1.117	1.590
Total Weight Saving (%)	21.3	29.8	1.590

This comparison can be further refined to show the weight savings gained from each part of the C-section.

Table 3 Structural weight savings for the composite floor beam with buildups

Optimized Structure	% weight saving
Flange	14.2
Web	37.5
Beam	29.8

It should be noted that the weight-saving gained due to the composite flange is small compared to the composite web weight-saving (See Table 3). Should ply dropoffs be incorporated into the design of the flange, weight savings could be as high as 35%.

PROCESSING

Several standard beam sections were manufactured which could be tested to investigate the efficiency of the design. A joggle was included at one end of the standard section, and its length was such as to allow for a variety of testing. The standard section also featured an area of ply buildup to similar to that of the full length composite floor beam.

A variety of processing techniques were to be employed, allowing a demonstration and development of manufacturing technology.

Equipment: All parts were formed on the autoclave at the University of Limerick, which was recently designed commissioned for polymeric diaphragm forming of continuous fibre reinforced composites. The autoclave has an internal working diameter of 0.6 m and an internal length of 1.8 m and is designed to operate at pressures up to 2.5 MPa and temperatures up to 450° C.

Materials: Two high performance thermoplastic materials were used on this programme. APC-2/AS4 unidirectional tape, made from ICI's PEEK semi-crystalline polymer, is a composite material suitable for continuous 120°C (250°F) service applications for primary aircraft structure. Also used on the programme were plain weave fabric and UD tape made from PEI/AS4 prepeg supplied by Ten Cate, suitable for 150°C (300°F) service structural applications.

The diaphragm forming process uses Upilex film, supplied by U.B.E. This type of Upilex has an elongation of 250-300% at temperatures from 315-425°C (600-800°F). Upilex, 0.13 mm (0.005 in) thick, has a lower modulus than other diaphragm materials such as Supral 1.3 mm (0.050 in) thick.

Forming: Two forming processes were used in this programme, Single Diaphragm Forming and Double Diaphragm Forming. When double diaphragm forming, an unconsolidated composite lay-up was placed between two elastic diaphragms. The diaphragms were clamped to a vacuum ring and the tool before a vacuum was drawn between the diaphragms. The fully sealed assembly was placed into the autoclave and heated to the processing temperature and pressurized. The process for single diaphragm forming is similar except that instead of placing the composite layup between two layers of Upilex, only the upper Upilex sheet is used. The bottom surface of the composite being directly in contact with the tool.

It was decided that low consolidation pressures should by assessed and two parts were formed at vacuum only. As the decrease in pressure below vacuum is difficult to ramp down to vacuum, a more controlled vacuum effect can be achieved by increasing the pressure on the outer surface of the upper diaphragm to 100 kPa, while leaving the inner surface open to atmosphere. A full list of the formed parts is given in Table 4. The beam sections were subjected to a variety of testing techniques including physical inspection, C-Scanning, Micro-Examination, Three Point Bending and Compressive Testing.

Table 4 List of demonstrator beam sections

Sample Number	Forming Method	Web	Flange
1	Double Diaphragm, 450 kPa pressure.	500 mm of $[0/90]_{2s}$	$[0/90]_{2s}$
2	Double Diaphragm, 450 kPa pressure.	300 mm of $[\pm/\pm/0/\pm/0]_s$ 200 mm of $[\pm/\pm/0/\pm/0]_s$	$[\pm/0_4/\pm/0_3]_s$
3	Double Diaphragm, 450 kPa pressure.	300 mm of $[\pm/\pm/0/\pm/0]_s$ 200 mm of $[\pm/\pm/0/\pm/0]_s$	$[\pm/0_4/\pm/0_3]_s$
4	Double Diaphragm, 450 kPa pressure.	300 mm of $[\pm/\pm/0/\pm/0]_s$ 200 mm of $[\pm/\pm/0/\pm/0]_s$	$[\pm/0_4/\pm/0_3]_s$
5	Double Diaphragm, 450 kPa pressure.	500 mm of $[\pm/\pm/0_4/\pm/0_3]_s$	$[\pm/0_4/\pm/0_3]_s$
6	Single Diaphragm, 450 kPa pressure.	300 mm of $[\pm/\pm/0/\pm/0]_s$	$[\pm/0_4/\pm/0_3]_s$
7	Single Diaphragm, Vacuum only.	300 mm of $[\pm/\pm/0/\pm/0]_s$	$[\pm/0_4/\pm/0_3]_s$
8	Single Diaphragm, Vacuum only.	75 mm of $[\pm/0/\pm/0]_s$	$[\pm/0/\pm/0]_s$
9	Double Diaphragm, 450 kPa pressure.	300 mm of $[\pm/\pm/0/\pm/0]_s$ 200 mm of $[\pm/\pm/0/\pm/0]_s$	$[\pm/0_4/\pm/0_3]_s$

RESULTS

It was found from NDE and optical microscopy that double diaphragm forming in an autoclave is a fabrication method capable of producing parts of excellent quality, see figure 2. Although there is a certain amount of distortion in the part dimensions, due to squeeze flow, the dimensions of the finished parts are within the tolerance limits specified by Short Brothers Plc. The parts are well formed at the web corners, and the ply configuration of the flange dovetails with that of the web to produce beam sections of excellent structural integrity.

