THE DESIGN, MANUFACTURE AND TEST OF A TAPERED COMPOSITE I-BEAM

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SUMMARY: A tapered composite I-beam was designed, manufactured and tested in four-point bending. The intention was to produce a structural element representing a curved flange to web connection which would fail in delamination and which could be used to validate failure predictions from finite element analysis. The design process involved the construction of numerous finite element models investigating various geometries before the final design was reached. The specimen was manufactured using carbon fibre composite HTA/913C pre-preg and tested in four-point bending. Initial failure occurred by delamination in the area intended at a load slightly higher than that anticipated from the design process.

KEYWORDS: finite element analysis, beam, delamination, flange-web joint, doubly curved laminate.

INTRODUCTION

Load bearing structures in aircraft are commonly curved and can be required to carry large bending moments. The most efficient way of carrying a bending moment is to use an I-shaped section as it maximises the second moment of area whilst minimising the structural mass. When a straight I-beam is made from a laminated composite material, there can be regions of tight curvature around the web-flange interface which introduce interlaminar stress concentrations that would not affect a metal I-beam. If the composite beam is curved, then the laminate is doubly-curved which leads to a 3-dimensional interlaminar stress field. It is possible that such a structure would fail in an interlaminar mode, which is undesirable.

The flange-web joint is widely covered in the literature, with a significant amount of research involving the through-thickness failure of the composite due to out-of-plane loading. Shenoi and Hawkins [1] investigated how varying the geometry of a bonded 'Tee Connection' affects the stress distributions in the various components and then attempted to quantify failure using Tsai-Wu, but were unsuccessful due to a lack of material data. Cope and Pipes [2] varied the size and shape of the spar-wingskin joint in order to optimise the strength and weight of the design. They found that the failure could be reasonably well predicted by using Tsai-Wu and the Maximum Stress criteria. Paul et al [3] looked at various test specimens designed to simulate flange/web or flange/skin joints in co-cured structures. They concluded that there is a need for standardised test procedures for assessing the strength and mechanical properties of the joints analysed.

Investigations of curved I-beam designs are more difficult to find, however. Johnson and Swanson [4] produced a closed form solution for the bending of curved beams, giving strains and overall deflections. They also report the unusual effects of the flange opening, or radial distortion, due to the curvature of the beam. They do not, however, show the interlaminar stress concentrations in the beam and the possible effect that these may have on the overall performance of the structure.

THE SEMI-CURVED I-BEAM SPECIMEN

The manufacture of a fully curved composite I-beam was investigated using unidirectional pre-preg but it was found difficult to maintain correct ply orientation and avoid wrinkling of the plies. In order to get around these problems, the concept of a ‘semi-curved’ I-beam which restricted the curvature to a small region in the middle was investigated. It was found that much of the wrinkling was eliminated in the curved region which allowed more consistent manufacture and therefore should lead to less variability in the specimen.

A schematic of the beam is shown in Fig. 1, the shallow, curved region can be seen in the middle of the specimen. The design was produced in order to cause failure in the doubly curved laminates of the specimen due to the curvature of the bottom flange and the tapering depth of the beam. It was intended that these two features should combine to make the lower half of the curved, laminated C-sections have the highest interlaminar stresses and therefore to suffer delamination when tested.

