The Airbus Floor Beam

Towards a Cost-effective Composite Design and Manufacture Research Project Sponsored by Airbus Industry

January 1992

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ABSTRACT

This report focuses on the introduction of Continuous Fibre Reinforced ThermoPlastic (CFRTP) materials in primary load bearing structures of civil aircraft. An actual Airbus floor beam was selected to demonstrate the feasibility of such a project. The decisive criterium for the application of CFRTP materials obviously is their projected cost-effectiveness compared to the present-day structure. Therefore the original design requirements, aiming at a mainly similar composite design, are found to obstruct the successfulness of this project. Thus the three parameters, dominating the cost-effectiveness of CFRTP structures, have been discerned and subsequently detailed in this report:

# Application of a relatively straightforward anisotropic design yielding a high structure efficiency.
# The further development and improvement of flexible, uncomplicated production processes to manufacture semi-prismatic beams.
# The need for interchangeability to integrate the (new) part in the surrounding structure.

Present-day practical research results and initial laminate calculations are detailed together with a survey of other recent developments in the field of CFRTP structural designs. A first resin material selection test has been performed, indicating that the Delft University rapid transfer rubber pressing process can provide the required manufacture technology to arrive at a low cost, low scrap and high speed (semi-)continuous production process for CFRTP beams. The way forward subsequently is shown to consist of two - interacting - research strategies:

# Continuation of the mechanical performance calculations on slender composite beams, modelling their deformation and failure modes (including shear buckling of the web). Definition of optimum shape and size of the system holes that are to be incorporated in the web.
# Both continuation of the determination of the mechanical performance level after processing and optimising the aforementioned manufacture technique are the two most vital topics to be addressed in near future.

The new large press production facility that has been purchased by Delft University and is scheduled to be operational in March 1992 will enable the manufacture and testing of relevant beam sections. Thus the design calculations will be validated. Also the optimum processing parameters with regard to the material properties after processing can be defined as this press will enable the repeatable manufacture of identical parts.

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<td></td>
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</tr>
</tbody>
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List of abbreviations

ACJ  Advisory Circular Joint
CFRTP  Continuous Fibre Reinforced ThermoPlastic
FIT™  Fibre Impregnée Thermoplastique, indicating that the strand has been enclosed in a thermoplastic hollow shaft, filled with similar thermoplastic powder
FST  Fire, Smoke & Toxicity (pertaining to flammability, smoke and toxic gas emission of aircraft materials)
LDF™  Long Discontinuous Fibre (Du Pont composite material)
MEK  MethylEthylKetone (a common aircraft cleaning fluid)
NCS  Non-Crimped Style (BASF weave style, using thermoplastic weaving thread for commingled fabric)
T_g  Glass transition temperature
T_m  Melt temperature
UD  UniDirectional (pertaining to the fibre orientation)

Thermoplastic resin materials

PAS  PolyArylSulfone
PEEK  PolyEtherEtherKetone
PEI  PolyEtherImide
PEKK  PolyEtherKetoneKetone
PES  PolyEtherSulfone
PPS  PolyPhenyleneSulfide
PSU  PolySulfone
1 Outline of the project set-up

The feasibility of the use of Continuous Fibre Reinforced ThermoPlastic (CFRTP) materials in primary load bearing aircraft structures is becoming a topic of primary interest in civil aviation. A Delft University/Airbus research cooperation has been set up to prove the possibility to replace the aluminium floor beams with cost-effective composite floor beams. Both the design and the manufacturing technology for a composite floor beam had to be studied. A typical U-shaped floor beam of the A310 (part identification code C56) was selected initially to be replaced with a composite version which should act as a demonstrator. The restrictions that had to be met with are detailed in the next chapter but essentially they come down to the next three items:

1 The composite floor beam at least should equal the stiffness of the current aluminium part; the strength and durability should be similar or preferably better.

2 The composite part has to fit into the existing surrounding structure without the need for any structural changes. This implies that the outer dimensions and the location of all the cut-outs have to be maintained while no significant modifications should be required to attach all additional parts and structures.

3 The overall cost (materials, production process etc.) of the composite floor beam should be competitive to the current beams (1991 price indication: DM 1600).

The aluminium floor beam is made from one single piece by a numerically controlled milling machine. This process facilitates the production of a changing geometry to optimise the strength and stiffness of each beam individually. This method has resulted in a rather complex design for each single floor beam and a very large scrap percentage (approximately 75%).

An earlier report [1] already provided an introduction to this project together with a review of the very first research results. The current report will fully outline the project status. The report consequently deals with the design (requirements, calculations, ease of production), the selection of an adequate manufacturing technique and research results on the validation of these processes. Bearing in mind the outcome of this survey the future research programme will be defined.

It will be shown that the specific nature of these materials, their inherent higher unit cost and their processing characteristics necessitate a change in the current design. This will enable the application of relatively straightforward manufacturing processes and a standard laminate lay-up in order to arrive at a cost-effective part.
2 Floor beam design

This chapter is split up in two separate sections. First the design requirements are briefly dealt with to provide the reader with a perspective view of the scope of the whole project. The second part will present an outline of the design considerations for a future CFRTP floor beam to meet all these requirements. Anticipating on the conclusions that will be drawn after the next two chapters it should be stated here that the introduction of CFRTP materials for floor beams -to our belief- can only be cost-effective if the design is based on the inherent material advantages and limitations. The initial prescriptions and requirements of the CS6 floor beam will therefore act as a more general framework. The predominant requirement is that the future floor beam will meet comparable requirements.

2.1 Design requirements

The requirements that both the current and the future CFRTP floor beam have to meet have been listed below and will be detailed in the ensuing paragraphs.
1 - Dimensions.
2 - Mechanical properties (strength, stiffness, durability).
3 - Thermal properties.
4 - Electric conductivity.
5 - Chemical resistance.
6 - FST-requirements.
7 - Reparability.

The specific description of test procedures, design values and allowables is presented in the preliminary Airbus justification programme[2]. The airworthiness requirements to be applied in general are those laid down in the A330/340 Airworthiness Requirements JAR 25 Change 12, in particular JAR 25.603 & ACJ 25.603. The damage-tolerance and fatigue evaluation of the composite structure should be based on the applicable requirements of JAR 25.571.

The basic principle of the justification is[2]:

"The structure must be designed to withstand ultimate load under appropriate environmental conditions for its entire service life. This applies to new structures as well as aged structures. An aged structure is a structure subject to damage and/or failure. These failures may either be identified but not repaired or may be present in areas inaccessible for inspection during operation. The structure should also meet rigidity requirements during its whole service life."

2.1.1 Dimensions.

The CFRTP floor beam that should replace the current aluminium CS6 part should have similar outer dimensions:
- overall length: 5,550 mm,
- height: 201 mm,
- flange width: 25 mm,
- strut attachment: 2125 mm from the midpoint.

Additional dimensions can be found in Fig. 1,2 & 3.

The location and shape of the holes as well as the attachments of seat rails and additional systems initially have to be maintained to guarantee the interchange of the current aluminium floor beam and the CFRTP part.
2.1.2 Mechanical requirements.

The mechanical loads on the floor beam can be attributed to several, sometimes interfering causes:
- gust
- crashes
- landing
- rapid decompression
- cabin pressure
- frame bending
- fatigue loading
- impact damage

The highest and thus normative loads for the strength of the C56 floor beam are those related to gust, crashes and a special landing case. The load diagrams are presented in Fig. 4 to 8. The corresponding bending moment envelop is also shown.

The positive limit manoeuvring load factor \([n]\) may not be less than 2.5 and need not be greater than 3.8; the negative limit manoeuvring load factor may not be less than \(-1.0\) (JAR 25.333 & 25.337). The gust load factor depends on the type of aircraft (JAR 25.341). The emergency landing conditions are specified in JAR 25.561; the loads on the structure are related to the ultimate inertia forces, acting separately relative to the surrounding structure, which are experienced by the occupants. The corresponding vertical loads are most relevant for the floor beam as shown in the shear load diagrams.

The (static) test with regard to the critical loads should be conducted on a structure after repeated loading and environmental exposure. The rigidity of the floor beam should at least equal the current version and will have to be guaranteed throughout the whole service life of the structure.

The loads caused by the additional factors listed above are detailed in the Airbus justification programme[2]. It should be noted that the regular ‘in service’ loads the floor beam will have to sustain are much lower due to the high gust and crash load factors. Thus the strain levels related to the fatigue loading are relatively low, reducing the effects of crazing and possible stress corrosion, two factors attributing to the degradation of composite structures.

2.1.3 Thermal requirements

Thermal loads are the forces related to the dimensional changes caused by temperature differences. The lower/upper maximum service temperatures have been defined as \(-40/+56\) °C on the ground (without operational loads) and \(-20/+56\) °C in flight (with maximum static load possible). The influence of moisture absorption should also be included. These thermal loads however do not involve the service climate which has been defined for environmental testing nor the temperature levels related to fire in the cargo hold. This case is detailed in §2.1.6.

2.1.4 Electric conductivity

The application of carbon fibres implies that the material is highly conductive if direct contact with the fibres is established. The resin however can act as a barrier between metal parts and the fibres, causing hazardous potential differences. Furthermore sufficient precautions against galvanic corrosion of the surrounding (metal) structure therefore should be taken. The use of titanium rivets and a glass cloth interlayer for example are highly recommended.

2.1.5 Chemical resistance

The floor beam should be resistant to solvents, (interior) cleaning agents, fuel and Skydrol. The resistance either has to be provided by an adequate protective coating or by the use of an inherently resistant resin material.
2.1.6 FST requirements

The floor beam has to meet the Airbus Industry Regulations (ATS 1000.001) and FAR Part 25 (§ 28.853 & Appendix F). In a nutshell this implies that the applied materials have to be self-extinguishing when tested vertically, the average burn length may not exceed 152 mm and the average flame time after removal of the flame source may not exceed 15 seconds. Drippings from the test specimen may not continue to flame for more than an average of 3 seconds after falling. Smoke density limits and toxicity limits have been defined in ATS 1000.001.

The FST requirements in general are sufficiently met with for all resin materials studied in this project. An additional requirement put up by Deutsche Airbus deals with the event that the cargo area catches fire. The CFRTP cross beam then does not have to outperform the aluminium beam. A selection test set-up has been defined in Ref. 2. This test was carried out at Delft Technical University and will be dealt with in §2.2.1 and Appendix A.

2.1.7 Reparability

Reparability, an essential aspect of maintenance, is a very important factor with regard to the cost-efficiency of composite structures. The application of spare parts usually is very expensive whereas intricate repair proceedings are associated with composite parts. Airline operators therefore sometimes prefer metals over composites, notwithstanding the initially lower structural weight[3]. The floor beams however are not often subjected to impact and handling damage but this topic should not be neglected. The advantage of thermoplastic resins over thermosets is their higher impact resistance although the difference is diminished by the reinforcing fibres. This obviously should be studied in detail together with the development of uncomplicated, fast and cheap repair techniques.

