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This chapter presents a summary and conclusions of the investigations conducted in this work, and recommendations for further research. Test results for the redesigned, semi-circular, I-section frames fabricated from graphite-epoxy tape are presented in section 6.1. The test results of the textile composite, J-section frames are presented in Section 6.2. Recommendations for further research are presented in Section 6.3.

### **6.1 Results from the tests of the redesigned frames**

Existing, six-foot diameter, semi-circular I-section frames fabricated from graphite-epoxy tape are redesigned for improved energy absorption by using the computer code developed by Woodson (1994). Only the width of the flanges can be reduced in the design of these frames, even though the code can use ply angles as design variables as well. The design is constrained by a specified maximum load. Static tests of the three redesigned frames, labeled 2I-1, 5I-2, and 6I-2, are performed in a universal testing machine under displacement control. (See Table 1.1 on page 6 for detailed descriptions of the frames.) Frame 2I-3 tested by Moas et al. (1994) is nominally the same as frame 2I-1, and serves as a baseline frame test to assess the redesign of frame 2I-1. Test results show that failures due to fracture of the web and inner flange occur at the center of the frame ( $q = 0^\circ$ ) where the load is applied, and at about  $q = \pm 45^\circ$  at both sides. This failure sequence has been observed in previous tests conducted on similar frames by Moas (1996). The method of fabrication of these frames results in a weak interface between the cap plies and the chan-

nel plies of the radially inboard flange. See Fig. 1.4 on page 6. Delamination of the cap plies and the channel plies is evinced at these failure sites.

The tests results from the redesigned graphite-epoxy frames 2I-1, 5I-2, and 6I-2 show an improved energy absorption relative to their original counterparts when compared on the basis of the maximum specified load for the redesigned frames (see Table 2.2 on page 24). The mathematical model for the design and analysis of the frames predicts the correct sequence and location of failure events. However, the specified maximum design loads for the redesigned frames are exceeded in the tests. Hence, the mathematical model does not predict the correct magnitudes of the force and displacement at the first major failure event. The reason for this could be related to the limitations of the analysis. For example, the progressive failure analysis does not consider delamination, and delamination is observed in the tests. Delamination by itself may not be a catastrophic failure event, but it does cause a reduction in the cross-sectional stiffness which, in turn, causes stress re-distribution. This stress re-distribution at the site of delamination would effect subsequent failure events. Nor does the analysis consider the local load distribution due to contact, but models the load as a point force. If the load is modeled as a distribution over the contact region rather than a point force, then a less severe stress state is expected. In addition, the cross-section is assumed to be rigid in its own plane (no curling of the flanges), and the analysis is geometrically linear.

In summary, Woodson's computer code predicts correctly the failure sequence and locations, and the slope of the load-deflection curves for the static crush tests performed on frames laminated from graphite-epoxy tape. There is also an improvement in the energy absorption up to the first failure event of the redesigned frames with respect to the baseline (original) frames. Nevertheless, the magnitude of the load at the first major failure event of the redesigned frames remains at the same level as for the baseline frames.

## **6.2 Results from the tests of the textile composite frames**

The five frames, labeled as A, B, C, D, and CF6F, available for testing are the size of a typical circumferential fuselage frame for a wide body commercial transport aircraft. They are nominally forty-eight degree circular arcs with an inside radius of 118 inches, and a

depth of 4.8 inches. Refer to Table 4.1 on page 78 for detailed dimensional data. These frames are fabricated from 2X2 2D triaxial braided textile composite preforms coupled with the resin transfer molding (RTM) process using 3M PR500 epoxy resin. The architecture of the preforms is  $[0^{\circ}_{18k}/\pm 64^{\circ}_{6k}]$  39.7% axial, and the yarns are made of AS4 graphite fibers. Frames A, B, and C were selected for testing. Frame A is used to provide coupons for the material characterization tests presented in Chapter 3. Static tests under a radially inward load are conducted on frames B and C.

The coupons cut from frame A are subjected to tensile and three-point flexure tests to determine some of the effective moduli and strengths of the textile composite material. Material property data from the coupon tests are compared to data available in the literature and to analytical predictions using the computer code TEXCAD (Naik, 1994a; 1994b). The maximum strength obtained from the flexure tests are larger than the strength obtained from the tensile tests. These results agree with what has been found by other authors (Bullock, 1974; Whitney et al., 1974; Zweben et al., 1979; and Macander et al., 1986). From surface inspection of the tensile and flexure tests specimens after failure, it is noticed that fracture tends to follow the zigzag path of the braid yarns across the width of the coupon. The effective modulus of elasticity and the effective Poisson's ratio calculated for the representative unit cell (RUC) modeled in TEXCAD are in very good agreement with the coupon tests. Also, the tensile strength calculated by TEXCAD code is in closer agreement with the strength obtained from the flexure tests than from the strength obtained from the tensile tests. TEXCAD predicts a larger value of the tensile strength than the value obtained from the tensile tests. The reason for the disagreement with the tensile test is related to the fact that TEXCAD, like many other codes developed to analyze braided composites, assumes a completely straight axial yarn. However, it is observed from samples of the 2D triaxial braided material that the axial yarns crimp, and when crimping is accounted for in the analysis (Naik, 1994b) the predictions of the tensile strength improves.

