COMPOSITE STRIPS WITH A CIRCULAR STRESS CONCENTRATION UNDER TENSION

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ABSTRACT

A series of tensile experiments were performed on S2 glass/toughened epoxy composite strips with a center hole or a pin joint at various temperatures within the range of -60^{o}C and 125^{o}C. Four different lay-up configurations each of 24 layers: [0°], [0°/90°], [45°/–45°] and [0°/45°/90°/–45°] and four different hole diameters: 1/8", 1/4", 3/8", 1/2" were used in both types of specimens. For certain configurations, strain gages were placed at locations around the hole to measure local strains. A loading-displacement curve was constructed for each configuration. The results indicate that the failure of the joints is significantly affected by stacking sequence, temperature, and hole size. The initial slope of the loading-displacement curve, i.e. the stiffness of the joint, increases with decreasing hole diameter or temperature. As expected, the [0°] specimens have the highest average stiffness and strength, whereas the [45°/-45°] specimens the lowest with the remaining configurations fall somewhere in between. The failure mode, on the other hand, depends only on the fiber orientation in an individual layer. Failure in [0°] layers is predominantly in shear-out mode whereas tension and shear failures are the main modes in [90°] and [±45°] layer, respectively. For the joint specimens, these average stiffness and strength also increase as the distance between the center of the pin joint and the free end of the strip decrease. Finally, a finite element failure model based on the Tsai-Wu tensor theory and progressive damage evolution was also developed. The results indicate that the failure model simulates the experimental data quite well.

INTRODUCTION

Use of composite materials is becoming widespread in U.S. Army applications. The future U.S. Army is required to be more mobile and lightweight. Thus, composite materials appear to be one of the best candidates to accomplish this goal. Several analyses have been developed for predicting failure strength and failure mode of composites with hole and joints [1-8]. The current project was designed to study the damage behavior of S2 glass/toughened epoxy composite strips and joints at room, elevated and low temperatures. In the earlier work [9-10], tensile and 3-point bending tests were conducted on composite specimens of various stacking sequences. In this study, the testing was extended to composite strips with a hole and joints. It was found that the temperature, stacking sequence and the size of the hole significantly affect the failure stress, stiffness and damage behavior of the composite. Also, it was determined that with the proper finite element model one can predict the location of failure initiation and damage progression.

In this project S2 glass/toughened epoxy composite strips with a hole and joints were tested at room, elevated (up to 125^{o}C) and low (up to -60^{o}C) temperatures in an MTS 810 Universal Testing Machine to determine their failure behavior. The composite strips and joints had various lay-up configurations, hole sizes, and hole locations. To determine the local strain field at critical locations (e.g. near hole boundary), strain gages were mounted to the composite strip specimens. The testing program was extensive. First, 24-ply composite strips with a hole were tested at room temperature. Four different hole sizes were used: .125", 0.25", 0.375" and 0.5". The testing was repeated on 4 lay-up configurations: $[0^{o}]_{24\text{-ply}}$, $[0^{o}_{2}/90^{o}_{2}]_{3s}$, $[+45^{o}_{2}/-45^{o}_{2}]_{3s}$ and $[0^{o}_{3}/+45^{o}_{3}/90^{o}_{3}/-45^{o}_{3}]_{s}$. On these specimens strain gages at strategic sites (around the hole) were mounted to measure the local strain. The tests were repeated at higher (75^{o}C, 125^{o}C) and lower (-20^{o}C, -60^{o}C) temperatures.

Next the same tests were repeated for composite joints, on all configurations (except 0.125" hole size) and again at high and low temperatures. Here another variable, namely the distance of the hole from the edge (H) was added. Two values of H were used: 0.75" 1.5". A vast amount of data was obtained during this study; only limited results are presented in this paper.

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THE MATERIALS AND SPECIMENS

The material used in this project was S2 glass/toughened epoxy composite. The fibers are S2 glass (round glass: 750ya/lb) and the matrix was a toughened epoxy resin (NCT-301). The composite was then manufactured, with a specified fiber volume fraction of 44%. For the testing two sets of composite strips were used: composite strips with a hole size: 0.125", 0.25", 0.375" and 0.5"; and composite joints with hole size: 0.25", 0.375" and 0.5". For the joints the distance from the center of the hole to the edge H was varied. For H, two values were used: 0.75" and 1.5". Figure 1 shows the typical composite strip with a center hole and the joint specimen set-up.