2.2 CFRTP design considerations & calculations

The cost-effectiveness of the floor beam project is determined by five important parameters once the requirements listed in the previous section are met with:

1. The structure efficiency, denoting the "performance" per unit mass[4].
2. The number of different part geometries that should be produced.
3. Definition of the maximum deviation of the beam properties & dimensions due to the manufacturing process.
4. The required amount of additional machining/forming (and thus the scrap percentage).
5. The type of material (e.g. preconsolidated sheet, prepregs or FIT™ material).
6. The need for (or better lack of) design changes of the surrounding structure.

These parameters obviously are determined by the floor beam design, the selected production process and the design of the surrounding structure (allowing for standard or modified beams). None of these items can be dealt with separately without affecting the others. This section will focus on the floor beam design whereas Chapter 3 will detail the appropriate manufacturing processes.

Dealing with composite materials implies that the requirements listed in the previous paragraphs are met by the fibre, the thermoplastic resin or the material as a whole. The use of carbon fibre is obvious as the high specific strength and stiffness will enable the weight reduction, contributing to the cost-effectiveness of the structure.

The shear loads and bending moment envelop, presented in Fig. 4-8 will be used as the normative design parameters for the CFRTP floor beam concerned in this report.
2.2.1 Thermoplastic resin selection

No final conclusions with regard to the choice of the matrix material can be drawn at this stage of the project as not all important parameters have been included in this project. Items such as the price, durability and the impact resistance still should be dealt with. A mayor distinction already can be made between the amorphous and semi-crystalline thermoplastic resins. A brief survey of these parameters is presented in Table I.

Table I: Important selection criteria for the type of thermoplastic resin.

<table>
<thead>
<tr>
<th>Significant parameter</th>
<th>Resin type</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Amorphous</td>
</tr>
<tr>
<td>Upper service temperature [°C]</td>
<td>160-180</td>
</tr>
<tr>
<td>Processing temperature [°C]</td>
<td>300 - 350</td>
</tr>
<tr>
<td>Chemical resistance / moisture absorption</td>
<td>-</td>
</tr>
<tr>
<td>Material cost</td>
<td>+</td>
</tr>
<tr>
<td>Ease of rapid processing (including spring-forward)</td>
<td>+/-</td>
</tr>
<tr>
<td>Flammability / smoke generation</td>
<td>+</td>
</tr>
<tr>
<td>Mechanical properties (strength/stiffness/impact)</td>
<td>+</td>
</tr>
</tbody>
</table>

1 The semi-crystalline matrices in particular are very sensitive to non-homogeneous cool down rates, causing differences in the local degree of crystallinity. This also attributes to the spring-forward effect. The stresses in the laminate that have built up during the rapid cooling down can introduce deformations after the product is released from the mould (Chapter 3).

Airbus has prescribed a material selection test[2] to study the temperature influence on the flexural behaviour of several CFRTP materials. This would provide them with a quantitative comparison to the original aluminium flexural behaviour. This test has been extended with a study on the influence of the rapid transfer rubber pressing (Chapter 3). Several specimen subsequently have been environmentally aged either by exposure to hot distilled water (70 °C) or Skydrol 500B hydraulic oil.

Five different materials have been included in this test based on the four thermoplastic matrices listed hereafter:

- PEEK
- PPS
- PAS
- PEKK

All materials contained unidirectional carbon fibres. The specific test procedure, materials and test results are extensively dealt with in Appendix A. The two mayor conclusions are that the elevated temperature test has shown that up to 250 °C the UD C/PEEK, C/PPS and C/PEKK (LDF™) can compete with the original aluminium since a similar or even better retention of the flexural stiffness has been measured. The amorphous PAS should not be heated too far above 150 °C - similar to other amorphous thermoplastics such as PEI and PES (not included in this test).

Secondly this 4-point bending test has indicated that neither the processing history (rubber pressed versus hot platen press consolidated flat sheet) nor the exposure to hot water or Skydrol substantially influence the magnitude of the measured bending modulus. This part of the test programme contributes to a general research project at Delft University, aimed at the quantification of the effect of processing on the mechanical properties[5]. It should be emphasized here that amorphous thermoplastic resins such as PAS, PEI, PES and PSU are known to be very sensitive to stress corrosion in a Skydrol environment (degradation of the adhesion between the fibres and the surrounding matrix)[6]. Furthermore MEK also seriously affects amorphous resins like PEI. The chemically resistant semi-crystalline thermoplastics on the other hand require higher processing temperatures in combination with a close temperature gradient control, determining the crystallinity degree. This will be detailed in section 4.3.
It is very important to comprehend that this test does not lend itself to judge the behaviour of the structure at elevated temperatures or after environmental exposure. To our belief the effects of stress corrosion, crazing, buckling etc. should be examined by manufacturing a representative part of the floor beam and consequently test it under the service conditions, either completely or by coupon tests, taken from this structure. This should validate the manufacturing technology and its reliability as well.

2.2.2 Laminate calculations

The advantage of a CFRTP floor beam partly lies in the inventive anisotropic design of the structure. Obviously the flanges of the floor beam will provide the bending stiffness, the web predominantly will be loaded in shear. Therefore a combination of ±45 and 0 degree fibre orientation was chosen (angle with respect to the length direction of the floor beam).

Initial calculations, based on the classical laminate theory and the engineering bending theory have been performed to study the stresses and strains in a specific cross section. The beam was modelled as a prismatic slender beam and the failure mode was restricted to fibre and shear failure only. The bending stiffness was compared to two representative cross sections of the aluminium beam. For the sake of simplicity the flexural behaviour of the complete beam was not comprised at this stage of the project. The initial results primarily are meant to provide an indication of the type of laminate lay-up and dimensions that are to be expected in the final design. Bearing in mind these simplifications the calculations demonstrated that some 30% weight reduction could be achieved with a maximum safety factor of about 7 for tensile loading, 3.5 for compressive loading (Azzi-Tsai-Hill failure criterium, applied to the maximum stresses in the laminate). The corresponding laminate lay-up and the exact description of the calculations and results are detailed in Appendix B.

The buckling behaviour initially was not included in these computations but later studies[7] already have shown that the most likely failure mode will be the local buckling of the web if no special precautions are included in the design. Present-day efforts therefore are aimed at modelling both the buckling and flexural behaviour of composite beams subjected to pure bending and transverse loading including the material characteristics[8]. A second study will be aimed at defining the optimum configuration of holes in the web. The shape, type of laminate etc. should be chosen as a function of both case of production and optimum mechanical behaviour. This topic will be addressed more detailed in section 4.2.
3 Manufacturing process

3.1 Survey of applicable techniques

Although a number of CFRTP materials has become commercially available over the past decade their applications predominantly are limited to special products only. Partly this can be attributed to their inherent high-(er) cost but another important factor is the lack of a mature and universal production process technology. The anisotropic nature, the viscous behaviour and conceivable resin degradation at (high!) processing temperature levels as well as the risk of both improper consolidation and insufficient fibre impregnation are some of the mayor complications related to this class of materials. Research at Delft University therefore is aimed at defining a framework for both the processing parameters and the resulting material properties rather than optimizing each individual process parameter.

Several production processes can be applied for the manufacture of a CFRTP floor beam. A concise description will be presented in this section together with a qualitative comparison of their specific pros and cons. This comparison was made by defining a number of significant parameters which to our belief are essential with regard to their economic attraction.

The processes, apt for manufacturing large (semi-)prismatic beams are listed below:
1. Autoclave diaphragm forming
2. (Die-less) roll-forming
3. Pultrusion
4. Sequential pressing
5. Integral matched die pressing,
6. Hand lay-up and subsequental autoclaving.

The parameters are:
1. The process cycle time,
2. The use of universal tooling equipment (e.g. control, transport and heating units, mold materials),
3. The (constant) product quality,
4. The complexity of the product that can be accomplished,
5. The demand for additional machining which should of course be little or none,
6. Low amount of scrap,
7. The energy efficiency,

An attempt to arrive at a global classification of these processes and parameters has been made in this report. Although this ranking has only been performed in a qualitative way it is meant to establish an analytical approach towards the selection of a suitable manufacturing process for the future floor beams. It should be stated here that for all pressing techniques mentioned hereafter the use of a rigid mold halve and a (silicone) rubber pressing block has been assumed. The rigid mold defines the final product dimensions whereas an all-sided pressure on the laminate can be accomplished by using the rubber. This is required to achieve a proper consolidation. This process, sometimes referred to as rapid transfer rubber pressing, currently is being investigated, modelled and optimized at Delft University of Technology. All processes detailed in this comparison however are presumed to have finished the developmental phase.

An explanation of the two tables (Table II & III) showing this classification, is presented on the next two pages.
Explanation of Table II & III

Eight process advantages, specified at the previous page, have been listed in Table II with their codes (A to H). A preference comparison matrix is shown behind these eight items; in this matrix each parameter has been compared to the others in pairs. The most important one has been assigned the digit 1, the other 0. Looking at the first block one can see that the process advantage A (Short cycle time) is believed to be more important than the advantages B, C, E and H but less important than D, F and G. In the second block of this comparison matrix advantage B (Universal tooling) has been compared to the six remaining advantages C to H (as it has already been compared to A in the first block).

At the right-hand side of Table II the frequency (F) is tabulated, denoting the times each individual parameter has been allotted the digit 1. A weight factor (WF) is assigned to this score; WF equals 1 if F is 0 or 1, WF = 2 if F = 2, 3 etc. Thus an order of their relative importance has been obtained. A high product quality (D) and low scrap (G) for example are believed to be of utmost but equivalent importance (WF = 4).

Next the six production processes (see previous page) have been examined to see whether they fulfilled these advantages. This is shown in Table III. For ease of presentation the process advantage codes of Table II have been used here. In this table the digit 1 indicates that the concerned process offers this specific advantage. In the last column the final ranking of the processes is shown. This number has been obtained by multiplying each 1 with the corresponding weight factor (WF) of Table II. Diaphragm forming for example has the advantages B, C, D and E. The score (9) thus is the sum of 2, 1, 4 and 2 successively.