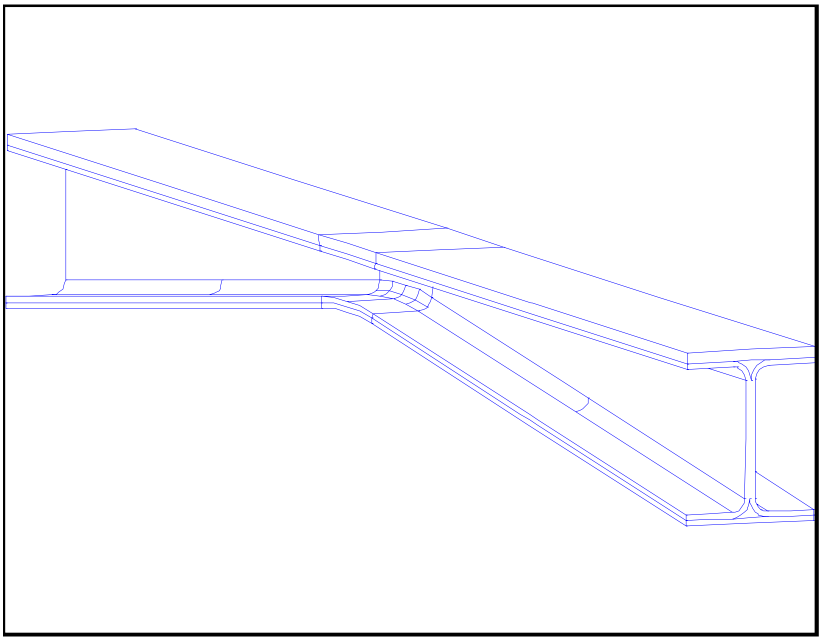

Figure 1 - Semi-Curved I-Beam Schematic

FINITE ELEMENT ANALYSIS

A number of finite element models were produced as part of this research, mainly for investigating different geometries of the semi-curved I-beam. I-DEAS Master Series [5] was used to create the 3D model meshes and ABAQUS Standard [6] was used to perform the stress analyses on those models. The material properties used in each case are detailed in

Table 1, the x-direction is the in-plane, the y-direction is transverse and the z-direction is interlaminar. The supplier [7] quotes the tensile modulus of HTA/913C in the fibre direction as 142GPa and the compressive modulus as 121GPa. It is common practice to use averaged properties when there are both tensile and compressive stresses in the fibre direction within a finite element model, so here 131.5GPa was used. This value was also used to calculate the 45° properties using laminated plate theory. The interlaminar properties of the pre-preg are from assumed transverse isotropy. All models were geometrically linear using parabolic brick elements with the designation C3D20R in ABAQUS Standard.

Material Property	HTA/913C 0°	HTA/913C 45°	HTA/913C 90°
E_x	131.5 GPa	17.2 GPa	9.2 GPa
E_y	9.2 GPa	17.2 GPa	131.5 GPa
E_z	9.2 GPa	9.2 GPa	9.2 GPa
ν_{xy}	0.3	0.766	0.021
ν_{xz}	0.3	0.114	0.45
ν_{yz}	0.45	0.114	0.3
G_{xy}	4.875 GPa	30.77 GPa	4.875 GPa
G_{xz}	4.875 GPa	3.9 GPa	3.103 GPa
G_{yz}	3.103 GPa	3.9 GPa	4.875 GPa

Table 1 - Material Properties for FEA Model

The local y-direction material axes in the I-beam model are shown in Fig. 2. The local x and 0° ply directions are longitudinal to the beam and z-direction perpendicular to y in the plane of the figure. There were approximately 4500 elements in the final model, most of which were concentrated in the doubly curved laminate. The mesh is relatively coarse and some elements are stretched, but it was believed that it was satisfactory for the design process.