Single diaphragm forming has the effect of reducing the normal pressure on the part during forming, and the parts produced exhibit closer dimensional control. The mechanical properties of the formed parts are on par with those of the parts produced by double diaphragm forming, see figure 3. The exposed lower surface of each part had poorer surface finish than the surface next to the diaphragm. Given that prior to dispatch each part must be coated with primer and topcoat, this aesthetic effect is of limited significance. Upilex-R Polyimide diaphragm forming material is notoriously expensive and contributes significantly to the recurring cost of this process. Thus there is real potential for reducing the recurring cost of expendable Upilex-R when diaphragm forming C-section parts by using only one diaphragm.

Vacuum pressure by itself is only capable of forming the parts into the required shape, and is insufficient to induce full consolidation, see figure 4. Only the corners of the C-Section part moulded by this method have acceptably few voids, where localised consolidation occurs before the part conforms to the tool profile, and pressure in the autoclave is considerably less than 100 kPa. High autoclave pressures (≈450 kPa) are necessary when forming UD APC-2 tape into parts with very few voids. Nonetheless, when tested in compression, sample 7 performed similarly to those parts with few voids.

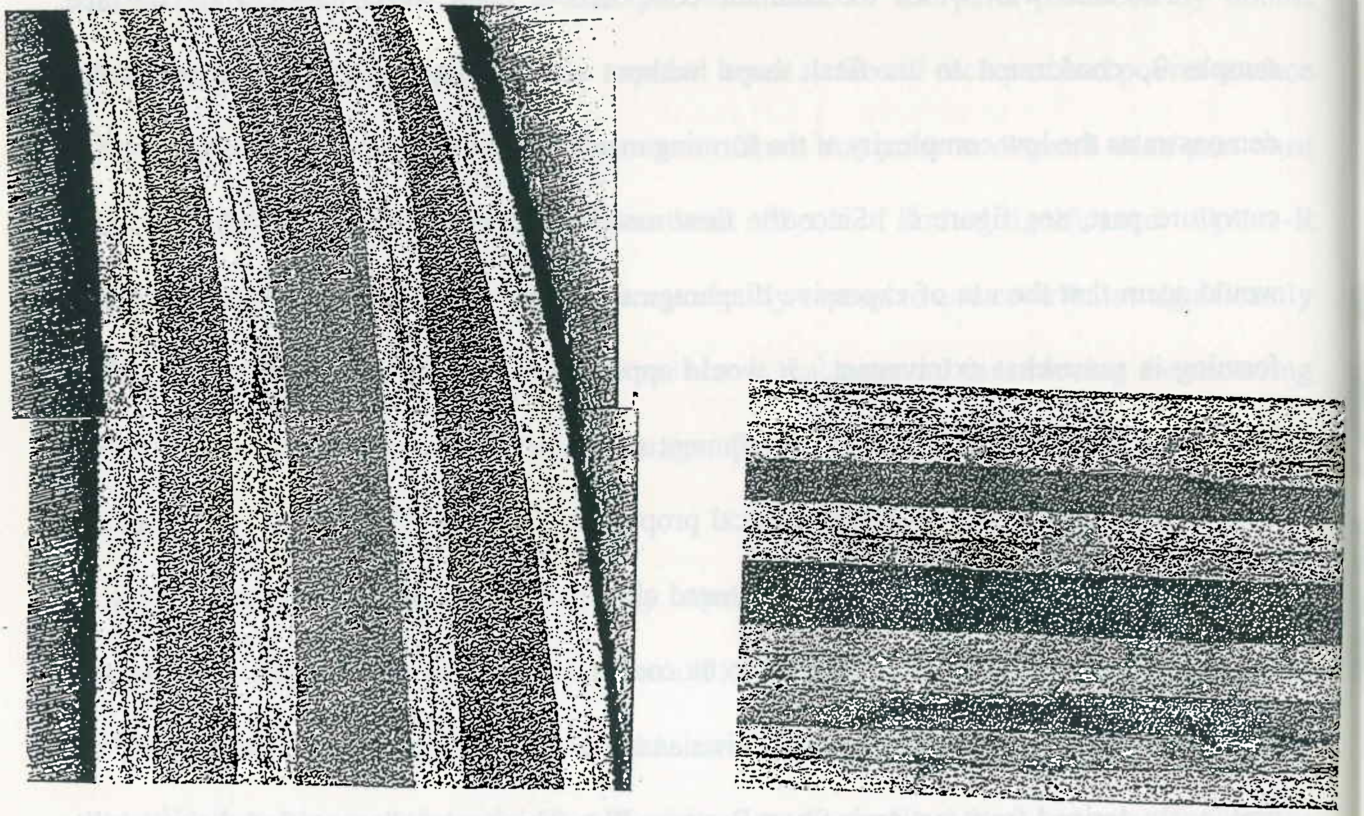
When flat fully pre-consolidated sheets are formed into C-section under vacuum pressure only, a small amount of deconsolidation occurs during remelt, see figure 5. Given the able performance of sample 7 under compression testing, it is expected that the mechanical properties of sample 8 will be excellent. The advantages of this are twofold. Vacuum forming equipment is considerably less expensive than other thermoplastic processing equipment. Secondly, the use of preconsolidated FORTRON sheets, supplied by Quadrax, reduces down the line costs such as layup and storage. Consequently, this option presents the manufacturer with a low cost method of making thermoplastic floor beams, without the need to make large capital investment in expensive processing equipment.

The ease with which the laminate composed of plain weave fabric and UD tape, sample 9, conformed to its final shape without any unwanted buckling or wrinkling, demonstrates the low complexity of the forming mechanisms involved in moulding this single curvature part, see figure 6. Since the flow mechanisms are relatively straightforward, it would seem that the use of expensive diaphragms to control the tension in the fibres during forming is somewhat extravagant. It would appear that there is real potential for making these C-section floor beams on less equipment such as a rubber press.