Similar load-deflection curves are exhibited in the static tests of frames B and C. The largest circumferential strain magnitude is compressive and occurs in the outer flange at the apex ( $q = 0^{\circ}$ ). A compressive circumferential strain of approximately one-half this

maximum value occurs in the inner flange at the ends of the frame ( $q = \pm 21.4^\circ$ ). The largest tensile strains are much less than the largest compressive strain magnitudes. In addition to in-plane bending and circumferential compression, these asymmetric J-section frames exhibit out-of-plane bending and torsion. Both frames B and C initially fail near the apex of the frame where the displacement is applied (refer to Fig. 5.1 and Fig. 5.2 on page 94). Nevertheless, they differ slightly in the development of damage. Cracks develop in frame B in the outer flange and radially along the web at the apex ( $q = 0^\circ$ ), and in the inner flange at the ends ( $q = \pm 21.4^\circ$ ). The cracks in frame C develop at several locations: in the outer flange at  $q = 0^\circ, \pm 5^\circ$ , and  $-7^\circ$ , and in the inner flange and web at  $q = -5^\circ$ . No cracks are observed at the ends of frame C. The reason for these different failure locations could be related to defects in the composition of the braided material. There may be voids, resin rich zones and resin starved zones, that could influence crack initiation sites and crack paths. Even though the majority of the frame is subjected to compressive circumferential strains, the surface fractures tend to follow the  $\pm 64^\circ$  bias yarns in the zigzag pattern similar to what is observed in the tensile and flexure test coupons. Further inspection of frame C after the test reveals a crack at the junction of the web and outer flange extending circumferentially from  $-9^\circ$  to  $9^\circ$ . Over this same circumferential arc length, two parallel, circumferential fractures isolate a ligament of material at the center of the outer flange, with some of this material slightly protruding from the flange. See the photograph in Fig. 5.14 on page 104. This ligament of material appears to be a filler inserted into the surface of the outer flange just above the junction with the web. Evidence of out-of-plane bending, local bending, local buckling, and curling of the cross-section have been noticed from the response of strain gages. The strain data suggests that cross-sectional distortion is significant near the failure load.

A model using the computer code ABAQUS (1998) is developed to compare with the test results. The frame is modeled as a series of quadratic beam elements (B32OS). These elements have seven degrees of freedom at each end node: three displacements, three rotations, and an out-of plane warping degree of freedom. Element B32OS includes deformations due to transverse shear. The overall stiffness matrix of the RUC obtained from the computer code TEXCAD is used as input to ABAQUS code for the computation of the

cross-sectional stiffness matrix. The predictions of the ABAQUS model are in good agreement with the test results. Strains and displacements predicted from this model were very similar the values obtained in the tests. There is also good agreement in the initial slope of the load-deflection curve with the analytical prediction only about 3% larger than the test result.

In summary, the stiffness properties computed from the TEXCAD code for the 2x2 2D triaxial braided composite material are in good agreement with the coupon tests. In addition, the overall stiffness matrix of the RUC computed by the TEXCAD code is implemented in a simple braided composite frame model in ABAQUS. The ABAQUS analysis compares favorably to the test results as well.

Although 2D braiding is a ply on ply process, early studies indicate that a certain amount of nesting occurs between the plies, and tests show significant improvement in damage tolerance over tape laminates (Barrie and Skolnik, 1993). These studies are in agreement with what has been observed in the tests on tape layup composite frames and braided composite frames conducted for this research. In general, the fractures in the braided composite frames are more confined than in tape layup composite frames, where the fractures are accompanied by extensive delamination.

### **6.3 Recommendations for future research**

1. Implement a progressive failure model for the 2D triaxial braided textile composite material into Woodson's optimization and analysis code. Currently, the progressive failure model is for intralaminar failure of graphite epoxy tape.
2. Assess the influence of the load redistribution due to contact problem between the platen and the frame on the stresses in the frame. This maybe most easily implemented using the ABAQUS code since it contains contact algorithms.
3. Develop a branched shell model of the braided composite frames to allow for cross-sectional distortions. Include geometric nonlinearity to assess if crippling is occurring.