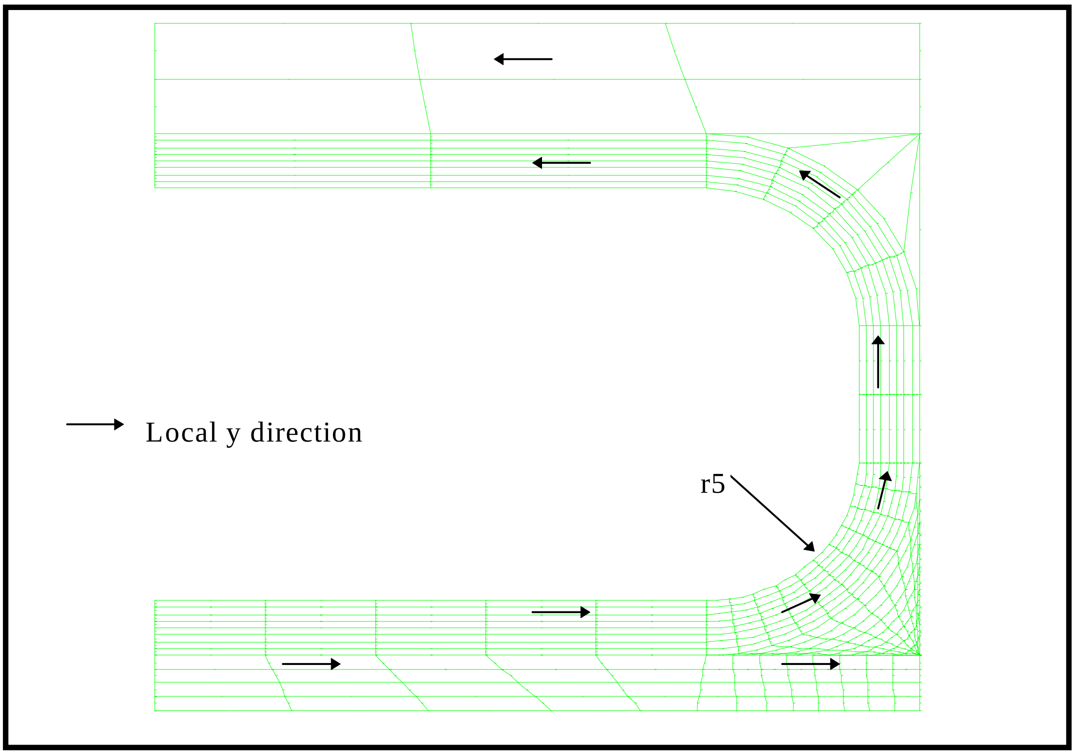

Fig.2 - I-Beam Model Material Orientation and Mesh

The top flange cap was composed of 32x0° plies (longitudinal to the beam) and, by assuming that each ply was 0.125mm thick, was modeled as a 4mm deep block. The curved bottom flange cap was made from 16x0° plies and was modeled as 2mm thick. The fill-in regions between the flange caps and the C-sections were filled with 0° tows. The tapered C-sections had a $[90°/\pm 45°]_{2S}$ lay up with each element representing 2 plies through the thickness of the laminate and having either 90° or 45° properties.

The test specimen was loaded in four point bending and this was simulated in the model. The boundary conditions imposed symmetry at the two centre-planes (right-hand edge and front surface) and a line of supports under the lower flange at 300mm from the centre-line. The load was applied downwards at one node in the web at a distance of 100mm from the centre. The models in this research had linear elastic material properties and linear geometric response.

FAILURE LOCATION ANALYSIS

This section concentrates on the stress levels in the centre of the model and the doubly curved laminates. Once the delamination location, mode and failure load were found, then other failure modes were checked, including web failure around the loading rollers.

A plot of the deformation of the section is included in Fig. 3. The 'opening' up of the lower flange is clearly visible, and it is this which leads to the bending in the doubly curved laminate. The resulting interlaminar stresses are shown in Figs. 4&5 for the above mesh and an applied load case equivalent to 20kN in the test.

