An experimental investigation of the biaxial strength of IM6/3501-6 carbon/epoxy cross-ply laminates using cruciform specimens

Jeffry S. Welsh*, Donald F. Adams

Composite Materials Research Group, Department of Mechanical Engineering, University of Wyoming, Laramie, WY 82071-3295, USA

Received 24 October 2001; accepted 6 February 2002

Abstract

Several variations of a thickness-tapered cruciform specimen have previously been used to experimentally determine the biaxial strength of an AS4/3501-6 carbon/epoxy cross-ply laminate. The present work represents a follow-up study of the original specimen design, and incorporates numerous specimen improvements made in an attempt to generate more accurate biaxial results. A total of 52 tests were performed at numerous biaxial stress ratios, utilizing six different specimen configurations. The experimental data generated in the present study for all specimen geometries, as well as a complete biaxial failure envelope in $\sigma_1-\sigma_2$ stress space for this laminate configuration, are presented. A desirable failure mode in the gage section of the specimen was achieved for all specimens tested in the present study, indicating that accurate biaxial stress states were being generated at ultimate specimen failure. The ability of the thickness-tapered cruciform specimen to determine the biaxial strength of composite materials at any stress ratio has been demonstrated. © 2002 Published by Elsevier Science Ltd.

Keywords: A. Laminates; B. Strength; D. Mechanical testing; Cruciform specimens

1. Introduction

One of the most frequently voiced concerns associated with the use of modern composite materials is the inability of researchers and designers to accurately predict the onset of failure under complex biaxial loading conditions [1–3]. A universally accepted failure theory for these nonhomogeneous and anisotropic materials has not been developed [1,2]. While this is certainly impeding the use of these advanced materials, it remains unclear how to best resolve this situation. At the present time there are numerous failure theories being proposed in the composites literature. Unfortunately, the various proponents of these failure theories have not had the opportunity to verify or modify their failure theories because of a lack of reliable biaxial experimental data. Test methods capable of generating these much-needed experimental data have not been well-developed [4–6].

If the goal of biaxial testing is to generate a failure envelope in $\sigma_1-\sigma_2$ stress space which can then be used by designers to predict the response of composite materials in structural applications, then a glaring omission is present in the current composites-related literature. This is the lack of a complete biaxial failure envelope. That is, a single study capable of generating experimental data in all three of the quadrants (T/T, T/C, and C/C), as required to produce a complete biaxial failure envelope in $\sigma_1-\sigma_2$ stress space, is difficult to find. Rather, most investigators have obtained results only in one or possibly two of the three quadrants [7–11], the most popular being T/T and T/C. Some investigators have suggested that reliable C/C biaxial data were not even available until 1990 [12], undoubtedly a consequence of stability issues pertaining to performing C/C tests. These are revealing statements about the difficulties associated with biaxial testing, and the shortcomings of the existing test methods.

In fact, most of the specific multiaxial test methods in use today to characterize the response of composite materials did not even exist fifteen years ago. As a result, there is considerable confusion as to what test procedures to use. The more recent recognition of the need for experimentally determining the multiaxial response of composite materials has led to the development of several new testing techniques. These testing techniques have been quite varied in the approach used to generate experimental results, and comparisons remain to be made. The effectiveness of these new test methods has been characterized by a variety of criteria [1], as will be discussed in the following paragraphs.

The first and most important criterion is the ability of
test method to accurately determine the property that is being sought. Unfortunately, the exact degree of accuracy is never known, as this would require knowledge of the true material property value prior to testing. Thus, the accuracy of a test method is reduced to a comparison with data which have been generated using other test methods, since a standard does not exist for biaxial testing of composite materials. That is, there is no single test method that has been generally accepted by the composites community as being superior to all others. For this reason, several additional indications of a successful test are frequently used [13–15]. These primary aspects include:

- The specimen gage section must be in a uniform stress state [1].
- Failure must occur in the gage section.
- Repeatable results must be obtained, frequently identified by mode of failure [2,7,16].
- It must be possible to determine the stress state without reliance on material stiffness properties [1].
- It must be possible to independently vary the biaxial stress components [1].