The composite joint was a double-lap joint with the lower strips made of steel to save on cost of composite and ensure failure of composite at the same location. The following four lay-up configurations were used for both composite strips with a hole and composite joints: $[0^o]_{24\text{-ply}}$, $[0^o{}_2/90^o{}_2]_{3s}$, $[+45^o{}_2/–45^o{}_2]_{3s}$ and $[0^o{}_3/+45^o{}_3/90^o{}_3/–45^o{}_3]_s$

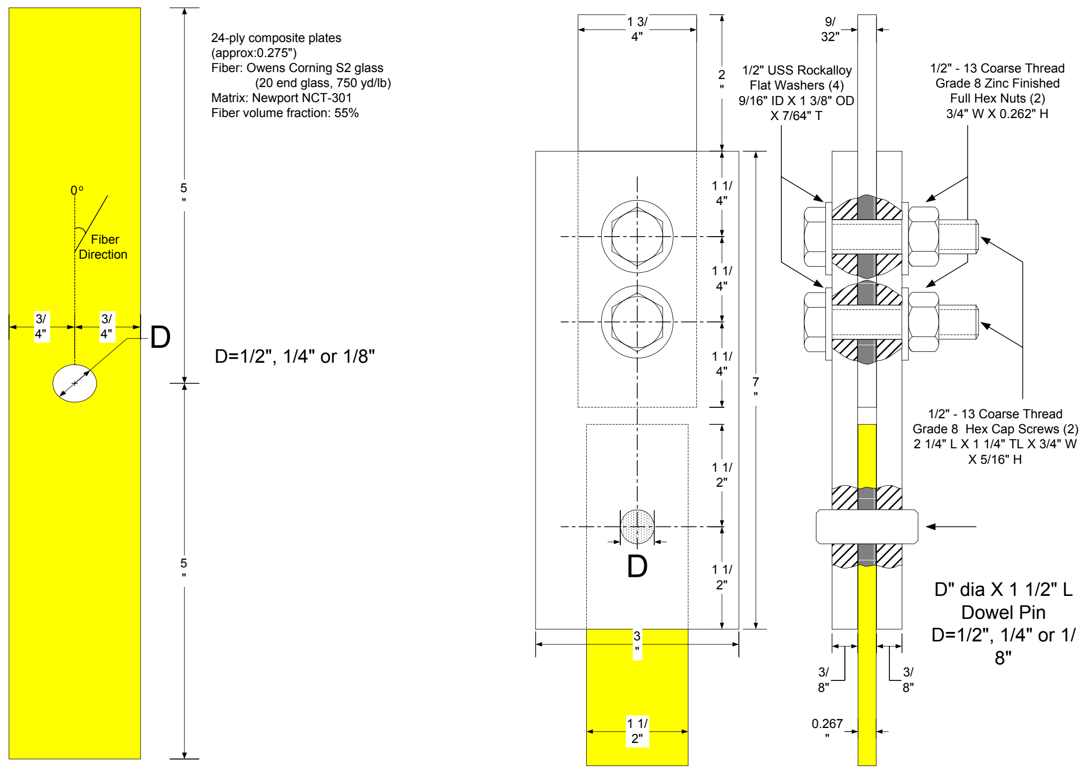


Figure 1. (a) Composite strip specimen with a center hole and (b) Joint specimen with metal-strip holdings.