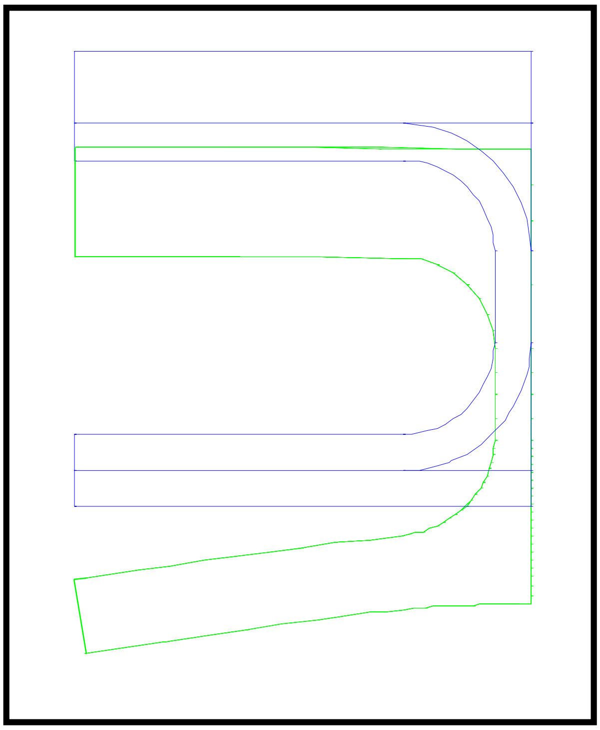

Fig. 3 : Deformation plot for semi-curved I-beam model

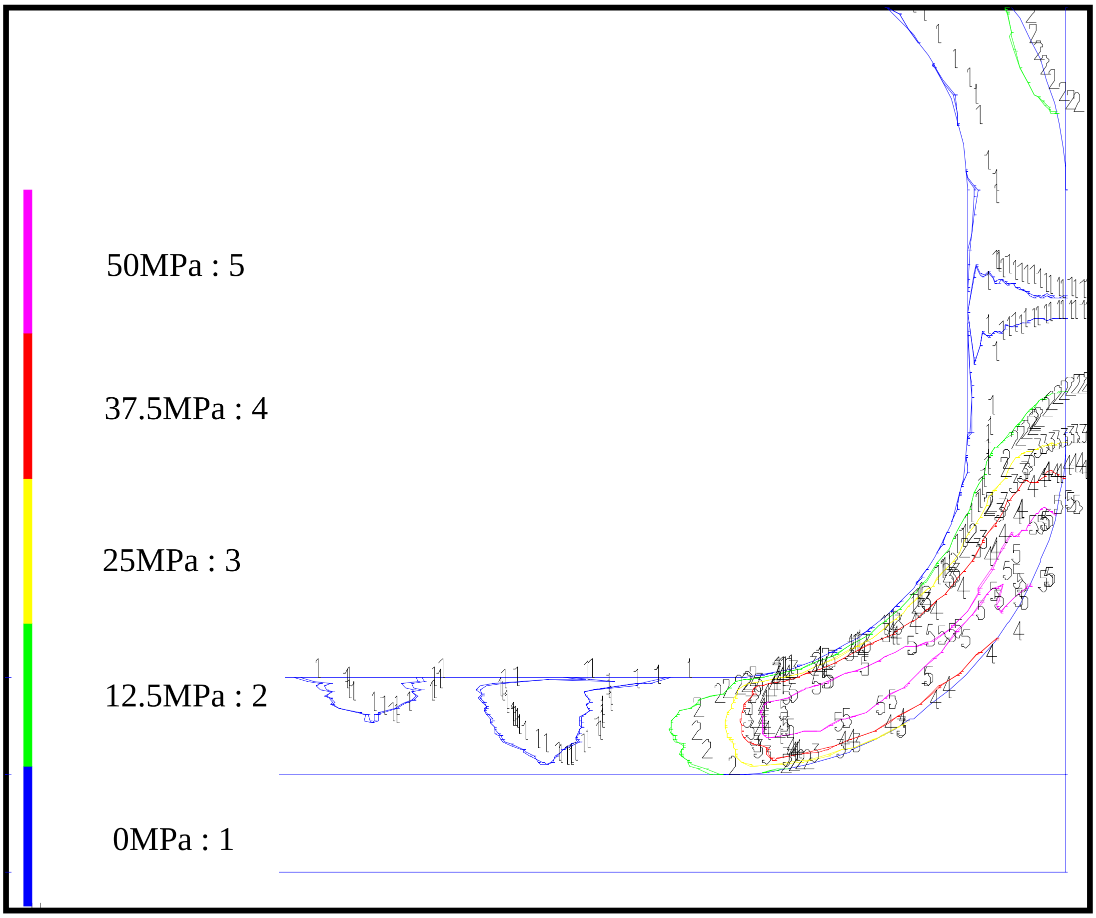

Fig. 4 : Interlaminar Tensile Stress in Region of Doubly Curved Laminate

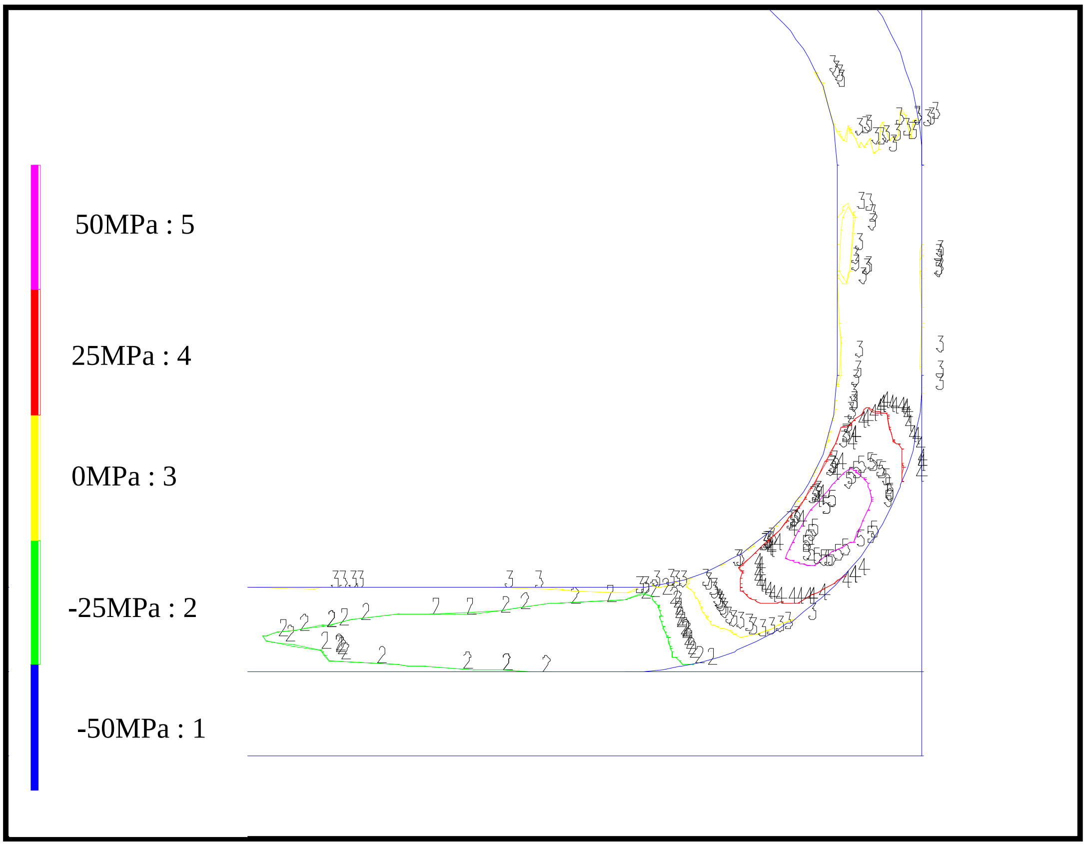

Fig. 5 : Interlaminar Shear Stress in Region of Doubly Curved Laminate

In order to optimize the design and achieve the target of delamination in the doubly curved laminates, two of the specimen dimensions were changed in the models. These were the web height in the centre and the flange width, the laminate curvature was set at 5mm radius and the radius of the curved section of the beam was fixed at 200mm because this was found to be the minimum possible for feasible manufacture. In order to simplify the design process, the lay-up of the C-sections ([90°/±45°]$_{2S}$) and the flange caps (0° longitudinal) were kept the same throughout. Each model had the same four-point bending load case applied and was analyzed for delamination in the doubly curved laminates. The objective was to maximize the interlaminar stresses in the model whilst trying to minimize the in-plane stress levels. Eqn 1 is based on the Tsai-Hill criterion and was used to make an initial prediction of the failure of a particular region of the section and was assessed in each element. The other interlaminar shear component was not used in the equation because the values were insignificant in the elements analyzed.