This score globally indicates how useful each process could be for the floor beam production. The reasoning behind each individual score will be detailed in the next three paragraphs where three fundamentally different routes have been discerned for the manufacture of the floor beam, based on these processes. The present state of the art does not allow for a more refined comparison without making more (intuitive) assumptions. Future research obviously will be aimed at producing the data required to accomplish a quantitative ranking.
Table II  Classification of process advantages (pertaining to manufacturing CFRTP products)

<table>
<thead>
<tr>
<th>Code</th>
<th>Process advantages</th>
<th>Preference comparison matrix</th>
<th>$F^1$</th>
<th>$W_f^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Short cycle time</td>
<td>1 1 0 1 0 0 1</td>
<td></td>
<td>4 3</td>
</tr>
<tr>
<td>B</td>
<td>Universal tooling</td>
<td>0</td>
<td>1 0 1 0 0 0</td>
<td>2 2</td>
</tr>
<tr>
<td>C</td>
<td>All materials applicable</td>
<td>0</td>
<td>0 0 0 0 0</td>
<td>1 1</td>
</tr>
<tr>
<td>D</td>
<td>High product quality</td>
<td>1</td>
<td>1 1 1 1 1</td>
<td>7 4</td>
</tr>
<tr>
<td>E</td>
<td>High product complexity</td>
<td>0</td>
<td>0 1 0 0 1</td>
<td>3 2</td>
</tr>
<tr>
<td>F</td>
<td>No additional machining</td>
<td>1</td>
<td>1 0 0 0 1</td>
<td>4 3</td>
</tr>
<tr>
<td>G</td>
<td>Low scrap</td>
<td>1</td>
<td>1 1 0 0 1</td>
<td>6 4</td>
</tr>
<tr>
<td>H</td>
<td>Energy efficiency</td>
<td>0</td>
<td>1 0 0 0 1</td>
<td></td>
</tr>
</tbody>
</table>

1 Frequency (= number of score '1')
2 Weight factor (1 for $F=0.1$ | 2 for $F=2.3$ | 3 for $F=4.5$ | 4 for $F=6.7$)

Table III  Classification of CFRTP production processes (based on the advantages listed above)

<table>
<thead>
<tr>
<th>Production process</th>
<th>Process advantages code (see upper table)</th>
<th>Score [*WF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diaphragm forming</td>
<td>A 0 B 1 C 1 D 1 E 1 F 0 G 0 H 0</td>
<td>9</td>
</tr>
<tr>
<td>Roll-forming</td>
<td>A 1 B 1 C 0 D 1 E 0 F 1 G 1 H 1</td>
<td>14</td>
</tr>
<tr>
<td>Pultrusion</td>
<td>A 1 B 1 C 0 D 0 E 0 F 1 G 1 H 1</td>
<td>10</td>
</tr>
<tr>
<td>Sequential pressing</td>
<td>A 1 B 1 C 1 D 0 E 1 F 0 G 1 H 1</td>
<td>14</td>
</tr>
<tr>
<td>Integral pressing</td>
<td>A 1 B 0 C 1 D 1 E 1 F 1 G 1 H 1</td>
<td>15</td>
</tr>
<tr>
<td>Hand lay-up &amp; autoclave</td>
<td>A 0 B 1 C 1 D 1 E 1 F 0 G 0 H 1</td>
<td>11</td>
</tr>
</tbody>
</table>
3.1.1 Continuous forming

The two conceivable manufacturing processes are:
- Pultrusion.
- Roll-forming, including the rotating wheel- or belt-press.

Both pultrusion and roll-forming are relatively new techniques with regard to the application of CFRTP materials and they have not yet been proven. The original thermoset pultrusion process has to be modified substantially to enable the application of thermoplastic composites[9]. The process usually lacks sufficient time for consolidation. Furthermore the low resin content and the high melt viscosity generate high pulling forces. These are associated with friction and compaction[10], dominated by the die geometry. If the materials contains no unidirectional fibres unacceptable material deformations can be introduced.

The roll-forming process basically very much resembles the pultrusion process but lower frictional forces are inflicted on the material. The most important process parameters and characteristics, introduced with the use of CFRTP, are listed hereafter[11]:
- Close temperature control.
- Fibre inextensibility and low fibre buckling resistance .
- Close control of roll positioning.
- Interlaminar slip.
- Adhesion between (cold metal) rolls and laminate.

This process predominantly can be applied for two-dimensional shapes having a constant cross section. An interesting variant to this process was developed by Alan Miller et al.[12], using two adjustable arrays of universal, computer-controlled rollers. This permits the manufacture of single-curved shapes which are long in their straight direction and of variable cross section along their length. Furthermore heating (induction) and bending are strictly local processes, reducing the size of the required equipment. On the other hand this also entails that complicated sections have to pass a number of times through the rollers before the final geometry has been accomplished. This technique is especially attractive for the manufacture of optimized floor beams with local changes in thickness. The applied induction heating technique however is not a very effective method when UD materials are applied. Furthermore it is not yet clear what production times can be achieved.

A third version of the roll-forming is the application of silicone rubber instead of the conventional polished stainless steel, either for the rollers or the mold. Thus an all-sided pressure can be obtained in the profile, improving the final product shape and consolidation. The application of circular rollers is not obligatory; a configuration using a kind of silicone rubber belt press is very well conceivable[13].

3.1.2 Sequential processing

The terms "sequential" or "semi-continuous" are associated with production processes showing individual heating, forming and consolidation phases repeated at distinctive intervals of time. The material transport is intermittent. Two different process configurations can be discerned.
- The material is being fed into several heated molds, gradually deforming and heating the thermoplastic laminate to the desired shape. The material finally is consolidated and cooled in the last mold[14].
- The material is heated by infrared radiation, induction or convection (hot inert gas oven) and subsequently rapidly transferred and pressed. Meanwhile the next part either has already been heated or is heated during the press phase.

Pros and cons of this technique are shown in Table IV and will be detailed below.
### Sequential pressing characteristics

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight semi-infinite products</td>
<td>Distinct transition zone from hot to pressed section</td>
</tr>
<tr>
<td>No preconsolidation required (usually)</td>
<td>Intermittent process complicates control</td>
</tr>
<tr>
<td>Changes in cross section thickness feasible</td>
<td>Yet uncertain production speed</td>
</tr>
</tbody>
</table>

The sequential process very much resembles pultrusion but the mayor differences are the lack of the high forces associated with the material transport through the forming die and the improved control of the lateral pressure. Thus unacceptable material deformations can be prevented and the (final) shaping mold length solely is limited by the cool down rate during the transport phase. An ample mold length is highly preferred as thermoplastic composites in particular require a discrete period of time during which a pressure is exploited on the material to achieve a proper consolidation. In this period the laminate cools down to a temperature level below $T_f$. Inevitably there will always be a distinctive transition zone from the consolidated (cold) part to the section that is being heated to a level well above the $T_f$ and that will be formed in the next step. Minimizing this region and defining its influence is one of the research topics at Delft University[12]. Although to our information only the manufacture of prismatic components is reported[14,15] this process in theory also enables the production of parts with a varying cross section geometries. This could be achieved by using different shaping dies at the end and by locally adding separate layers. The geometry however has to be compatible with the other sections to prevent distortion of the final product. This is largely dominated by the fibre orientation. Furthermore no information on process speed or adequate control of the temperature could be achieved as this is a proprietary AEA Harwell Laboratory development[16].

#### 3.1.3 Integral component production

Diaphragm forming, hand lay-up and integral pressing enable the manufacture of the complete floor beam in one single step. The advantages and disadvantages of this approach should be thoroughly identified.

- Autoclaving in particular affords a precise process control and proper consolidation
- Integral pressing offers short cycle times and a narrow processing window, provided the process has been optimized.
- All three processes guarantee a largely similar processing history for the whole material. This will minimize the spread of the product properties.
- The integral component production lends itself very well to preparing the blank completely (the blank is the initially flat laminate, containing all the individual layers which make up the final product). If necessary the blank can even be consolidated prior to the final pressing sequence although this would increase both the production time and cost.

The arguments against the integral manufacture approach:

- Autoclaving inevitably involves long cycle times and high energy consumption. The use of diaphragms also substantially raises the cost.
- The purchase of a special press and corresponding heating & transport equipment generate huge investments. Process control then also involves the rapid closing of the die and immediate pressure build-up, uniformly heating of an approximately 6.0 by 0.5 metre blank, instantaneous transport of either this blank or the heating devices and so forth.
- The production process flexibility is very limited. Firstly changes in product dimensions (length!) can be difficult to cope with. Secondly other products can not be produced efficiently with this equipment (autoclave - long cycle time; press - surplus or lack of capacity).
- Tremendous amounts of rubber are required for the manufacture and maintenance of the matching rubber mold half.
3.2 Design restrictions & research results of production processes

The single-step manufacture of the entire floor beam to our belief will not be cost-effective based on these restrictions and disadvantages. Too large investments are involved which are not being counterbalanced by the anticipated advantages. The logical consequence is that the floor beam will have to be manufactured in a more flexible and economic way, either in a step-by-step operation or in a continuous process.

The most straightforward shape of a floor beam is a prismatic L-loaded in shear and bending. In order to optimize each beam for the specific loads the laminate lay-up, fibre orientation and thicknesses of the individual beams will vary inevitably. This involves high labour and material cost. An alternative route, aiming at the cost-effectiveness of the CFRTP floor beam, could be the manufacture of prismatic beams. They should solely meet the general strength and stiffness requirements. Additional (standard) elements should be applied for attachments and local load introduction. Especially the use of standard metal fittings for the strut attachment is highly recommended. Although this inevitably will generate an increase of the structural weight the cost of materials and manufacture to our believe could be substantially lowered. Provided an adequate standard geometry can be defined and system holes, fittings and other attachment can be realised in an uncomplicated way, this approach might contribute to the introduction of CFRTP structural parts in civil aircraft. This will be treated extensively in chapter 4.

The selection of a proper manufacturing technique obviously contributes significantly to the feasibility of the CFRTP floor beam project (see also §2.2). Not all manufacturing techniques however allow for each design to be realised.

The application of a form of rubber pressing technology looks rather attractive as an all-sided pressure can be imposed on the laminate. The rubber furthermore tolerates small irregularities both in the rubber mold and in the material thickness, which can not be achieved using (expensive) matching metal molds. Yet the high temperature resistant silicone rubbers are very prone to cracking under tensile loading and get easily damaged should any incidental misalignment of the two molds occur[17]. Thus uncomplicated geometries are highly preferred, allowing for the replacement of a plain outer "wear-layer".

Implementation of this technique should be based on four important - general - process characteristic which have been formulated after extensive rubber pressing trials at Delft University:
1. The pressure distribution in the rubber mold is not hydrostatic and depends on the mold geometry, mold dimensions and tolerances, the type of rubber and the tension in the laminate[18].
2. The fibre inextensibility usually causes the whole laminate to deform, disturbing the fibre orientation throughout the product. Local fixation of the laminate prior to pressing only partially hinders this mechanism.
3. The rubber deformability, frictional forces and tensile stresses in the laminate, all three being induced during the closing of the mold, substantially hinder the realisation of sharp corners and edges. This should be taken into account in the very early design phase.
4. The simultaneous rapid deformation and instantaneous cooling down of the laminate inevitably introduce residual stresses in the product. These stresses can cause the product to deform after it has been released from the mold. They also can lead to unexpected premature failure.