The actual values of the mechanical properties exhibited by the parts when tested, in compression and three point bending, showed close correlation with those predicted by the stress model, though the latter did tend to be conservative. This stress model was based on techniques used for thermosetting composites and incorporated a variety of data that had been previously derived from testing in Short Brothers Plc. This project has verified the reliability of this existing data and demonstrated the effectiveness of having such information prior to design.

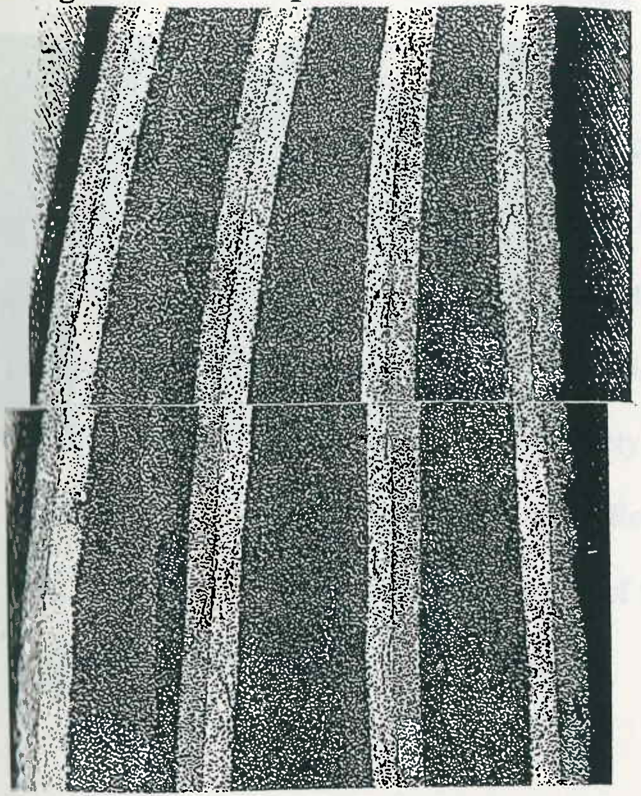
When subjected to three point bending, the parts made a complete recovery of shape immediately after the buckling load was removed. After being torsionally deformed to the order of 20% at the each end, the parts showed only a 40% loss of mechanical properties upon recovery. This characteristic is symptomatic of the capability of the resin phase to yield and absorb energy, and is particularly significant when a structure is subjected to adventitious out of plane loadings. In such cases the enhanced strength of thermoplastic materials in comparison to similar structures made from brittle matrix materials makes thermoplastic designs significantly more failsafe.