Other aspects of evaluating a test method include the simplicity of performing the test, and the expense and effort associated with both specimen and fixture fabrication [6,17]. It is desirable for the test specimens to be constructed from simple laminates with simple geometries, preferably from the same composite panel from which other mechanical properties are determined, as this minimizes preparation time, panel-to-panel variations, and expense. Additional procedures such as bonding tabs or machining to very close tolerances add even more expense, and introduce more variables to be controlled. Unfortunately, the complicated nature of multiaxial testing and the lack of reliable experimental data often dominates some of these concerns. That is, it is generally accepted that multiaxial testing will be a relatively expensive and difficult task to perform regardless of the particular test method being used. As a result, these criteria are often considered to be secondary when evaluating multiaxial test methods.

While these criteria are important when evaluating multiaxial test methods, the present authors believe that perhaps the most important criterion is whether the test method is capable of performing tests throughout the entire stress space. That is, a biaxial test method must be capable of testing all stress ratios in $\sigma_1 - \sigma_2$ stress space, since the goal is to generate a biaxial failure surface. The usefulness of multiaxial test methods that are only capable of producing partial failure surfaces is questioned.
Fig. 2. Detail of the original biaxial test specimen gage section.

2. Previous specimen configuration

Considering the numerous factors just described that must be considered when attempting to perform successful biaxial tests, the present authors decided to pursue testing cruciform specimens. Previous biaxial tests performed using an AS4/3501-6 carbon/epoxy cross-ply laminate by the authors [18,19] indicate the potential of using thickness-tapered cruciform specimens to successfully generate accurate experimental data. Schematic diagrams of the specific specimen configuration used in that prior study are repeated here as Figs. 1 and 2. While these tests are believed to have demonstrated the potential of this test method, the actual biaxial test specimen was not optimized. Acknowledging the complexity of thickness-tapered cruciform specimens, it is unrealistic to believe that the optimum configuration will be easily achieved.

Using the criteria described in the previous section to evaluate the performance of these tests, several possible improvements to the test specimen configuration were identified. Two wedge grip alignment holes in each arm were originally specified to provide precise alignment of the wedge grips with respect to the cruciform loading arms. The first improvement was to remove the inboard wedge grip alignment hole from each of the cruciform loading arms. Because the uniaxial stress in each loading arm is zero at the outboard edge, and increases to the maximum value at the inboard edge of each wedge grip, it was recommended that the inboard wedge grip alignment hole be deleted. The stress concentration surrounding the remaining hole is in a lower stress region of the loading arm, thus minimizing the possibility that undesirable failures will occur in the cruciform loading arms.

Another modification to the previous specimen design that the authors believed should be investigated involves the geometry of the cruciform loading arms. The performance of the biaxial test specimen could be improved by increasing the width of each loading arm to the full 31.8 mm (1.25 in.) capacity of the test fixture. This modification will lower the uniaxial stress state in each loading arm, again minimizing the possibility that undesirable failures will occur in the cruciform loading arms.

In addition, the width of each loading arm should then be tapered in the region between the end of each wedge grip and the gage section. This modification has several consequences. The first is that, depending on the amount of taper, the dimensions of the gage section will be significantly reduced. This is advantageous from many perspectives, including the fact that the maximum amount of force required to fail a specimen will be reduced. Most importantly, reducing the size of the gage section increases the effect of thickness-tapering the geometry. This increases the likelihood of failure occurring in the gage section, and increases the possibility that other laminate configurations can be successfully tested.

It was also recommended that specimens fabricated from
thicker laminates be tested, to increase the likelihood that failures occur in the gage section. Thirty-six-ply laminates, approximately 5.1 mm (0.20 in.) thick, were previously tested. The gage section thickness of these specimens was reduced to approximately 2.0 mm (0.08 in.), producing a stress riser of approximately 2.5 for most specimens. Maintaining the gage section thickness and increasing the thickness of the cruciform loading arms by using thicker parent laminates would increase this thickness ratio. Thus, the objective of the present study was to implement these specimen improvements in an attempt to improve the performance of the thickness-tapered cruciform specimens.