$$\left(\frac{\sigma_{ZZ}}{\sigma_0}\right)^2 + \left(\frac{\tau_{YZ}}{\tau_0}\right)^2 \geq 1 \qquad (1)$$

The material strength values were taken from unidirectional 16-ply interlaminar tensile and shear strength specimens tested using the same method as that used in Ref. 8. The values used here were $\sigma_0 = 114MPa$ and $\tau_0 = 102MPa$ and were chosen because the doubly curved laminates in the I-beam are 16 plies and should therefore have a similar strength.

Early on it was seen that the top flange was under high axial compression forces which were high enough to give concern over buckling failure. The decision was made to increase the flange cap thickness from 2 to 4mm and this eliminated the problem.

It was found that by reducing the web height and therefore the second moment of area of the I-beam the predicted delamination load also reduced. This was due to the increased bending stress acting in the flanges of the beam, leading to a higher flange opening moment acting at the doubly curved laminates.

As the flange width was increased, the interlaminar stresses increased. There is a constant force in the flange if the applied load is constant, the stress increase was due to the increase in moment arm with increasing flange width.

From these studies, the dimensions were chosen to be 40mm flange width and 25mm total beam depth in the centre. The Tsai-Hill method gave rise to a predicted failure load of around 19.5kN for the four-point bend test. None of the other stress or strain values in the centre of the specimen at this load caused concern and are not reported. The stress levels in the web between the rollers were of some concern, though. Despite the optimisation process, the required load for failure meant that there would be approximately 10kN applied at each roller. The shear stress in the 45° plies would be around 250MPa, above the quoted rail shear strength of 200MPa. This could obviously be reduced by making the specimen longer than the proposed 650mm and increasing the roller separation from 600mm, but the increase in required material and the loading rig size were seen to be prohibitive and it was decided, instead, to fill the section with aluminium powder filled epoxy underneath and between the rollers.

The nature of the specimen and the load case meant that there were three likely failure locations. The first was delamination in the doubly curved laminate, this was difficult to assess as it would be a mixed mode failure. The second was local crushing failure under the rollers which could also affect the web. The third was shear failure of the web in between the rollers.

In order to eliminate the web failures it was decided to fill the beam under and between the rollers. This should carry a significant portion of the load and therefore remove the possibility of web failure before delamination of the doubly curved section.

MANUFACTURE

The laying up process had to be carried out very carefully to avoid the wrinkling of the plies around the curved region of the C-sections. These $[90°_2/\pm45°]_{2S}$ laminates were laid up using unidirectional pre-preg (HTA/913C) over aluminium tooling machined to the shape and dimensions of the inside of the tapered C-sections. The laminates were consolidated under vacuum pressure every two plies which helped keep the plies flat and limited wrinkling.

Once completed, the two C-sections were butted together to form the basic I-section shape. At the top and bottom of the web there were two regions which required the insertion of 0° tows along the beam to fill them. Film adhesive was then applied (supported, AF-163-2K-0.06 lbs/ft^2 from 3M) to ensure a good bond with the precured flange caps. These were 32x0° plies for the flat top and 16x0° plies for the curved lower cap. The whole component was then cured in an autoclave at 120°C and 100p.s.i. for 1 hour, according to the manufacturers instructions. Once cured, the web was supported before testing using an epoxy resin filled with aluminium powder which was applied between the loading points.

TESTING

A diagram of the test specimen and the loading rollers are shown in Fig. 6. Testing was carried out on an Instron 1342 using a four-point bending rig. The distance between the outer rollers was 600mm and the distance between the inner rollers 200mm. The test was carried out under displacement control at a rate of 1mm/min. The specimen was loaded until a number of cracks were heard, indicating some damage in the structure. At this point, no overall structural degradation could be detected, either visibly or on the load-displacement plot.