With regard to the (elliptical) system holes a few separate comments should be made here. First efforts have been aimed at pressing the w-profile and the holes simultaneously. "Pressing a hole" means here that elliptical shaped dimples with a bevelled edge have been pressed in the laminate, the height being 10 mm. A representative section of the C-56 floor beam was selected to study the deformation behaviour in practise. Initial simulation, using a computer model (Drape - Delft University programme), did not account for the interaction introduced by the simultaneous forming of numerous shapes. Two mayor conclusions can be formulated:
- Both the height and the angle of the bevelled edge turned out to be very critical, dominating the occurrence of laminate wrinkling in between the dimples (using a ±45 degree laminate).
- Notwithstanding the formability of a weave, the pressing of dimples in the web significantly affects the fibre orientation in the vertical flanges. Thus a unidirectional fibre orientation can not be preserved, this being a requirement of paramount importance for the floor beam mechanical properties[19].
Consequently it was tried to press the individual system holes in a second phase, after the production of the omega-profile. The inner section was cut out first to allow for the deformations. A part of the laminate then was heated and pressed to form the raised border. The local heating and forming thus should not affect the surrounding laminate quality and fibre orientation. The results indicated that this approach might be applied successfully in the future, provided a better process control can be realised. Minimizing the transition from the heated to the cold region and achieving a uniform heat distribution turned out to be quite troublesome. The maximum deformation that could be accomplished obviously is governed by the fibre orientations and the possibility to cut the laminate prior to the pressing phase [20]. The Du Pont LDF material conforms very well to the demands made by this technique.

The elliptical shape however was purely translated from the original CS6 floor beam. Defining an optimum shape first, based on the use of CFRTP materials, has the highest priority (see Chapter 4).
4 Future research procedure

All previous chapters have been aimed at providing a comprehensive review of the state-of-the-art in CFRTP design and manufacture at Delft University. An outline of future research efforts will be presented hereafter, conceivably being the most important chapter of this report. Four successive sections will deal with the CFRTP manufacturing process characterization, the design of the floor beam, the durability of the structure and the testing programme envisaged to validate the ideas and resulting parts. As stated before these items interact significantly and can not be dealt with individually.

4.1 Process characterization

A thorough definition and understanding of the process characteristics is of predominant importance for the manufacture of CFRTP structures. Research at Delft University on this topic thus will be continued. The new Fontijn press (scheduled for March 1992) will enable the repetitive manufacture of rubber pressed parts. The press configuration consists of an infrared heating unit, a rapid transport system and a fast closing 1.6x0.5 meter bed. Subsequently testing and comparison to autoclaved parts will allow for a quantitative definition of the influence of the processing history on the mechanical properties.

Other research project(s)[20,21] have suggested that the application of mold materials other than metals substantially could slow down the cool down rate in the mold. This is believed to contribute significantly to the reconsolidation and the reduction of internal residual thermal stresses. Materials like wood and ceramics have a much larger heat capacity than metals while the heat transfer rate is considerably lower.

A third research proposal focuses on the heating of CFRTP by means of infrared radiation. Long wave length radiation is known to penetrate deeper in this kind of materials but the corresponding type of heaters intrinsically have very long response times. This seriously obstructs a quick and precise temperature control. Short and medium wave length radiators on the other hand do have a very short response time (1-4 seconds) but tend to heat the outside surface predominantly. Yet they would enable an accurate temperature control, using a remote sensing pyrometer. The ensuing heating through the thickness of the material merits further study[22]. This research will also provide more insight into the feasibility of local heating (and forming) of CFRTP products.

Finally the present-day research on the semi-continuous manufacture of CFRTP profiles will be continued. The process control merits further refinements and the influence of repeatedly heating and forming of discrete sections of the profile has not yet been quantified. Evaluation of the results in combination with the reported characteristics of roll-forming eventually will lead to the selection of a proper manufacturing technique (once again: also based on the floor beam design).

4.2 Structural design

The recent fusion between the b2- (materials, design and manufacture) and c- (constructions) Departments, forming the Structures & Materials Laboratory, has initiated a research proposal aimed at the simultaneous computational design and manufacture of a (representational) part of the floor beam. Both continuation of the analytical approach (Appendix B) and a Finite Element modelling are scheduled for the first half of 1992. The new Fontijn press (see §4.1) will allow for the realisation of this part. Up till now only very limited maximum part dimensions can be realised. This study initially will focus on the flexural behaviour and failure
A second study will detail the optimum configuration for the inevitable system holes that are to be incorporated in the web. The stress distribution as a function of the external loading and hole geometry will be studied. Subsequently manufacture and testing of CFRTP specimen will provide the essential correlation between theory and reality.

Finally the attachment of additional systems and the support struts has to be studied. Two standard metal fittings will allow for a conventional joint and a well distributed load introduction in the floor beam. The seat rail supports which are now bolted and riveted to the floor beam preferably should be replaced by fittings, bonded to the web. These details also have to be studied in the initial design phase.

4.3 Environmental resistance

The application of semi-crystalline thermoplastic resins seems inevitable with regard to the environmental resistance requirements (§2.1.5). Yet they also introduce higher cost, higher processing temperatures and a difficult control of the temperature history. In this respect the amorphous resins are much more attractive. Thus a research project was started aiming at the improvement of the environmental resistance of amorphous resins. Two approaches are considered simultaneously.

- The resin can be coated by a semi-crystalline film which has been applied prior to (or during) the processing of the material. The combination of amorphous materials like PEI with PEEK, PPS or PA may lead to an adequate cohesion[23]. This technique in particular will be applicable to diaphragm forming, allowing for smooth deformation rates and control of the consolidation.
- A second study was set up to provide an inventory of all present-day coating techniques (on thermoplastic substrates). This has to lead to a selection of one or more techniques which are both appropriate and applicable in present-day manufacturing processes. These techniques subsequently will be studied in more detail, using relevant materials and environments[24].

4.4 Testing programme

The testing programme with regard to the certification of the CFRTP floor beam predominantly will be defined by Airbus. Yet considerable tests should be performed at Delft University as already briefly mentioned in §4.1. Representative parts of the floor beam have to be designed and manufactured to study the structure behaviour rather than ending up in ceaseless coupon testing. The relevant failure modes and the possible decrease of material properties after processing will have to fed into the computational modelling to arrive at reliable prognoses. The results of the numerous impact tests, performed at Delft University, should also be linked to the design. The tests that have been performed on the material durability will be extended to the behaviour of the structure.
5 Conclusions

Although it has been stated often before, the application of CFRTP for use in future floor beams will only be cost-effective if the initial design is based on the materials specific properties, taking into account their advantages and limitations.

Design & calculations.

- Future research predominantly will be aimed at modelling and understanding the CFRTP floor beam mechanical behaviour. This will enable the conclusions below to be filled in more quantitative.
- The final floor beam design should be relatively simple, (semi-)prismatic and standard, based on the following considerations:
  - The inherent higher cost per unit of weight (compared to aluminium).
  - The processing characteristics of CFRTP: all deformations affect the fibre orientations throughout the product.
  - The huge costs involved in the development of special equipment and the inherent lack of flexibility.
  - Standard profiles substantially lower both the production cost and the spare part price.
- The penalty of the weight increase compared to the application of an optimized design with varying thicknesses of the web and the flanges to our opinion will only be small and will be outweighed by the aspects listed above.
- The most likely first failure will be local buckling of the web. The design therefore should incorporate both 0/90 and ±45 degree fibre orientation in the web with additional unidirectional fibres in the flanges. The application of local dimples in the web might also be feasible, considerable increasing the critical buckling load.
- The system holes that have to be included in the design should be optimized for two fundamental requirements:
  - Optimum mechanical performance.
  - Feasibility of production.
  Pressing of the individual system holes in a second phase, after the production of the profile, was studied but found to be troublesome. The Du Pont LDF™ material potentially is most suited for this approach.
- The support strut attachment to the floor beam will be realised with a bonded metal fitting, allowing for an easy assembly and a proper load introduction. Additional joints preferably will be realised by bonding metal or short fibre reinforced thermoplastic parts to the floor beam.

Production process.

- Integral matched-die rapid transfer rubber pressing would produce both the best but also the most expensive floor beams. This would allow for local changes of the thickness and fibre orientations.
- Production techniques like semi-continuous pressing and roll-forming however are to be preferred with regard to the component overall cost. These processes benefit by a prismatic design and will be studied in more detail.
- The expected costs will then have to be assessed, based on the number of parts, the investment in the development and purchase of special equipment, material cost etc. These cost comparisons however require the input of Airbus information.
Conclusions (continued)

Material selection.

- Although the use of carbon fibres is quite obvious no final conclusions can be drawn with regard to the type of matrix. The Airbus 4-point bending test has indicated that the processing history and the exposure to hot water or Skydrol hardly influence the measured bending modulus. The elevated temperature test shows that up to 250 °C the UD C/PEEK, C/PPS and C/PEKK LDF™ can compete with the original aluminium. The amorphous PAS should not be heated too far above 150 °C, similar to PEI and PES (not included in the test programme). Yet the test itself is no absolute standard to represent the behaviour of the structure as it does not include the effects of e.g. stress corrosion (crazing), buckling, interlaminar shear, impact damage and compressive or tensile failure.
- The coating of an amorphous thermoplastic might turn out to be a serious alternative for the application of a semi-crystalline thermoplastic resin.
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Figure 1  Drawing of the aluminium C56 floor beam
Figure 2 Drawing of a representative part of the C56 floor beam
Figure 3  Drawing of a the strut attachment section of the C56 floor beam
Figure 4  Shear loads during crash-case (-8 nz / 2) - C56 floor beam
Figure 5  Shear loads during crash-case (+8 nz / 5) - C56 floor beam
Figure 6  Shear loads during landing-case (L 236) - C56 floor beam
Figure 7 Shear loads during gust-case (B2T6) - C56 floor beam
Bending Moment Envelop

Figure 8  Bending moment envelop - C56 floor beam
A Four point bending test procedure

A.1 Test set-up and materials used.

The Airbus floor beam justification programme [Deutsche Airbus Bericht Nr 10 X 002 74 107 P20] prescribed a four point bending test series to be performed for the material selection. The application of Continuous Carbon Fibre Reinforced Thermoplastic materials for the composite floor beam was already shown to be most likely and therefore the following test procedure was agreed upon:

4-point bending test of UD specimen, continuous carbon fibre reinforced.