3. New specimen configurations

In addition to incorporating the modifications described in the previous section, two additional aspects of the thickness-tapered cruciform specimen were investigated in the present study. The first was the corner radius that joins two intersecting loading arms. Specimens manufactured for the present study contained either a 3.18 mm (0.125 in.) or a 6.35 mm (0.250 in.) radius fillet for this critical section of the specimen. The second involved the specific shape of the gage section. Because of the complex stress state generated in a thickness-tapered cruciform specimen, it was unclear whether a square or round gage section would produce more desirable results. For this reason, specimens were fabricated with both round and square gage sections, each having two specific sizes, referred to as large and small. Figs. 3–5 show the major geometric features of the specific thickness-tapered cruciform specimens used in the present study.

One aspect of the thickness-tapered cruciform specimen that was not altered from previous studies was the laminate configuration. Some investigators [2,6,20–22] believe that using cruciform specimens to determine the biaxial strength of laminated composites contains a fatal flaw as a result of biaxial strengthening effects as discussed in the following paragraph. While the present authors believe biaxial strengthening to be only slightly restrictive, we do believe that care should be demonstrated when selecting potential laminate configurations, and that thickness-tapered cruciform specimens have the ability to overcome this detrimental effect.

Biaxial strengthening refers to the fact that most laminated composites exhibit a higher failure strength under biaxial loading conditions compared to uniaxial loading. This phenomenon is easily identified by examining the shape of most biaxial failure surfaces generated by higher-order failure theories. In general, this shape can be described as an elliptical surface with the major axis along a 45° line between the first and third quadrants in $\sigma_1-\sigma_2$ stress space when plotted in standard rectangular coordinates. Using biaxial cruciform specimens, it is therefore reasonable to expect unacceptable failures to occur in one of the loading arms (which are loaded uniaxially) rather than in the biaxially loaded gage section. As previously mentioned, the authors encountered this unacceptable failure mode in
Fig. 4. Schematic drawing of the biaxial test specimen containing a (large) 6.35 mm (0.250 in.) corner fillet.

Fig. 5. Round and square gage section details for the thickness-tapered cruciform test specimens.
Table 1
Average biaxial ultimate strengths obtained by testing a [0/90]_{10s} IM6/3501-6 carbon/epoxy laminate—phase I (NA—not applicable)

<table>
<thead>
<tr>
<th>Stress ratio</th>
<th>Fillet radius</th>
<th>Gage section geometry</th>
<th>Area corr*</th>
<th>Ultimate (MPa)</th>
<th>Strength (ksi)</th>
<th>CV (%)</th>
<th>Ultimate (MPa)</th>
<th>Strength (ksi)</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/0</td>
<td>S&lt;sup&gt;b&lt;/sup&gt;</td>
<td>LS&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.84</td>
<td>594</td>
<td>86.2</td>
<td>3.2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>1/1</td>
<td>S&lt;sup&gt;b&lt;/sup&gt;</td>
<td>LS&lt;sup&gt;c&lt;/sup&gt;</td>
<td>NA</td>
<td>532</td>
<td>77.2</td>
<td>1.6</td>
<td>525</td>
<td>76.2</td>
<td>3.4</td>
</tr>
<tr>
<td>1/0</td>
<td>L&lt;sup&gt;d&lt;/sup&gt;</td>
<td>LS&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.84</td>
<td>595</td>
<td>86.3</td>
<td>7.9</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>1/1</td>
<td>L&lt;sup&gt;d&lt;/sup&gt;</td>
<td>LS&lt;sup&gt;c&lt;/sup&gt;</td>
<td>NA</td>
<td>522</td>
<td>75.7</td>
<td>2.0</td>
<td>532</td>
<td>77.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

* Area correction factor.
<sup>b</sup> Small (3.18 mm).
<sup>c</sup> Large square.
<sup>d</sup> Large (6.35 mm).

previous studies [18,19]. However, due to the low level of biaxial strengthening exhibited by cross-ply laminates as a result of their low in-plane Poisson’s response, it is believed that cross-ply laminates can be tested successfully using thickness-tapered cruciform specimens. For this reason, only cross-ply laminates were tested in the present study. It is anticipated that other laminate configurations can be successfully tested using this approach in future studies.