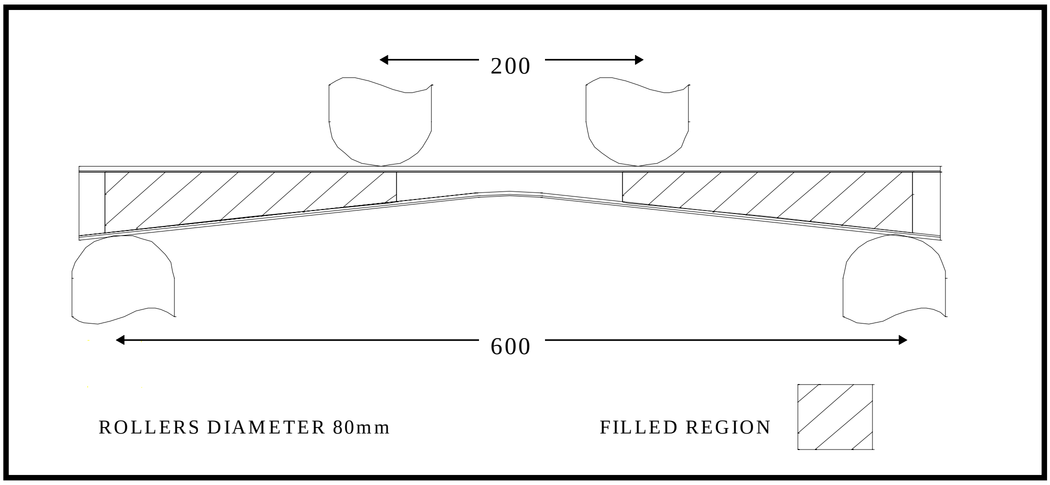

Fig. 6 : Specimen Test Arrangement

Eight strain gauges were fitted to the specimen at the longitudinal mid-plane in order to provide data for monitoring failure progression. During the test, only those on the lower flange indicated any discontinuities in their curves. The sense of these discontinuities were such that the lower flanges were clearly deforming more for the same load. The lack of overall structural degradation along with the strain gauge results was indicative of a series of small delaminations occurring within both of the doubly curved laminates.

The first of these delaminations occurred in the doubly curved laminate on one side of the beam at an applied load of 22.4kN, the next happened on the other side at a load of 24kN. The first test was terminated at 27.7kN where five delaminations could be detected on the strain gauge plots. The specimen was unloaded and examined for evidence of surface cracks, but none were found. It was decided that another test should be carried out on the specimen.

This second test was performed under the same conditions as the first, but this time the specimen was loaded to catastrophic failure. No evidence of further significant damage was detected before an applied load of 37kN where the specimen failed catastrophically, and a drop in load to around 13kN occurred. The lower flange cap had separated from the curved region of the lower flange taking the fill-in region and the first two 90° plies of the C-sections with it. This implies that the final failure occurred in the doubly curved region of the C-section and was initiated by a delamination.

Further examination of the specimen revealed that there were a number of delaminations in the doubly curved laminates. There was a great deal of damage which would have occurred at final failure, especially because of the large amount of energy released by the process.

The initial delamination estimate was around 13% conservative which is adequate, but could be improved upon using a more refined mesh and taking account of the stressed volume which has been shown to have a significant effect on interlaminar failure [8].

CONCLUSIONS

A specimen was designed with a curved flange to web interface which could be manufactured reliably from unidirectional pre-preg material. The structure was intended to fail by delamination in the doubly curved laminates at the flange-web interface and this was achieved during testing. The catastrophic failure of the specimen was initiated by further delamination and left the structure in two, largely intact, pieces.

Further testing of these semi-curved I-beam specimens will be carried out to check for consistency of manufacture and strength, full correlation with failure predictions from detailed finite element analysis can then be undertaken.

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