Specimen size 150 x 25 x 4 mm.
Fibres in longitudinal (150 mm) direction.
Support span L 100 mm.
Load span 50 mm. (L/2)
Nose radius 7.5 mm.
Determination of load at 3 mm. deflection of the midsection and the flexural modulus. Additionally the failure mode is studied.
Influence of rubber pressing and successively exposure to water and Skydrol.

The test parameters other than prescribed by Airbus were defined in accordance with ASTM D 790M-86 and are detailed on the following pages.

The materials involved in this test programme are listed in Table I. All materials have been supplied by the manufacturers, free of cost.
Table I: Materials included in the 4-point bending test

<table>
<thead>
<tr>
<th>Resin Material</th>
<th>Supplier</th>
<th>Fibre volume [%]</th>
<th>Trade name, remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEEK</td>
<td>ICI</td>
<td>61</td>
<td>APC-2, UD AS4 prepreg tape</td>
</tr>
<tr>
<td>PAS</td>
<td>Amoco Chemical</td>
<td>62</td>
<td>Resin trade name Radel, T650-42 UD prepreg tape</td>
</tr>
<tr>
<td>PPS</td>
<td>Phillips 66</td>
<td>59</td>
<td>Ryton PPS, AS4 fibre, UD prepreg tape</td>
</tr>
<tr>
<td>PEKK</td>
<td>Du Pont de Nemours</td>
<td>58</td>
<td>Long Discontinuous Fibres (LDF), AS4, supplied as a panel</td>
</tr>
<tr>
<td>PEEK</td>
<td>BASF</td>
<td>62</td>
<td>Hybrid yarn, commingled carbon/PEEK AS4 Non Crimped Style (NCS) UD fabric</td>
</tr>
</tbody>
</table>

Six different material treatments were used.
1 Specimen are consolidated as specified by the manufacturer.
2 Specimen (heated in a flat platen press) are pressed in a mould consisting of a silicone rubber upper die half and a metal lower die half, both at room temperature.
3 Similar to 2 but the metal die half is heated just below the $T_g$ of the resin.
4 Specimen are exposed to distilled water at 70 °C; the weight is monitored to determine the saturation point prior to testing.
5 Specimen are exposed to Skydrol 500B (room temperature); the weight is monitored to determine the saturation point prior to testing.
6 Specimen are tested at different temperatures, ranging from room temperature, 100, 150, 200 and 250 °C.

This is shown in Table II. At least five specimen have been used for each series. The pretreatments are indicated by their specific number listed above.

Table II: Test matrix of UD four point bending test specimen.

<table>
<thead>
<tr>
<th>Series</th>
<th>Pretreatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>1, 2</td>
</tr>
<tr>
<td>C</td>
<td>1, 3</td>
</tr>
<tr>
<td>D</td>
<td>1, 2, 4</td>
</tr>
<tr>
<td>E</td>
<td>1, 2, 5</td>
</tr>
<tr>
<td>F</td>
<td>1, 3, 4</td>
</tr>
<tr>
<td>G</td>
<td>1, 3, 5</td>
</tr>
<tr>
<td>H</td>
<td>1, 6</td>
</tr>
</tbody>
</table>

Due to the preliminary character of the test procedure only a limited number of specimen was tested for each parameter. This number was even further reduced occasionally by the amount of material supplied by the manufacturers and incorrect processing. The final number of specimen for each serie that have been tested, yielding valid test data, is shown in Table III.
Table III: number of specimen tested in 4-point bending procedure

<table>
<thead>
<tr>
<th>Material</th>
<th>Processing history</th>
<th>Rubber pressed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Consolidated as prescribed</td>
<td>Cold mould</td>
</tr>
<tr>
<td></td>
<td>Exposed to heat [°C]</td>
<td>O</td>
</tr>
<tr>
<td>C/PEEK (AFC-2)</td>
<td>6 5 5 5 5 8 6 8 6 5 5</td>
<td></td>
</tr>
<tr>
<td>C/PAS</td>
<td>6 5 5 5 5 8 6 7 8 8 8</td>
<td></td>
</tr>
<tr>
<td>C/PPS</td>
<td>6 5 5 5 5 7 6 8 6 5 5</td>
<td></td>
</tr>
<tr>
<td>C/PEKK</td>
<td>6 5 5 5 5 8 8 8 8 8 7</td>
<td></td>
</tr>
<tr>
<td>C/PEEK (BAST)</td>
<td>7 7 7 7 7 5 5 5 5 5 5</td>
<td></td>
</tr>
</tbody>
</table>

1. Original, tested after rubber pressing.
2. Rubber pressed and subsequently exposed to Skydrol.
3. Rubber pressed and subsequently exposed to distilled water at 70 °C.

A.2 Description of test parameters.

Most of the formulas quoted hereafter can be found in Ref. 1. The crosshead motion rate was calculated with [1],

\[
R = \frac{ZL^2}{6d}
\]  

where:
R = rate of crosshead motion [mm/min],
L = support span [mm],
d = specimen depth [mm],
Z = rate of straining of the outer fibre [mm/mm·min]. Z shall equal 0.01.

Thus \( R = 9.375 \text{ mm/mm·min} \) was used.

The load - central displacement curve was plotted for each specimen, allowing for the determination of the load at 3 mm. deflection of the midsection and the calculation of the tangent modulus of elasticity \( E_B \). Therefore a tangent to the steepest initial straight-line portion of the load - deflection curve is drawn and equation [2] is applied.

\[
E_B = \frac{11mL^3}{64bd^3}
\]

where:
b = specimen width [mm],
d = specimen depth [mm],
m = slope of the tangent to the initial straight-line portion of the load - deflection curve [N/mm of deflection].
As the UD specimen are highly anisotropic a correction factor \( S \) for the shear deformation is introduced, calculated with [3],

\[
S = \frac{3h^2E_B}{2L^2G_{xz}}
\]  

(3)

where:

\( G_{xz} \) = the interlaminar shear modulus [GPa] (with \( z \) being the specimen depth direction).

Rewriting Eq. 2 yields

\[
E_B = \frac{11PL^3}{64bd^3[w - \frac{3PL}{16bdG_{xz}}]}
\]  

(4)

where:

\( P \) = load at a given point on the load-deflection curve [N],

\( w \) = centre deflection at the same point on the load-deflection curve [mm].

As the interlaminar modulus is not known in many cases it may be approximated by the in-plane shear modulus \( G_{xy} \) (Ref. 2). This is especially valid for unidirectional materials where usually no separate layers can be discerned after processing. The influence of this correction factor \( S \) is relatively small for the materials included in this test. This is shown best in equation 5,

\[
E_B = \frac{mL^3}{64bd^3}(11 + 8S)
\]  

(5)

This equation is similar to Eq. 2 but now includes the correction factor. Calculating this expression with the given specimen dimensions and using an average \( E_B \) of 150 Gpa and \( G_{xy} = 6.5 \) Gpa demonstrates that the increase of \( E_B \) is in the order of 3-4 %.

The maximum stress of the outer fibres of the specimen at the prescribed 3 mm centre deflection \( \sigma_m \) and the corresponding maximum shear stress \( \tau_m \) are calculated with Eq. 6 & 7,

\[
\sigma_m = \frac{3PL}{4bd^2}
\]  

(6)

\[
\tau_m = \frac{d}{L}\sigma_m
\]  

(7)

where:

\( P \) = load at 3 mm centre deflection [N].
The arithmetic mean of all values and the standard deviation are calculated using [6],

\[ s = \sqrt{\frac{\sum x^2 - n \bar{x}^2}{n - 1}} \]  

(8)

where:
- \( s \) = estimated standard deviation,
- \( x \) = value of single observation,
- \( n \) = number of observations,
- \( \bar{x} \) = arithmetic mean of the set of observations.

A.3 Test results

A.3.1 Hot/cold pressing of specimen.

The time-temperature history for all materials has been monitored using six thermocouples placed at the bottom side (two), in the middle (two) and at the top side (two). The bottom side is pressed onto the aluminium mould, the top side is pressed onto the silicone rubber block. The average specimen thickness was 4 mm; the two groups of thermocouples were placed some 100 mm apart. The temperature curves are given for each material (Fig. 1-7), pressed in a hot or a cold mould. The large differences in the local temperatures (up to 90 °C for APC-2, pressed in a cold mould!) are obvious and sometimes caused the initially flat plates to curve perpendicular to the fibre direction after cooling down. This phenomenon can be attributed to the differences in heat capacity and conductivity, in particular in the laminate thickness direction. These residual thermal stresses cause the distortion of the laminate in the least stiff direction. This has been described in more detail in Ref 3, 4 & 5. It should be noted that this characteristic behaviour might cause serious problems in manufacturing CFRTP parts if no adequate precautions are taken.

After the rubber pressing the material has also been C-scanned to get an indication of the consolidation quality. The C-scan photographs however could not yet be included in this report for lack of time. In a future report it will be tried to correlate the bending test results with the C-scan images.

A.3.2 Environmental exposure.

The water and Skydrol exposure test lasted for almost 2,400 hours. The weight of one specimen for each type of material has been monitored to define the saturation level. The initial weight has been determined after drying the specimen for 12 hours at 60 °C in a ventilated hot air oven. The weight/time curves are shown in Figure 8 & 9.

Altogether twenty specimen have been monitored, their individual codes consist of two indicators defining the material type and the pretreatment. They are explained in Table IV below:
Table IV: exposure specimen identification code

<table>
<thead>
<tr>
<th>First Code</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>BASF C/PEEK (Hybrid yarn)</td>
</tr>
<tr>
<td>PAS</td>
<td>Amoco C/PAS (Radel)</td>
</tr>
<tr>
<td>PPS</td>
<td>Phillips 66 C/PPS (Ryton)</td>
</tr>
<tr>
<td>LDF</td>
<td>Du Pont C/PEEK (LDF)</td>
</tr>
<tr>
<td>I</td>
<td>ICI C/PEEK (APC-2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Second Code</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Rubber pressed in a Cold mould</td>
</tr>
<tr>
<td>H</td>
<td>Rubber pressed in a Hot mould</td>
</tr>
</tbody>
</table>

The final saturation level is shown in Table V:

Table V: specimen saturation level

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>Saturation weight increase (%) Water</th>
<th>Skydrol</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH</td>
<td>0.157</td>
<td>0.070</td>
</tr>
<tr>
<td>BC</td>
<td>0.180</td>
<td>0.106</td>
</tr>
<tr>
<td>PASH</td>
<td>0.642</td>
<td>0.205</td>
</tr>
<tr>
<td>PASC</td>
<td>0.797</td>
<td>0.545</td>
</tr>
<tr>
<td>PPSH</td>
<td>0.028</td>
<td>0.043</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>Saturation weight increase (%) Water</th>
<th>Skydrol</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPSC</td>
<td>0.047</td>
<td>0.033</td>
</tr>
<tr>
<td>LDFH</td>
<td>0.600</td>
<td>0.273</td>
</tr>
<tr>
<td>LDFC</td>
<td>0.911</td>
<td>1.627</td>
</tr>
<tr>
<td>IH</td>
<td>0.159</td>
<td>0.062</td>
</tr>
<tr>
<td>IC</td>
<td>0.156</td>
<td>0.061</td>
</tr>
</tbody>
</table>

* Determined after 2,400 hours exposure - immersed in H₂O (distilled) at 70 °C / Skydrol 500B at RT.