4. Experimental results

The number of specimens that would be required to generate complete failure envelopes for all possible geometric combinations is quite large. Because the fabrication of the specimens used in the present study is quite time consuming and expensive, the experimental test matrix used in the present study was broken down into three phases. By optimizing the test matrix, the number of specimens required to investigate these different geometric combinations was minimized. Complete laminate and specimen fabrication and testing procedures are described in Ref. [18], and will only briefly be described here.

Each laminate fabricated for the present study utilized conventional autoclave curing techniques including the use of two caul plates to ensure parallel laminate surfaces which eventually became loading surfaces. Each laminate was cured at 177 °C (350 °F) in accordance with the manufacturer’s recommendations. Each specimen was machined on a computer numeric controlled (CNC) milling machine adapted to guide a 20,000 rpm commercial router using carbide or diamond coated router bits. All specimens were tested at room temperature and negligible residual thermal stresses were neglected. A total of 52 biaxial [0/90]_{10s} IM6/3501-6 carbon/epoxy specimens were tested in the present study.

The objective of the first phase of testing was to determine which loading arm fillet geometry would produce the best results. A total of twelve thickness-tapered specimens (six specimens per configuration) were fabricated that utilized either a 3.18 mm (0.125 in.) or a 6.35 mm (0.250 in.) radius loading arm fillet and the large square gage section, as shown in Fig. 4. The specimens were then loaded in $\sigma_1 - \sigma_2$ stress space with either a 1/0 or 1/1 stress ratio. Although not a complete biaxial failure envelope, it was believed that these loading configurations would be sufficient to determine the overall effectiveness of the two loading arm geometries. Table 1 presents the average results for all [0/90]_{10s} IM6/3501-6 carbon/epoxy specimens tested in Phase I. Each average value shown in Table 1 was obtained by testing three specimens.

One of the most noticeable features of the data presented in Table 1 is that the data scatter is very low, the coefficient of variation values being typically less than 3.4%. There is little difference in the measured strength for specimens containing the large or small fillet radius at both the 1/0 and 1/1 stress ratios as the average measured strengths were approximately 594 MPa (86.2 ksi) and 527/528 MPa (76.5/76.6 ksi), respectively. It is worth noting that for a 1/1 stress ratio, the ultimate strengths in the x- and y-directions should be identical. Inspection of the data presented in Table 1 indicates that for both gage section geometries, this desirable result was achieved within reasonable data scatter. The measured area correction factor was 0.84 for both specimen geometries presented in Table 1. Because there were only minimal differences between the results of Table 1, it was arbitrarily decided that the large loading arm fillet (6.35 mm, i.e. 0.250 in.) should be used for the remainder of the tests performed in the present study.

The purpose of the uniaxially loaded tests shown in Table 1 was to determine the area correction factor that must be used when testing thickness-tapered cruciform specimens. Previous studies involving the use of cruciform specimens [18] indicated that determination of the actual stress in the gage section requires careful consideration. Because cruciform specimens contain loading arms that are common to two independent loading axes, it is possible for a significant portion of the applied force in each direction to bypass the gage section and be reacted by the material surrounding the gage section. While this situation is unavoidable using cruciform specimens, it is quantifiable.
Utilizing a single uniaxial strain gage placed in the center of the gage section, the actual stress level in the gage section of a thickness-tapered cruciform specimen was obtained by multiplying the indicated strain by the modulus of elasticity of the material being tested. To minimize extraneous variables during this procedure, the cruciform specimen was only tested in a uniaxial configuration, i.e., by loading one pair of opposing loading arms. The stress results generated using this configuration were then simultaneously compared to stress values obtained by dividing the applied force (average value of both opposing load cells) measured along a loading axis by the cross-sectional area of the thickness-tapered cruciform specimen gage section. A comparison of these two stress values quantifies the amount of load (as a percentage) that is bypassing the gage section of the cruciform specimen as the area correction factor. That is, the area correction factor is obtained by dividing the stress level determined from the strain measurement divided by the stress level determined from the applied force measurement. It should be noted that the motivation behind quantifying the area correction factor in terms of stress levels as described above is that it eliminates the need for strain instrumentation on all specimens, which would otherwise not be needed to determine the biaxial strength of a material. While this is a new data reduction approach, the authors have considerable confidence that it is an approach that accurately accounts for material nonlinearity and volumetric changes, which are both minimal for the material tested in the present study, that may occur during the progression of a biaxial test. This confidence is a product of the accurate results generated and documented in previous studies [23].