Figure 2 **Sample no.4**

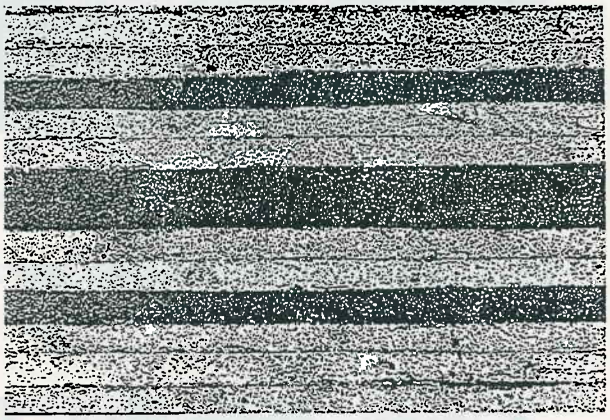


(a) Squeeze flow effect at corner **(b) Section of web**

Figure 3 **Sample no. 6**



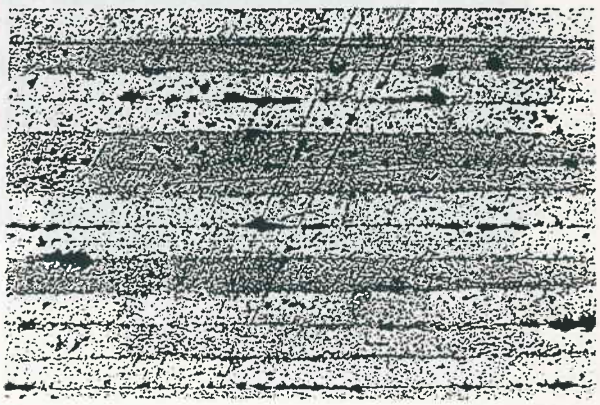
(a) Squeeze flow effect at corner



(b) Section of web

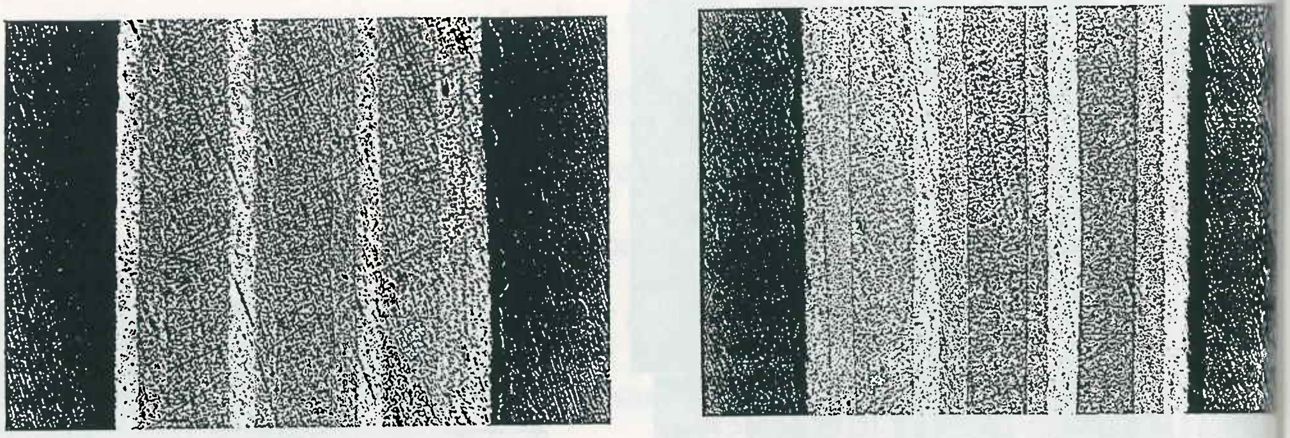
Figure 4 **Sample no. 7**

(a) Squeeze flow effect at corner



(b) Section of web

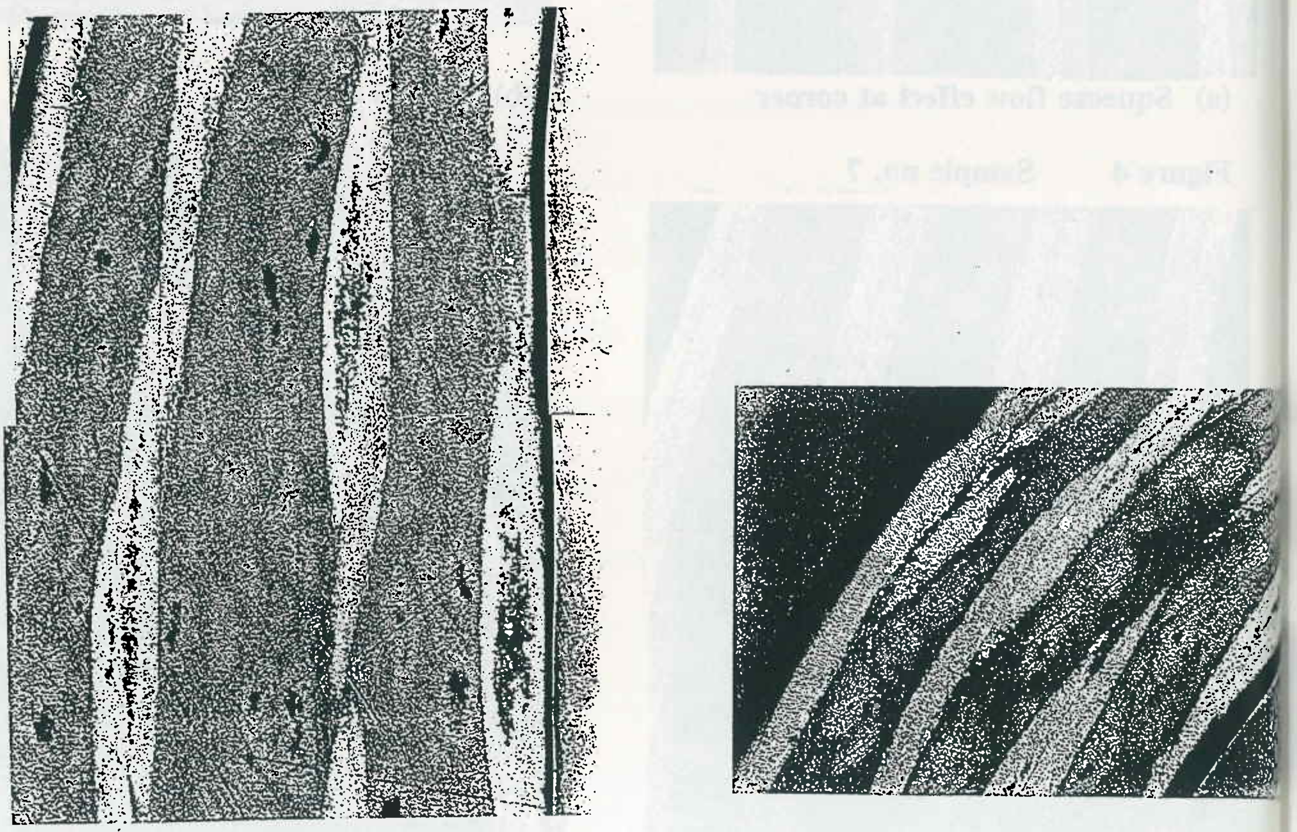
Figure 5 Sample no. 8



(a) Section of flange

(b) Section of web

Figure 6 Sample no. 9



(a) Squeeze flow effect at corner

(b) Section of corner

COST ANALYSIS

A cost estimation model was developed to analyze various thermoplastic materials and processing methods and help guide in the future design cost-effective, thermoplastic composite applications. The data used in the analysis was taken from a variety of studies[12-17]. In surmising the potential advantages of making a floor beam from thermoplastic composite material a variety of factors must be considered: Technical risk; Certification cost; Non-Recurring cost; Recurring Material Cost; Recurring Process cost; Cycle Time; Weight saving. A variety of fabrication methods shall be assessed in the light of the cost data previously derived:

Baseline
Method A. Hand-layup of UD FORTRON tape and forming on large press
Method B. Hand-layup of UD FORTRON tape and forming incrementally on a press
Method C. Same as method A, but with ATL
Method D. Same as method B, but with ATL
Method E. Hand-layup of UD APC-2 and double diaphragm forming
Method F. Hand-layup of UD FORTRON and single diaphragm forming
Method G. Vacuum forming of preconsolidated FORTRON sheet

The Baseline production method is the same method that is presently used by the subcontractor in supplying the Aluminium beams, and involves forming the beams with a large two-stage press.