The cold pressed (aluminium/rubber mould) specimen clearly show a higher saturation level than the specimen pressed in a hot mould. To our belief this is due to the rapid cool-down of the material hindering the smooth reconsolidation and allowing for the formation of voids. This has not yet been checked however by microscopic evaluation. LDF and PAS reach the highest values which can be explained by the amorphous nature of PAS (lower chemical resistance) and the typical behaviour of the LDF-material which tends to delaminate when heated without pressure. This frequently occurred during transportation of the material from the hot platen press to the rubber/aluminium mould.

A.3.3 Elevated temperature bending tests.

The testing temperature levels have been defined in Table II. The results are presented in Fig. 10 & 11. The first shows the bending modulus which has actually been measured while Fig. 11 depicts the values that have been obtained by relating each value to the original (room temperature) bending modulus - for each material individually. In that way a better comparison can be made between the materials with regard to the decrease of the modulus. The exact values are also presented in Table VI. The estimated standard deviation (Eq. 8) has also been added in this table to indicate the accuracy of the bending modulus. It clearly can be seen that the 250 °C values show a larger distribution. This was also due to the occasional premature failure of the specimen by local buckling and the tendency to a nonlinear force-deflection behaviour.
It should be pointed out that especially the aluminium and LDF specimen showed a dramatic decrease of the elasticity at 250 °C. The initial stiffness is still acceptable but the load required to achieve a 3 mm deflection is much lower. This can be checked in Table VII, giving the measured force at 3 mm deflection compared to the calculated force which is equal to m · 3 (m being the slope of the tangent to the initial straight-line portion of the load-deflection curve).

### Table VI: 4 point bending test results - Bending modulus at elevated temperatures

<table>
<thead>
<tr>
<th>Material</th>
<th>Tangent modulus of elasticity [GPa]</th>
<th>In brackets: estimated standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 °C</td>
<td>100 °C</td>
</tr>
<tr>
<td>C/PEEK (APC-2)</td>
<td>141.16 (3.92)</td>
<td>136.89 (4.32)</td>
</tr>
<tr>
<td>C/PAS</td>
<td>162.22 (3.15)</td>
<td>156.93 (2.99)</td>
</tr>
<tr>
<td>C/PPS</td>
<td>133.56 (2.63)</td>
<td>127.03 (5.95)</td>
</tr>
<tr>
<td>C/PEKK</td>
<td>129.51 (2.46)</td>
<td>123.46 (4.49)</td>
</tr>
<tr>
<td>C/PEEK (BASF)</td>
<td>116.47 (6.52)</td>
<td>118.41 (2.48)</td>
</tr>
<tr>
<td>Al (34364 T7351)</td>
<td>83.79 (0.00)</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table VII: Comparison of measured and calculated force to achieve 3 mm centre deflection.

<table>
<thead>
<tr>
<th>Material</th>
<th>Measured force at 3 mm deflection versus calculated force [kN]</th>
<th>In brackets: ratio of calculated to measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 °C</td>
<td>100 °C</td>
</tr>
<tr>
<td>C/PEEK (APC-2)</td>
<td>4.24-4.13 (0.98)</td>
<td>4.13-3.92 (0.95)</td>
</tr>
<tr>
<td>C/PAS</td>
<td>4.81-4.56 (0.95)</td>
<td>4.40-4.39 (1.00)</td>
</tr>
<tr>
<td>C/PPS</td>
<td>3.61-3.47 (0.96)</td>
<td>3.48-3.38 (0.97)</td>
</tr>
<tr>
<td>C/PEKK</td>
<td>4.74-4.54 (0.96)</td>
<td>4.42-4.34 (0.98)</td>
</tr>
<tr>
<td>C/PEEK (BASF)</td>
<td>3.26-3.15 (0.97)</td>
<td>3.12-3.01 (0.97)</td>
</tr>
<tr>
<td>Al (34364 T7351)</td>
<td>2.36-2.34 (0.99)</td>
<td>–</td>
</tr>
</tbody>
</table>

1) No significant stiffness left (Tg-PAS = 220 °C).
2) Not tested for lack of sufficient specimen.
3) Several specimen failed (local buckling) prior to reaching 3 mm displacement.
A.3.4 Rubber pressed - exposed specimen bending tests.

Finally the results of rubber pressing in a hot or cold mould and subsequently exposure to water or Skydrol have been combined in Fig. 12. Here also the values are related to the initial value. This value was obtained using the material consolidated according to the prescribed procedure. The codes used in this figure were already detailed in the test matrix [Table II]; for convenience they are briefly resumed hereafter:

- **Org** or **O** means original material,
- **CP** stands for pressed in a cold mould,
- **HP** thus denotes that the material was pressed in a hot mould,
- **S** and **W** indicate that the specimen were exposed to Skydrol and distilled water.

The exact values are presented in Table VIII together with the estimated standard deviation.

Table VIII: 4-point bending modulus of original, rubber pressed and exposed specimen

<table>
<thead>
<tr>
<th>Material</th>
<th>Original</th>
<th>Cold pressed</th>
<th>Hot pressed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>initial</td>
<td>Skydrol exposed</td>
</tr>
<tr>
<td>C/PEEK (APC-2)</td>
<td>141.16 (3.92)</td>
<td>122.35 (6.21)</td>
<td>140.98 (7.18)</td>
</tr>
<tr>
<td>C/PAS</td>
<td>162.22 (3.15)</td>
<td>146.11 (6.31)</td>
<td>148.57 (9.24)</td>
</tr>
<tr>
<td>C/PPS</td>
<td>133.56 (2.63)</td>
<td>128.82 (4.02)</td>
<td>129.25 (4.23)</td>
</tr>
<tr>
<td>C/PEKK</td>
<td>129.51 (2.46)</td>
<td>111.79 (6.82)</td>
<td>127.26 (5.06)</td>
</tr>
<tr>
<td>C/PEEK (BASF)</td>
<td>116.47 (6.52)</td>
<td>116.62 (6.14)</td>
<td>118.71 (2.53)</td>
</tr>
</tbody>
</table>

The exact values are presented in Table VIII together with the estimated standard deviation.

Figure 12 shows that no significant effect of the pressing and exposure conditions can be noticed in the values for the bending modulus. It should however be noted that not all values are absolutely reliable. This is indicated by the value of the estimated standard deviation displayed in the table above. Compared to the standard deviation values of the original material (Table VI) it is evident that the distribution has increased. This indicates that this type of processing does influence the material properties but only to a limited extent. Yet the influence of Skydrol was evident for both the C/PEKK and the C/PAS specimen. The compressive stresses on the upper side of the specimen caused local buckling and cracking of the top layers which had never occurred in any of the other tests. The hot pressed BASF specimen showed a considerable variation in the thickness along the length, rendering the test results not really reliable, also due to the limited number of available specimen.
A.3.5 Failure mode.

For each material the failure mode has also been determined. All specimen failed at the contact area with one of the loading noses. The failure mode was a combination of delamination (due to the in-plane shear) and fibre failure (due to the tensile/compressive stresses) except for the C/PAS. This material failed predominantly due to the shear loads and local buckling of the top layers underneath the loading noses. No tensile fibre failure occurred with C/PAS. The maximum tensile stress $\sigma_m$ at failure (Eq. 6) was of a magnitude of 1.2-1.5 Gpa for all materials, the maximum shear stress $\tau_m$ at failure (Eq. 7) than equalled 40-60 MPa.

As Hercules AS4 and Amoco T650-42 carbon fibre are quite comparable with regard to the maximum tensile failure strain, strength and modulus, the explanation very likely is to be found in the different resin properties. A change of the test set-up will enable a better quantitative qualification of the resins which has been omitted so far, due to the preliminary character of the tests and the Airbus test set-up. One additional exception should be made for the rubber pressed C/PEKK specimen which have been exposed to Skydrol. These specimen failed significantly unlike the others. The top layer usually delaminated, forming an oppositely curved layer in between the loading noses. The specimen consequently failed underneath one of the loading noses with parts of both the top and the bottom layers delaminating from the specimen. This probably is due to the delamination which frequently occurred during the processing as described in section A.3.1.

A.4 Test conclusions

The most important conclusion which can be drawn, looking at Figure 12, is that the processing history and the environmental exposure hardly influence the bending modulus, using the test configuration described in this chapter. The application of a heated mould tends to have a small beneficial effect over pressing in a cold mould.

Yet it should be noted that this test by no means is decisive for the behaviour of the structure itself as several important parameters are not included such as stress corrosion, fatigue, creep, buckling loads etc. The dual character of the failure mode should be precluded in a future test set-up in order to study the influence of the (re-)consolidation.

References


Cool down of Amoco C/PAS in hot mould (initial mould temp. 170°C, mat nr. 0)

Temperature (°C)

Time (s)

Position of thermocouple in the laminate

Top
Centre
Bottom

Thermocouple failure

Figure A.1
Cool down of Amoco C/PAS in cold mould
Rubber pressed specimen, 4 mm thickness

(Two thermocouples have failed)

Figure A.2

Position of thermocouple in the laminate:
- Top
- Centre
- Bottom
- Bottom
Cool down of Du Pont C/PEKK in hot mould
(initial mould temp. 135°C, mat. nr. 4)
Cool down of Phillips C/PPS in hot mould

(initial mould temp. 90 °C, mat nr. 3)
Cool down of Phillips C/PPS, cold mould
Rubber pressed specimen, 4 mm thickness

Temperature (°C) vs. Time (s)

Position of thermocouple in the laminate:
- Top
- Centre
- Bottom

(Specimen nr. 1)
Cool down of ICI C/PEEK in cold mould
Rubber pressed specimen, 4 mm thickness

(First thermocouple at top side has failed)
Cool down of ICI C/PEEK in hot mould
(initial mould temp. 150 °C, mat nr. 3)
Water absorption of CFRTP

(immersed in distilled water, 70 deg C)

- BH
- Δ BC
- Θ PASH
- + PASC
- ▲ PPSH
- ● PPSC
- ▼ LDFH
- ◊ LDFC
- □ IH
- ▼ IC

**Figure A.9**

Weight increase (%)

Time (hours)
Temperature effect on bending modulus
UD Carbon/TP and Aluminium

Modulus of elasticity in bending [GPa]

Temperature [°C]

PAS
APC-2
PPS
LDF
BASF
Alu

* = initial stiffness only, substantial decrease of elasticity
Temperature effect on bending modulus
UD Carbon/TP and Aluminium

Bending modulus (compared to RT-value)

Temperature [°C]

PAS
APC-2
PPS
LDF
BASF
Alu

* = Initial stiffness only, substantial decrease of elasticity
The diagram illustrates the influence of matrix type and processing on the bending modulus of UD-carbon specimens in a 4-point bending test. The bending modulus is compared to the original value for different materials and treatments. The material treatment codes are: Org, O/CP, O/HP, S/CP, S/HP, W/CP, and W/HP. Each bar represents different resin systems: APC2, PAS, PPS, LDF, and BASF. The asterisk (*) indicates an unreliable value due to a lack of sufficient specimen.