Once the area correction factor has been determined for each specimen configuration, the procedure to determine the actual stress level is simply to multiply the stress determined by the applied force of the load cells by the area correction factor. Obviously, any geometric modifications to the thickness-tapered cruciform specimen will require that a new area correction factor be determined. The area correction factor has already been applied to all experimental data presented in this paper.

The objective of the tests performed during Phase II of the present study was to investigate the effects of the gage section shape on the measured failure strengths. Specimens containing all four gage section geometries described in Fig. 5 were tested at three different load ratios during this phase of testing. All specimens contained a 6.35 mm (0.250 in.) radius loading arm fillet based on the Phase I results. Table 2 presents the average biaxial results for Phase II testing. Each average value shown in Table 2 was obtained by testing two individual specimens. Individual specimen fabrication and testing procedures are described in Ref. [18].

As expected, the data presented in Table 2 indicate that the specific geometry of the thickness-tapered cruciform gage section has an effect on the measured biaxial strength. Several factors must be considered when evaluating the data presented in Table 2 to determine which gage section geometry is the most desirable. One noticeable difference between the specimen groups shown in Table 2 is the area correction factor. The area correction factors were 0.69, 0.75, and 0.98 for the small square, small round, and large round gage section geometries, respectively. Recalling from Table 1, the area correction factor was 0.84 for the large square gage section. This range of values indicates that nearly all of the applied load (98%) can be directed through the gage section by using the large round gage section geometry. In contrast, an area correction factor of 0.69 for the small square gage section indicates that about 30% of
the applied load bypasses the gage section during a biaxial test. While the area correction factor is not considered to be a critical factor in determining the most desirable geometric configuration of a biaxial test specimen (as long as it can be accurately determined), the present authors are cautious to embrace values much lower than 0.69.

Another noticeable feature of the data presented in Table 2 is that individual test specimens tested at specific stress ratios generated reasonably consistent results, as indicated by the low CV values. Coefficient of variation values less than 5% have typically been difficult to achieve when experimentally determining the failure strength of composite materials [24, 25]. Although only two specimens were tested at each stress ratio shown in Table 2, the low CV values obtained is viewed as a confirmation of the quality of the specimen fabrication and testing techniques.

While the previous issues were considered when determining which of the gage section geometries tested in Phase II should be used in Phase III, the most consideration was given to the measured biaxial strengths. Noting that the primary objective of testing various gage section geometries was to experimentally investigate the effects of the stress concentrations caused by each, higher measured biaxial strengths were generally considered an indication of a more desirable test specimen geometry. That is, knowing that the result of stress concentrations located near the gage section is always lower measured strengths, higher measured strengths must then be an indication of less severe stress concentrations. With this in mind, it was determined that the small square gage section with the large (6.35 mm, i.e. 0.250 in.) radius loading arm fillet was the optimal configuration for the parameters considered in the present study. A review of the data presented in Table 2 indicates that the small square gage section generated higher biaxial strengths for nearly all stress ratios tested in Phase II.

The final phase of the present study was to utilize the results from Phases I and II to generate a complete biaxial failure envelope in $\sigma_1-\sigma_2$ stress space. The results of Phase I and II indicate that a thickness-tapered cruciform specimen incorporating a 6.35 mm (0.250 in.) radius loading arm fillet and a small square gage section was most desirable. Fig. 6 is a photograph of the gage section of a thickness-tapered cruciform specimen containing the 6.35 mm (0.250 in.) radius loading arm fillet and a small square gage section. The high quality of the specimen fabrication procedures used in the present study is evident from Fig. 6.