Using this information a decision matrix was developed. The advantages associated with each production method are shown in figure 7, where all factors are equally balanced. In assessing the feasibility of each of these fabrication methods for a particular programme, each of the parameters will be scaled according to its perceived significance. For example figures 8, 9 and 10 demonstrate the respective advantages in programmes where wieght savings and cycle times are seen to be critical. A similar comparison cam be made between sub-contracted manufacture of the floor beams, and is shown in figures 11 to 14.

It can be seen that when the process of decision-making is extended to embrace a wide variety of factors, thermoplastic floor beams offer a significant advantage over Aluminium beams. Considering the variety of in-house production methods, it is clear that while there are many advantages associated with the baseline production method, thermoplastic production is competitive in many areas.

Perhaps the most critical advantages associated with baseline are the very low non-recurring cost and the lower certification cost. Lengthy certification procedures can be exceptionally expensive, and can cost up to £500K. However, with this production method, the lower cost of certification is offset by the high non-recurring cost of the large forming press.

Vacuum forming of preconsolidated FORTRON sheets is clearly a cost-effective option. The high certification cost associated with these components is compensated for by the very low equipment cost. Therefore, when all factors are equally balanced, Method G of producing thermoplastic floor beams is the most expedient. If certain factors are seen to be more crucial than others, eg weight saving and cycle time, the overall advantages associated with various methods of producing thermoplastic floor beams become more significant.

Forming on a large press is as advantageous as diaphragm forming in an autoclave when all factors are equally scaled. But in situations where cycle time is seen to be more critical, the short forming time makes forming on a large press, via method A, marginally more attractive than other options such as diaphragm forming and incremental forming. While automating the layup process can reduce cycle times and lower overall production costs, these advantages are offset by higher technical risk, and higher non-recurring cost.

In sub-contracting the production of these beams there are less factors to play with. Although the incumbent production method has its advantages, when weight savings and cycle times are seen be critical, the sub-contracted thermoplastic floor beams have more points in their favour.

It has been shown that the production of thermoplastic composite floor beams can be cost competitive for a variety of production methods. When this cost information is considered in the light of the weight savings and cycle times estimates, it becomes clear that the manufacture of thermoplastic floor beams at Short Brothers Plc. is a feasible prospect. In programmes where weight savings and cycle time reductions are of particular significance, Aluminium floor beams can scarcely compete.