Figure A.12

Bending Modulus [compared to original]

<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Org</td>
<td>O/CP</td>
</tr>
<tr>
<td>O/HP</td>
<td>S/CP</td>
</tr>
<tr>
<td>S/HP</td>
<td>W/CP</td>
</tr>
<tr>
<td>W/HP</td>
<td></td>
</tr>
</tbody>
</table>

* = Unreliable value for lack of sufficient specimen
B Floor beam laminate calculations

B.1 Introduction

This appendix details the initial calculations that have been performed. These should provide a straightforward basic understanding of the mechanical behaviour. The design therefore was based on a prismatic slender U-shaped beam. The next assumptions thus should be taken into account:
- The laminate stresses and strains have been calculated using the Delft University computer program PLAMOR, based on the classical laminate theory [Ref. 1].
- The mechanical behaviour was modelled with the engineering bending theory [Ref. 2].
- The beam is loaded in shear and pure bending only; the transverse force thus acts through the shear centre. Torsional forces are assumed to be carried by the floor panels and the seat rails.
- Failure modes are either tensile, compressive or shear failure; buckling is not accounted for in the model.
- The two flanges have equal thicknesses and consist of the same laminate. The web is modelled as a flat plate without any cut-outs or local reinforcements.
- The outer dimensions are fixed: the height is 201 mm, the flange width 25 mm.
- The basic ply data are those of APC-2, unidirectional carbon fibre reinforced PEEK of ICI [Ref. 3]. The ply data are listed in Table I.

Several types of laminates have been calculated and put in a data file. The floor beam model, which will be described hereafter, was put in a Lotus 123 spreadsheet file together with the laminate data base. The programme (BEAMCALC - R. de Kok) requires the selection of two laminate types for the web and the flanges and a total thickness. Subsequently the stress distribution over the beam cross-section is calculated. These can be visualised by using the Lotus graph menu. The Azzi-Tsai-Hill failure criterium is used to calculate the laminate failure or rather the safety factor. This is detailed in section B.2.2.3.

<table>
<thead>
<tr>
<th>Strength properties</th>
<th>[GPa]</th>
<th>Stiffness properties</th>
<th>[GPa]</th>
<th>Strain properties</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{xx}$</td>
<td>2.13</td>
<td>$E_x$</td>
<td>134</td>
<td>$\epsilon_{xx}$</td>
<td>1.45</td>
</tr>
<tr>
<td>$S_{xx}$</td>
<td>-1.1</td>
<td>$E_y$</td>
<td>8.9</td>
<td>$\epsilon_{xx}$</td>
<td>-2.42</td>
</tr>
<tr>
<td>$S_{yy}$</td>
<td>0.08</td>
<td>$G_{xy}$</td>
<td>5.1</td>
<td>$\epsilon_{yy}$</td>
<td>1.00</td>
</tr>
<tr>
<td>$S_{yz}$</td>
<td>-0.18</td>
<td>$\nu_{xy}$</td>
<td>0.28</td>
<td>$\epsilon_{yz}$</td>
<td>-6.7</td>
</tr>
<tr>
<td>$S_{xy}$</td>
<td>0.3</td>
<td></td>
<td></td>
<td>$\gamma_{xy}$</td>
<td>17.2</td>
</tr>
</tbody>
</table>

Individual ply thickness 0.15 mm  Fibre volume fraction $v_f = 60 \%$
Specific weight $\rho = 1.6 \text{ g/cm}^3$.  

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B.2 Floor beam mechanics

This chapter will detail all the formulas that have been used to model the floor beam. As the stiffness of the web and the flange may differ the stiffness of the web will act as the reference stiffness to calculate the equivalent statical moments and moments of inertia as well as the equivalent centre of gravity. First the notations used in the formulas will be explained.

B.2.1 List of notations

UPPER CASE NOTATIONS

A  Area (length)^2
D  Transverse shear force
E  Young's modulus of elasticity
I  Moment of inertia of an area
M  Bending moment
S  Statical moment of the area

LOWER CASE NOTATIONS

l  Length
T  Thickness
u  Coordinate along the flange
v  Coordinate along the web
x,y  Coordinates with regard to the equivalent centre of gravity
x,g  Horizontal distance from the equivalent centre of gravity to the centre of the web
\sigma  Tensile or compressive stress
\tau  Shear stress

SUPERSCRIPTS

*  Equivalent value of the term (corrected for differences in local stiffness)

SUBSCRIPTS

f  Flange
w  Web
x,y  Value with respect to the axes through the equivalent centre of gravity
u,v  Local coordinate, denoting the length of a specific section
B.2.2 Analytical theory of the model

The \( \omega \)-profile used in this model is shown in Fig. 1. The height is fixed; \( l_w = 201 \text{ mm} \), the width is also fixed; \( l_f + t_w = 25 \text{ mm} \). The local coordinates \( u \) and \( v \) are used to calculate the shear stress distribution. The transverse shear force always acts through the shear centre (see section B.1). The XY-axes are shown in Fig. 2 and originate from the centre of gravity of the cross-section. Also shown is are the \( \bar{x}_{cg} \) & \( \bar{x}_{sw} \)-coordinates, defined as the horizontal distance from the vertical symmetry axis (\( y \)-axis) of the web. These will be used to calculate the first and second moments of the areas.

The value of \( \bar{x}_{cg} \) is calculated using Eq. 1:

\[
S_y = \int_A x A^* - \int_A (\bar{x}_{centre \ of \ gravity}) A^* = 0 \tag{1}
\]

This can be rewritten, using the given dimensions of the profile, yielding:

\[
\bar{x}_{cg} = \frac{2[(\frac{1}{2}f(l_f+t_w)^3) - (\frac{1}{2}t_w f(l_f+t_w))]}{2A_{flange} E_w + A_{web} E_f} \tag{2}
\]

The nominator consists of two terms with the first representing the statical moment of both flanges with respect to the left vertical boundary of the profile, the second accounts for shifting this \( y \)-axis to the centre of the web. The contribution of the web with respect to this \( y \)-axis of course will be equal to zero.

Now that the position of the equivalent centre of gravity is known the second moments of inertia \( I_{xx}^* \), \( I_{yy}^* \) and \( I_{xy}^* \) can be calculated with Eq. (3), (4) & (5):

\[
I_{xx}^* = \frac{1}{12}(l_w-2t_f)^2 t_w + 2\frac{1}{12}f f_f^3 + tf_f(\frac{1}{2}(l_w-2t_f))^2 \frac{E_f}{E_w} \tag{3}
\]

The first term gives the contribution of the web, the second term represents the contribution of the flanges (with a shifting term).

\[
I_{yy}^* = 2\frac{1}{12}f(l_f+t_f)^3 + (\frac{1}{2}(l_r+t_w) - \bar{x}_{cg})^2 f f_f(l_f+t_f) + \frac{1}{12}(l_w-2t_f)^3 + \bar{x}_{cg}^2 f_f(t_w-2t_f) \tag{4}
\]

In the previous equation the second moment of inertia of the flanges with regard to their own centre of gravity is calculated, followed by a term which results from shifting this axis to the \( y \)-axis through the equivalent centre of gravity of the whole profile. The third and fourth term similarly denote the contribution of the web.

Due to the symmetry Eq. 5 can be written as:

\[
I_{xy}^* = 0 \tag{5}
\]

Having determined these values the equation for the normal stress \( (\sigma_{xx}) \) distribution over the cross-section can be written, using Ref. 4 (no axial load nor temperature distribution and \( M_y = 0 \)).

The first equation for the web (Eq. 6) shows that the normal stress is proportional with the distance to the \( x \)-axis. The second equation gives the stress in the flanges (Eq. 7), where the stress is assumed to be constant (due to the small flange thickness-to-width ratio).

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\[
\sigma_{\text{web}} = \frac{M_x}{I_{xx}^w} \cdot y
\]  
(6)

\[
\sigma_{\text{flange}} = \frac{M_x}{I_{xx}^w} \left( \frac{1}{2} (l_w - 2t_f) \right) \frac{E_f}{E_w}
\]  
(7)

The shear stress distribution, due to the transverse shear force \( D_y \), is calculated using the method presented in Ref. 3. The transverse load is assumed to act through the shear centre. Two local coordinates are introduced: \( u \) for the upper flange and \( v \) for the web as shown in Fig. 1.

The shear stress as a function of \( u \) can be written as Eq. 8.

\[
\tau_u = \frac{D_y}{t_f} \frac{S_{xx}^*}{I_{xx}^w} = \frac{D_y}{t_f} \frac{1}{l_f} (l_w - t_f) u \frac{E_f}{E_w}
\]  
(8)

The shear stress at \( v \) can be calculated with Eq. 9.

\[
\tau_v = \frac{D_y}{t_w} \frac{S_{xx}^*}{I_{xx}^w} = \frac{D_y}{t_w} \left[ \frac{1}{2} (l_f + t_f) \frac{E_f}{E_w} - t_w \frac{1}{2} (l_w - 2t_f) \right]
\]  
(9)

Here the first term represents the equivalent statical moment of the upper flange, the second term accounts for the contribution of the part of the web with length \( v \).

The location of the shear centre now follows from the equilibrium of moments with respect to the centre of the web - Eq. 10.

\[
2 \frac{1}{2} (l_w - t_f) \int_{\text{flange}} \tau_u dA = D_y \bar{z}_{sc}
\]  
(10)

The shear stress in the web is a linear function of \( u \) and therefore this equation can easily be transformed to Eq. 11, using the relation \( l_f + t_w = 25 \) mm.

\[
\bar{z}_{sc} = - \frac{\frac{1}{2} (u - 25)(l_w - t_f)}{D_y}
\]  
(11)
B.2.3 Results and computer presentation

Some twelve different laminates, built up from 0°, 90° and ±45° plies, have been modelled in PLAMOR to determine the engineering constants \( E_x, E_y, G_{xy} \) and \( \nu_{xy} \). These materials were then fed into the Lotus spreadsheet programme BEAMCASIC to enable the stress distribution analysis over the cross-section of the \( u \)-profile. The basic laminate type for both the flanges and the web has to be specified together with an arbitrary multiplication factor determining the final profile dimensions. Two basic categories of floor beams should be discerned.