Nine different stress ratios were used in Phase III to completely describe the failure envelope in $\sigma_1-\sigma_2$ stress space, with three individual specimens tested at each stress ratio. Table 3 presents the average biaxial failure strength values obtained in the present study for Phase III. Because several individual specimens of the proper geometry had already been tested in Phase I and II, it was only necessary to test enough specimens at these

![Image](image.jpg)

Fig. 6. Photograph of a [0/90]_10 IM6/3501-6 carbon/epoxy biaxial test specimen gage section, prior to testing.

<table>
<thead>
<tr>
<th>Stress ratio</th>
<th>Fillet radius</th>
<th>Gage section geometry</th>
<th>Area corr(^a)</th>
<th>Average $x$-direction</th>
<th>Average $y$-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ultimate (MPa)</td>
<td>Strength (ksi)</td>
</tr>
<tr>
<td>1/1</td>
<td>L(^b)</td>
<td>SS(^c)</td>
<td>NA</td>
<td>607</td>
<td>88.1</td>
</tr>
<tr>
<td>2/1</td>
<td>L(^b)</td>
<td>SS(^c)</td>
<td>0.68</td>
<td>580</td>
<td>84.1</td>
</tr>
<tr>
<td>0/0</td>
<td>L(^b)</td>
<td>SS(^c)</td>
<td>NA</td>
<td>573</td>
<td>83.1</td>
</tr>
<tr>
<td>2/−1</td>
<td>L(^b)</td>
<td>SS(^c)</td>
<td>0.68</td>
<td>602</td>
<td>87.3</td>
</tr>
<tr>
<td>1/−1</td>
<td>L(^b)</td>
<td>SS(^c)</td>
<td>NA</td>
<td>487</td>
<td>70.7</td>
</tr>
<tr>
<td>1/−2</td>
<td>L(^b)</td>
<td>SS(^c)</td>
<td>NA</td>
<td>282</td>
<td>40.9</td>
</tr>
<tr>
<td>−1/0</td>
<td>L(^b)</td>
<td>SS(^c)</td>
<td>0.74</td>
<td>−508</td>
<td>−73.7</td>
</tr>
<tr>
<td>−1/−2</td>
<td>L(^b)</td>
<td>SS(^c)</td>
<td>NA</td>
<td>−322</td>
<td>−46.7</td>
</tr>
<tr>
<td>−1/−1</td>
<td>L(^b)</td>
<td>SS(^c)</td>
<td>NA</td>
<td>−531</td>
<td>−77.0</td>
</tr>
</tbody>
</table>

\(^a\) Area correction factor.

\(^b\) Large (6.35 mm).

\(^c\) Small square.
stress ratios so that each stress ratio had three individual test specimen results. The average values for all three individual specimens are repeated in Table 3 for completeness.

5. Discussion of experimental results

Although the data presented in Table 3 are useful in comparing average results obtained using specific ratios, it is difficult to interpret these data in tabular form when evaluating the overall material response in $\sigma_1-\sigma_2$ stress space. Therefore, Fig. 7 is a graphical representation of these data. One of the most noticeable features of the biaxial data presented in Fig. 7 is that the amount of scatter among the three specimens tested at a particular stress ratio was small for most stress ratios. With the exception of the $-1/1$ stress ratio, which exhibited failure strength differences as large as 18%, most stress ratio groups failed within 8% of each other. While data scatter values as high as 18% are undesirable, similar levels of scatter for biaxial tests of an AS4/3501-6 carbon/epoxy material system were obtained in prior studies for a quasi-isotropic laminate configuration [9,26]. The authors did expect slightly higher strength values for this material system at all stress ratios, and are unsure why even the uniaxial tension and compression strengths were unexpectedly low. However, it should be noted that each of the individual specimens failed very near the desired stress ratio, which is an indication of the accuracy of the loading apparatus.