Figure 7 **Direct comparison of in-house production methods**

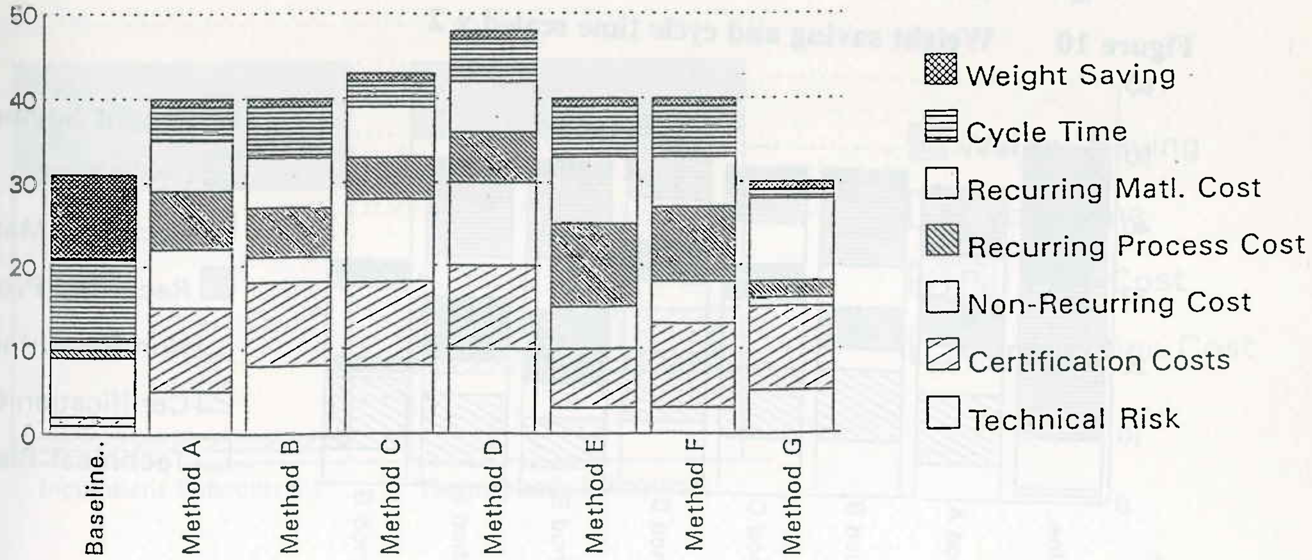


Figure 8 Weight-saving scaled x 2

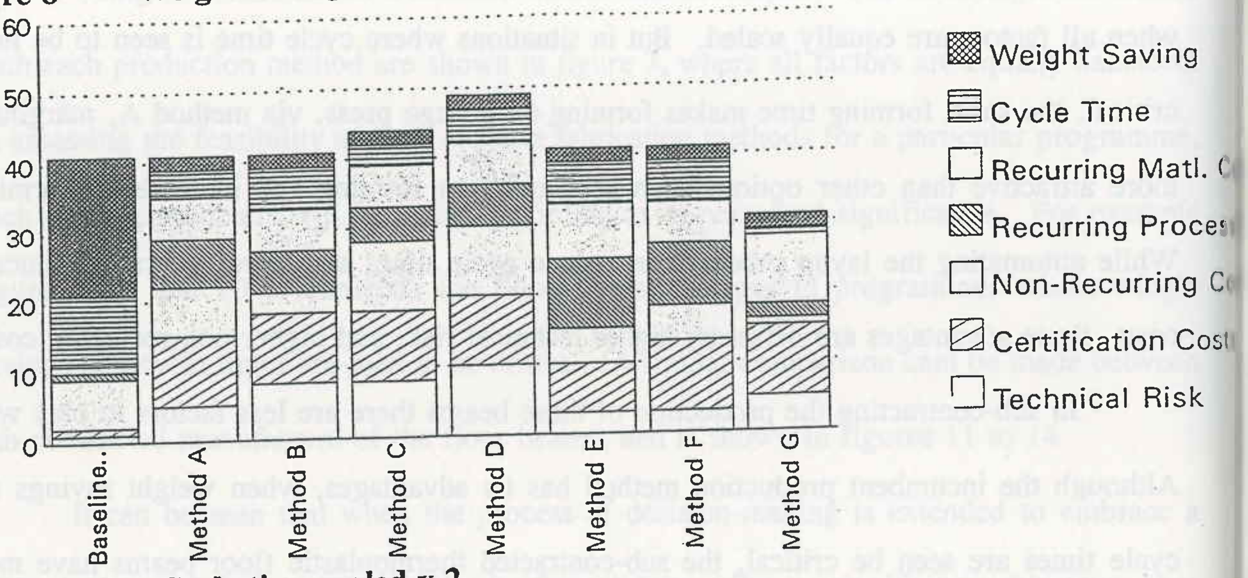


Figure 9 Cycle time scaled x 2

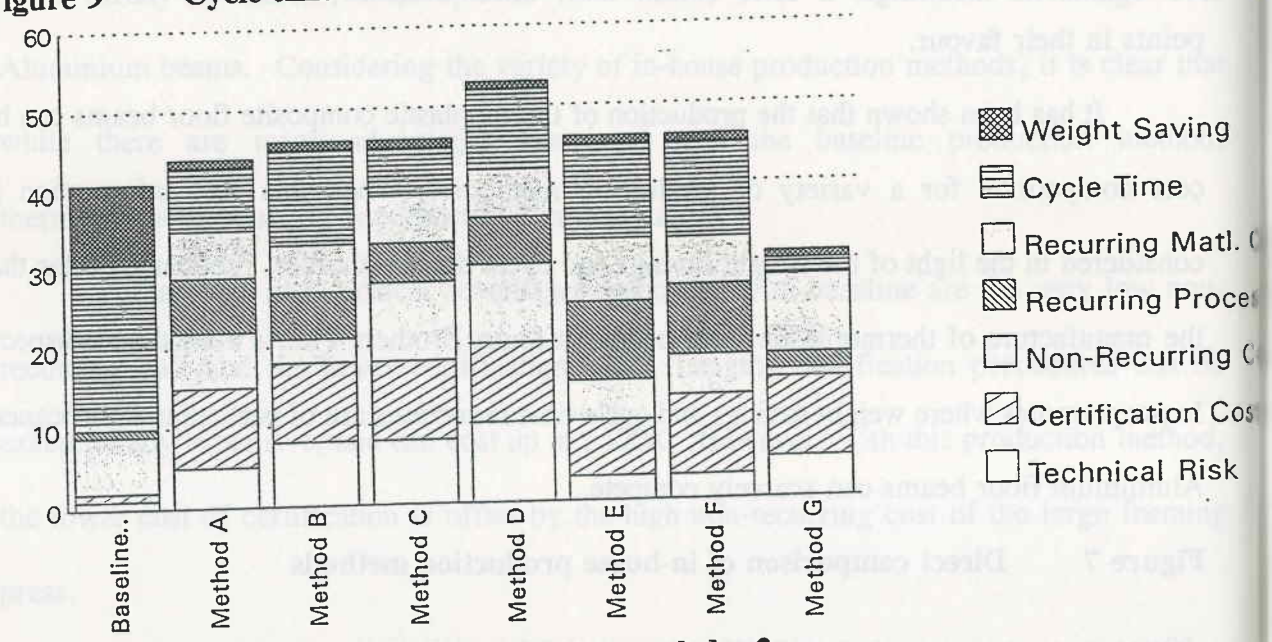


Figure 10 Weight saving and cycle time scaled x 2

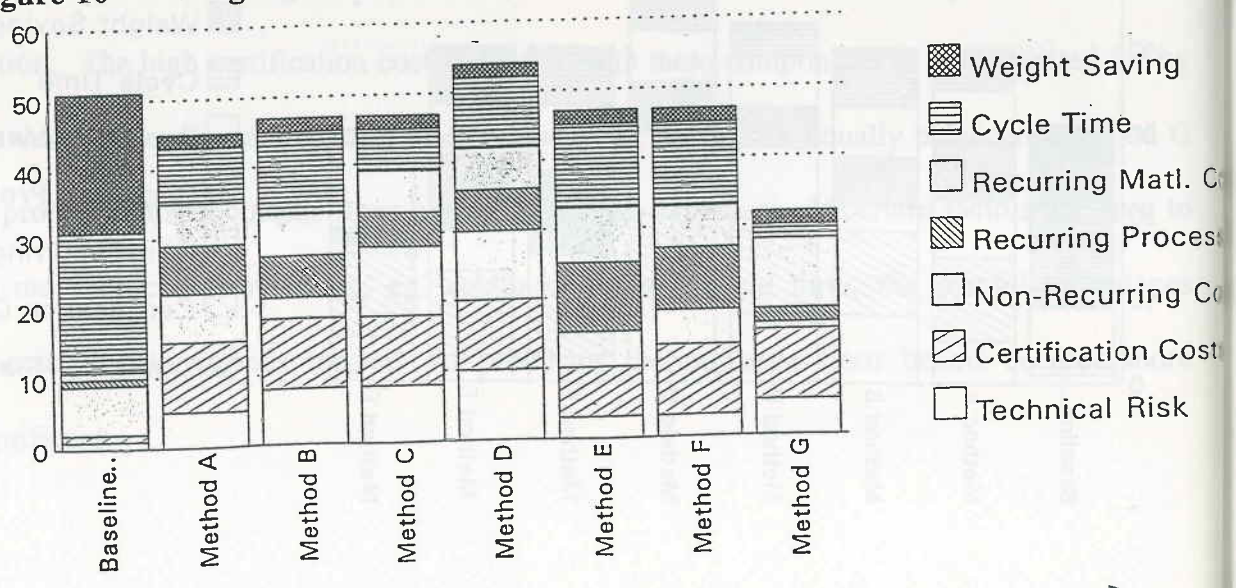


Figure 11 Direct Comparison of sub-contracted floor beam production

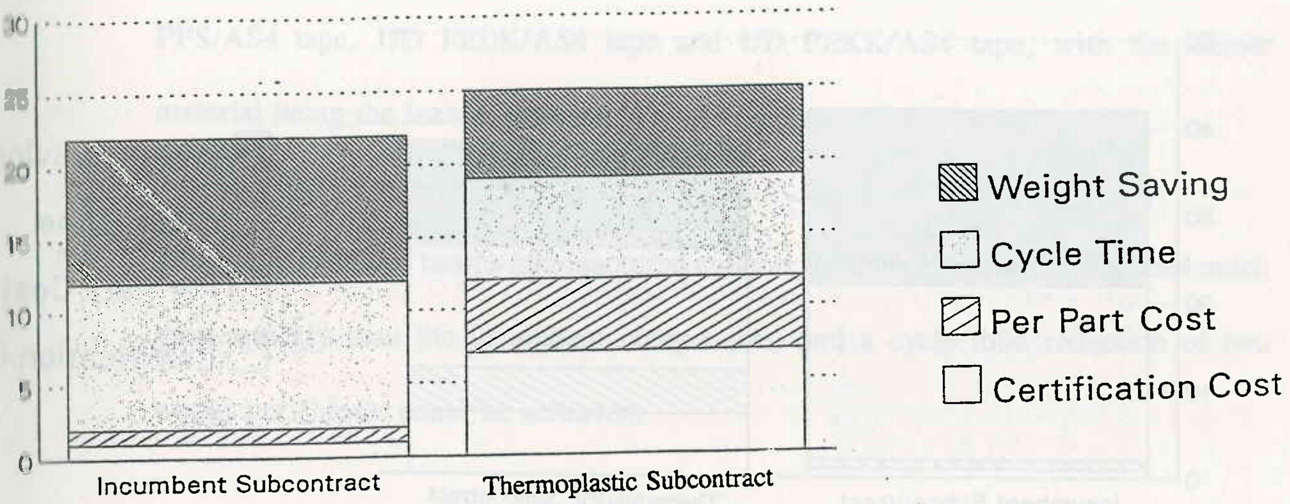


Figure 12 Weight-saving scaled x 2

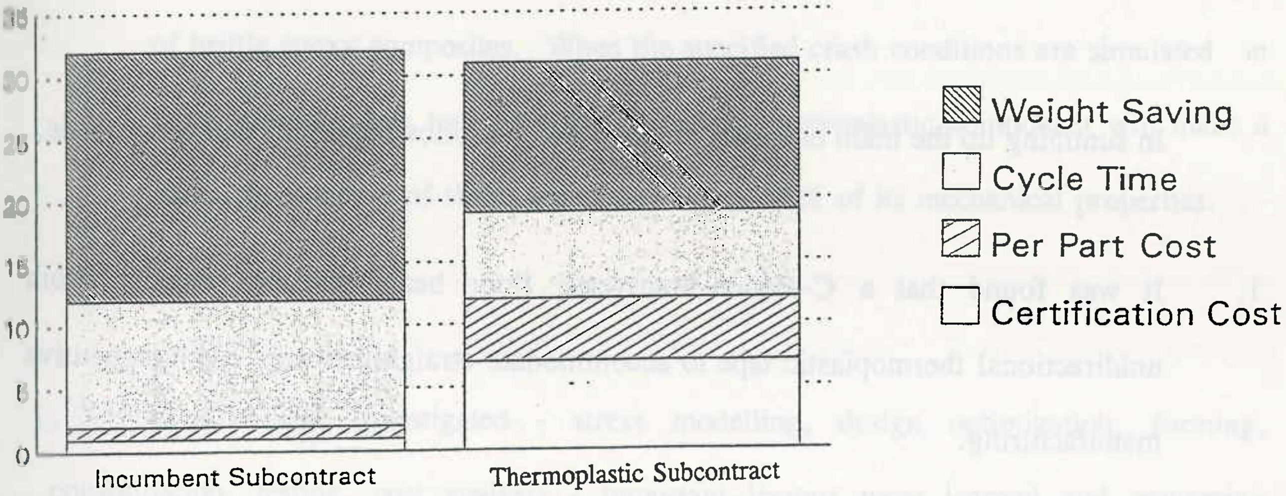


Figure 13 Cycle time scaled x 2

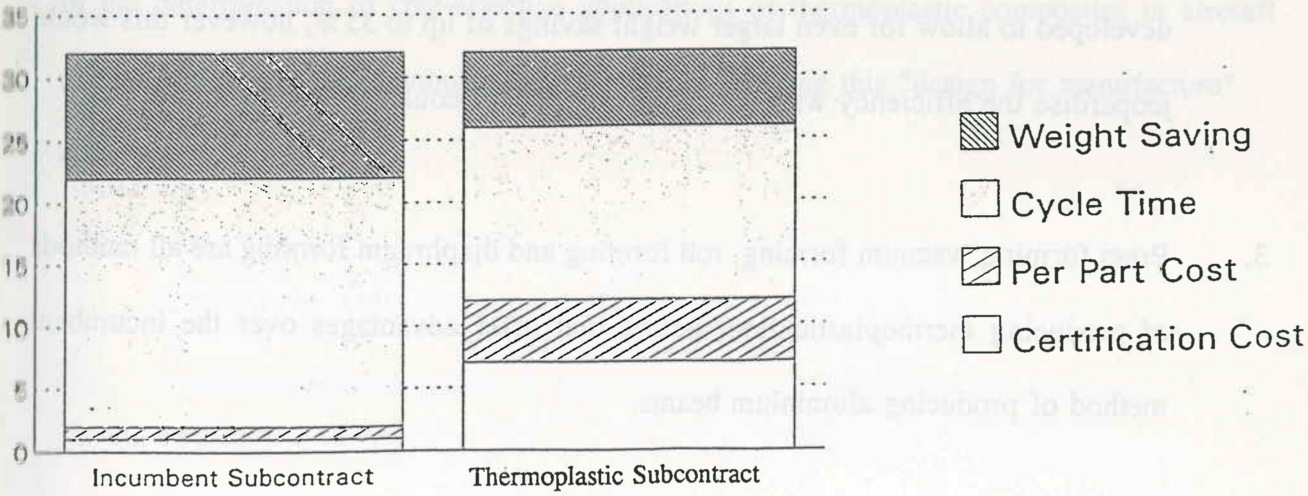
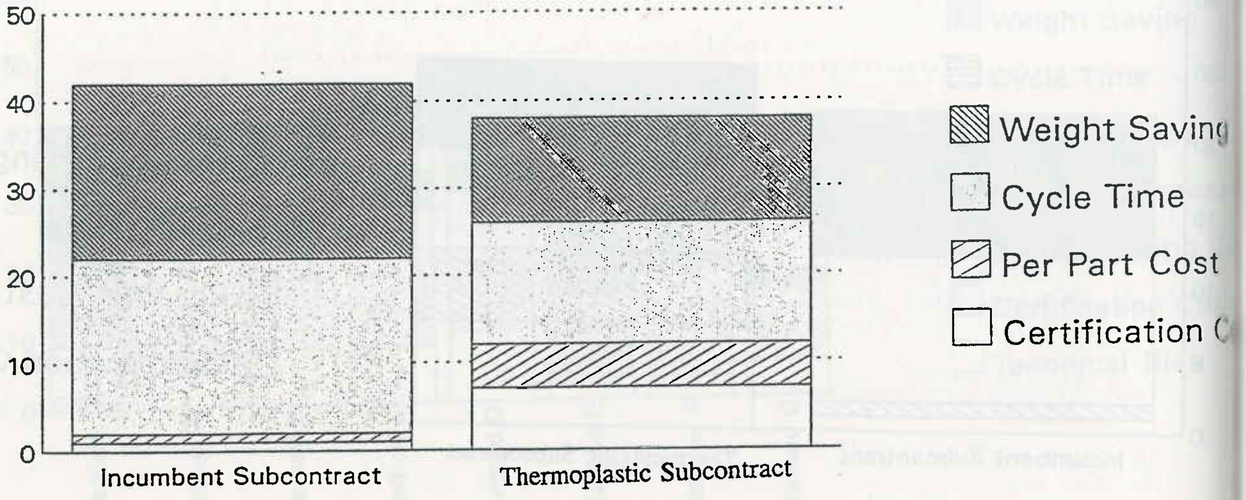


Figure 14 **Weight saving and cycle time scaled x 2**



CONCLUSIONS

In summing up the main elements of this work the following points can be be made.