The first group consists of beams built up from one single type of laminate which can only be thicker at the flanges by repeatedly applying this laminate.

The second group, although it also comprises one type of laminate, contains additional unidirectional reinforcements in the flanges only to increase the bending stiffness. Both categories incorporate ±45° fibres in the flanges to decrease the shear-lag effect (the diminishing of the longitudinal stresses in the flanges due to shear strain). The 90° plies have been included to improve the buckling strength of the web. This failure mode is believed to determine the initial failure of the composite floor beam (see main report section 2.2.2). The transverse shear load and the bending moment were taken from the Deutsche Airbus load diagrams. A load of 16,000 N and a bending moment of 9,000 Nm have been applied, acting simultaneously on the cross-section.

The shear and tensile/compressive stress distribution over the cross section can be visualised in the spreadsheet. This is achieved by selecting the 'GRAPH', 'NAMES' and 'USE' options in the worksheet menu. The resulting maximum stresses that have been calculated are subsequently being fed back into the PLAMOR programme. These stresses are applied on the specified laminate to determine the stresses and strains in the individual plies. Furthermore, the Azzi-Tsai-Hill stress criterion (Eq. 12) has been applied to determine the safety factor for all laminates.

\[
\left( \frac{\sigma_x}{S_{x_{\text{max}}}} \right)^2 + \left( \frac{\sigma_y}{S_{y_{\text{max}}}} \right)^2 - \frac{\sigma_x \sigma_y}{S_{x_{\text{max}}}} + \left( \frac{\tau_{xy}}{S_{xy_{\text{max}}}} \right)^2 \leq 1
\]

(12)

In this formula either the maximum compressive or tensile stress has to be filled in, depending on the sign of the actual stress. These values are also listed in Table I. The safety factor is defined as the value by which the actual stress should be multiplied to reach the maximum combined stress limit. Two values thus can be obtained; one for tensile (positive) and one for compressive stresses (negative). The positive safety factor, calculated according to the prescribed procedure, is substantially reduced when 90° plies are applied. Transverse tensile failure of these plies however will hardly affect the mechanical behaviour of the floor beam and therefore this lower value is shown in between brackets only. Both categories of floor beams show the highest stresses at the junction between the flange and the web and failure is thus predicted to occur in that area, never due to shear at the midsection of the web.

The first results are presented in Table II & III.

These tables also present a very rough weight comparison between the composite beam and the original aluminium floor beam. The composite beam therefore is modelled as a prismatic, undisturbed 5.5 metre long part. The weight ratio is defined by Eq. 13 (with \( W_{Al} = 8.8 \) kg).

\[
\frac{W_{\text{APC-2}}}{W_{Al}} = \frac{A_{\text{cross-section}} \cdot 5.5m \cdot \rho_{\text{APC-2}}}{8.8} \cdot 100\%
\]

(13)
Finally the bending stiffness $EI_{xx}$ has also been compared to two important cross-sections of the aluminium floor beam. This also serves to get a first indication of the performance of the future beam. The two locations are listed below, together with the significant local dimensions.

1. At the support strut attachment:
   - $t_{\text{upper flange}}$: 7.3 mm
   - $t_{\text{lower flange}}$: 6.5 mm
   - $t_{\text{web}}$: 2.3 mm

2. Halfway the support and the middle (the most slender section):
   - $t_{\text{upper flange}}$: 2.6 mm
   - $t_{\text{lower flange}}$: 2.8 mm
   - $t_{\text{web}}$: 2.1 mm

References

1. PLAMOR - Computer programme for the analysis of plies and laminates. P. Stevens & A. Nijhof, Fibre Technology Department, Faculty of Mechanical Engineering, Delft University of Technology.


3. ICI Fiberite data sheets 1-7.

4. Aircraft Constructions II (in Dutch). Lecture notes (nr. 8503), Faculty of Aerospace Engineering (8-1983).
Table II  One basic laminate, different thicknesses.

<table>
<thead>
<tr>
<th>LAMINATE:</th>
<th>( t_{\text{flange}} ) [mm]</th>
<th>( t_{\text{web}} ) [mm]</th>
<th>( E_{I_{\text{APC-2}}}/E_{I_{\text{Al}}} ) [%]</th>
<th>( W_{\text{APC-2}}/W_{\text{Al}} ) [%]</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\pm 45/0]_{3s}) (t = 1.2 mm)</td>
<td>4.8</td>
<td>2.4</td>
<td>87 - 150</td>
<td>60</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>7.2</td>
<td>2.4</td>
<td>110 - 189</td>
<td>65</td>
<td>6.4</td>
</tr>
<tr>
<td>([\pm 45/0]_{3s}) (t = 2.1 mm)</td>
<td>2.1</td>
<td>2.1</td>
<td>50 - 85</td>
<td>47</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>2.1</td>
<td>68 - 118</td>
<td>52</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>2.1</td>
<td>87 - 150</td>
<td>57</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>4.2</td>
<td>96 - 163</td>
<td>93</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>8.4</td>
<td>2.1</td>
<td>105 - 180</td>
<td>62</td>
<td>6.1</td>
</tr>
<tr>
<td>([\pm 45/0]_{3s}) (t = 1.5 mm)</td>
<td>4.5</td>
<td>1.5</td>
<td>82 - 142</td>
<td>41</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
<td>3.0</td>
<td>123 - 211</td>
<td>74</td>
<td>7.1</td>
</tr>
<tr>
<td>([\pm 45/0]_{4l}) (t = 1.8 mm)</td>
<td>5.4</td>
<td>1.8</td>
<td>106 - 183</td>
<td>49</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>7.2</td>
<td>3.6</td>
<td>158 - 270</td>
<td>88</td>
<td>9.2</td>
</tr>
<tr>
<td>([\pm 45/90/0]_{4s}) (t = 2.1 mm)</td>
<td>4.2</td>
<td>2.1</td>
<td>88 - 150</td>
<td>52</td>
<td>5.2 (3.0)</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>2.1</td>
<td>112 - 190</td>
<td>57</td>
<td>6.6 (3.9)</td>
</tr>
<tr>
<td>([\pm 45/90/0]_{2s}) (t = 1.5 mm)</td>
<td>6.0</td>
<td>3.0</td>
<td>95 - 163</td>
<td>74</td>
<td>5.8 (3.3)</td>
</tr>
<tr>
<td>([\pm 45/90/0]_{3s}) (t = 1.8 mm)</td>
<td>5.4</td>
<td>1.8</td>
<td>88 - 151</td>
<td>49</td>
<td>5.2 (3.0)</td>
</tr>
<tr>
<td>([\pm 45/90/0]_{2s}) (t = 1.8 mm)</td>
<td>7.2</td>
<td>1.8</td>
<td>80 - 136</td>
<td>53</td>
<td>4.8 (2.8)</td>
</tr>
</tbody>
</table>

N.B. The small value for the safety factor in tension, in between brackets, corresponds with the 90° layer!
Table III  One basic laminate with additional UD-plies in the flanges

<table>
<thead>
<tr>
<th>LAMINATE</th>
<th>t_{flange} [mm]</th>
<th>t_{web} [mm]</th>
<th>E_{APC-2}/E_{Al} [%]</th>
<th>W_{APC-2}/W_{Al} [%]</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tension</td>
</tr>
<tr>
<td>flange: [0]</td>
<td>2.4</td>
<td>1.2</td>
<td>53 - 91</td>
<td>30</td>
<td>3.0</td>
</tr>
<tr>
<td>web : [+45]_6</td>
<td>3.0</td>
<td>1.2</td>
<td>65 - 111</td>
<td>31</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
<td>2.4</td>
<td>125 - 214</td>
<td>62</td>
<td>7.2</td>
</tr>
<tr>
<td>flange: [+45/0]_6</td>
<td>3.6</td>
<td>1.8</td>
<td>48 - 81</td>
<td>45</td>
<td>2.7</td>
</tr>
<tr>
<td>web : [+45]_6</td>
<td>4.8</td>
<td>2.4</td>
<td>62 - 107</td>
<td>60</td>
<td>3.5</td>
</tr>
<tr>
<td>flange: [+45/0]_6</td>
<td>2.4</td>
<td>1.8</td>
<td>48 - 82</td>
<td>42</td>
<td>2.6</td>
</tr>
<tr>
<td>web : [+45/0]_6</td>
<td>3.6</td>
<td>2.7</td>
<td>70 - 120</td>
<td>62</td>
<td>3.9</td>
</tr>
<tr>
<td>flange: [+45/0]_6</td>
<td>4.5</td>
<td>1.8</td>
<td>65 - 111</td>
<td>47</td>
<td>3.7</td>
</tr>
<tr>
<td>web : [+45]_6</td>
<td>3.0</td>
<td>1.8</td>
<td>60 - 102</td>
<td>43</td>
<td>3.3</td>
</tr>
<tr>
<td>flange: [+45/0]_6</td>
<td>4.5</td>
<td>2.7</td>
<td>87 - 150</td>
<td>64</td>
<td>4.9</td>
</tr>
<tr>
<td>web : [+45/0]_6</td>
<td>3.6</td>
<td>1.2</td>
<td>56 - 96</td>
<td>33</td>
<td>3.2</td>
</tr>
<tr>
<td>flange: [+45/0]_6</td>
<td>5.4</td>
<td>1.8</td>
<td>82 - 141</td>
<td>49</td>
<td>4.8</td>
</tr>
<tr>
<td>web : [+45/0]_6</td>
<td>3.6</td>
<td>1.8</td>
<td>71 - 122</td>
<td>45</td>
<td>4.0</td>
</tr>
<tr>
<td>flange: [+45/0]_6</td>
<td>5.4</td>
<td>2.7</td>
<td>104 - 178</td>
<td>66</td>
<td>5.9</td>
</tr>
<tr>
<td>web : [+45/90/0]_6</td>
<td>8.4</td>
<td>2.4</td>
<td>124 - 213</td>
<td>67</td>
<td>6.0 (4.4)</td>
</tr>
<tr>
<td>flange: [+45/90/0]_6</td>
<td>7.2</td>
<td>2.4</td>
<td>103 - 176</td>
<td>65</td>
<td>5.3 (3.6)</td>
</tr>
</tbody>
</table>

N.B. The small value for the safety factor in tension, in between brackets, corresponds with the 90° layer!
Figure B.1 Definition of floor beam cross-section dimensions

Figure B.2 Definition of XY-axes of the floor beam cross-section