One subtle feature of the data shown in Table 3 and Fig. 7 is that it represents a complete failure envelope in $\sigma_1-\sigma_2$ stress space. Noting by physical arguments that the experimental data can be mirrored across the axis of symmetry shown in Fig. 7, it can easily be seen that the response of this material system is completely described in $\sigma_1-\sigma_2$ stress space. It is difficult to find such complete data sets in the literature of biaxial testing [18]. In fact, the present authors believe this is the most complete biaxial data set generated to date for a single composite material system and laminate configuration. The fact that an entire biaxial failure envelope from T/T to C/C can be generated using a single specimen configuration is viewed as a significant advantage to testing thickness-tapered cruciform specimens. In addition, inspection of the data presented in Fig. 7 shows the minor biaxial strengthening effect associated with this material system and laminate configuration. A comparison of existing failure theories for composite materials and the data presented in Table 3 and Fig. 7 would be illustrative, but is outside the scope of the present study.

As previously discussed, one of the most critical aspects of testing any cruciform specimen is the location of the ultimate specimen failure. Noting that the only section of a cruciform specimen that is subjected to biaxial stresses is the gage section (where the loading arms intersect), failures must occur in this region to be considered a valid biaxial test. Specimen failures initiating anywhere else in the cruciform specimen, as encountered in previous studies [18,23], precludes any meaningful biaxial results from being generated. The authors are pleased to report that very desirable
failure modes were encountered in the present study. All of the specimen failures occurred in the gage section of the thickness-tapered cruciform specimens, regardless of the particular stress ratio being tested.

As examples, Figs. 8 and 9 are photographs of two individual thickness-tapered cruciform specimens that were tested to failure under a $-1/1$ stress ratio. As can be seen in these figures, the ultimate failure in both specimens is located diagonally (in both directions) from opposite loading arm fillets. The symmetry of the failure shown in these figures indicates that the specimen fabrication procedures as well as the testing procedures used in the present study are sufficiently accurate. Noting that the $-1/1$ stress ratio has historically been one of the most difficult biaxial tests to successfully perform, the failures shown in Figs. 8 and 9 are viewed as a strong confirmation of the present biaxial test method. While the exact influence of stress concentrations located near the gage section has not yet

been adequately defined, the fact that these specimens produced failures at the gage section represents a significant improvement over previous studies [18,23].

Further evidence of the desirable specimen failure modes encountered in the present study is offered as Fig. 10. As can be seen in Fig. 10, the post-failure analysis of this specimen indicates that a very symmetric failure (with respect to the laminate mid-plane) occurred for this, and almost all other, specimens. The symmetry of the failure shown in Fig. 10 is significant primarily because it indicates symmetric loading conditions were present at ultimate specimen failure. Had any unequal loading of any of the loading arms or out-of-plane bending moments been present at failure, it is unlikely that a symmetric failure mode would have been generated. Again, the desirable failure modes that were achieved in the present study are believed to be a strong confirmation of the specimen fabrication and testing procedures used.

5. Conclusions

Overall, the authors believe that the objectives for this study were met. The ultimate biaxial strength of an IM6/3501-6 cross-ply laminate was investigated by testing numerous thickness-tapered cruciform specimens. By altering the geometry of the cruciform specimens to determine the effect on the measured ultimate strength, it is believed that, while not yet optimized, significant improvements to the specimens have been made. Having all specimen failures occur in the specimen gage section, as in the present study, is rarely achieved when performing biaxial tests on composite materials. In addition, the excellent failure modes encountered provide further evidence that the desired biaxial stress states were achieved at failure using the thickness-tapered cruciform specimen geometry incorporating a 6.35 mm (0.250 in) radius loading arm fillet and a small
square gage section. Because of these results, along with the fact that a complete biaxial failure envelope was generated in $\sigma_1 - \sigma_2$ stress space using a single specimen geometry, the authors believe further investigation into the use of thickness-tapered cruciform specimens to determine the biaxial strength of composites materials is justified.

Acknowledgements

The authors are grateful for the continuing support of the Federal Aviation Administration, Office of Research and Technology Application, through FAA Grant No. 94-G-009. The technical direction and encouragement of Mr. Donald W. Oplinger, Technical Monitor, FAA Technical Center, is sincerely appreciated. The authors would also like to acknowledge the numerous contributions of CMRG staff members Scott Coguill, Ronda Coguill, Welby Peters, and James Green.

References