1. It was found that a C-section transverse floor beam can be designed from unidirectional thermoplastic tape to accommodate straightforward, cost-competitive manufacturing.

2. A potential weight saving of 30% has been achieved, and this could be further developed to allow for even larger weight savings of up to 35%, however this would jeopardise the efficiency with which the component could be manufactured.

3. Press forming, vacuum forming, roll forming and diaphragm forming are all methods of producing thermoplastic floor beams that offer advantages over the incumbent method of producing aluminium beams.

4. Three suitable thermoplastic composites for this application are unidirectional PPS/AS4 tape, UD PEEK/AS4 tape and UD PEKK/AS4 tape, with the former material being the least expensive.

5. Thermoplastic floor beams manufactured at Short Brothers Plc. can be produced much more quickly than the incumbent components, and a cycle time reduction of two weeks per shipset could be achieved.

6. The design of C-section floor beams from thermoplastic composites is safer than that of brittle epoxy composites. When the specified crash conditions are simulated in three point bending tests, the highly ductile thermoplastic component will make a complete recovery of shape and retain almost 60% of its mechanical properties.

In all areas investigated - stress modelling, design optimization, forming, consolidation, testing, cost analysis - important lessons were learned and competing methodologies and techniques were evaluated. The result has been a significant step forward in the determination of cost-effective applications of thermoplastic composites in aircraft primary structure, and demonstrates the merit in adopting this "design for manufacture" approach.

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