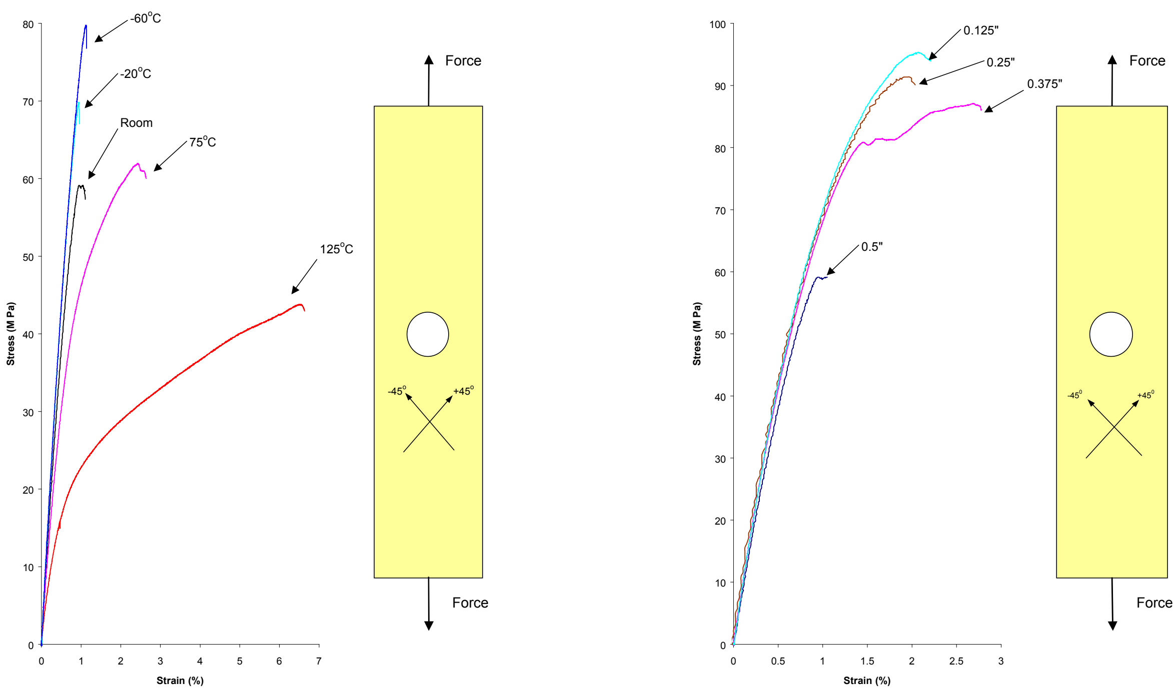
DESCRIPTION OF EXPERIMENTS

The composite strips with a hole with varying lay-up configurations were first tested in an MTS testing machine equipped with an environmental chamber. To determine the local strains and stresses at locations around the hole, strain gages were mounted on the specimens. Then the specimen was mounted on the MTS testing machine with a maximum pre-set displacement. The average strain was calculated by dividing the motion of the crosshead with the length of the specimens. The average stress was determined by dividing the corresponding force with the far field area. Specimens were loaded until failure. For each specimen a stress-strain curve was constructed. The tests were conducted at room 75^{o}C, 125^{o}C, –20^{o}C and –60^{o}C. For the high and low temperatures an environmental chamber was used. Each test was repeated for 3 or 4 specimens.

As for the composite joint testing, the procedure was similar to the testing of composite strips with a hole. However, in this case the composite joints were a double lap structure, where the lower strips were made of steel to save on the use of composite materials. Also no strain gages were used due to the concealment of the composite specimen between the metal-strip holdings. Again the stresses and the strains were calculated as in the previous case. Based on these values stress-strain curves were constructed.

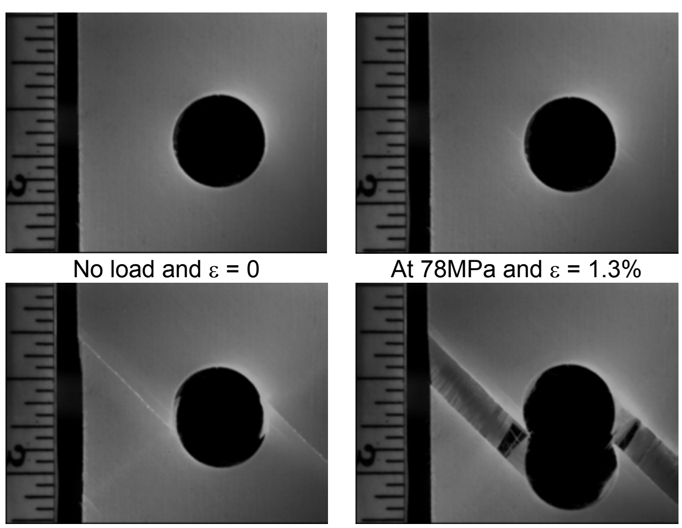
EXPERIMENTAL RESULTS AND DISCUSSIONS

For tensile testing of composite strips with a center hole in MTS, several parameters (such as temperature, hole size, stacking sequence) were varied; a vast amount of data was obtained. Figure 2(a) shows the effect of the hole size on the behavior of the $[+45^o{}_2/–45^o{}_2]_{3s}$ composite at room temperatures. The results indicate that the hole size has a significant effect on the failure stress and stiffness of the material. Both the failure stress and the stiffness increase with decreasing hole size. For example, the failure stress increases from approximately 60 MPa to 95 MPa as the hole size is decreased from 0.5” to 0.125”. Similar results also obtained for $[0^o{}_3/+45^o{}_3/90^o{}_3/-45^o{}_3]_s$ specimens. Figure 2(b) shows the effect of temperature on $[+45^o{}_2/-45^o{}_2]_{3s}$ laminates for the hole size (D=0.5”). The effect of temperature for other hole sizes is not shown in this paper. However, similar results were also obtained for other hole size specimens. The results indicate that as expected temperature has a very significant effect on both the failure stress and stiffness of the composite strips. Both the stiffness and the failure stress increase as the temperature decreases. The effect on stiffness is more pronounced at the higher temperatures than lower temperatures.



(a) (b)

Figure 2. The effects of (a) hole size on the behavior of the $[+45^o{}_2/-45^o{}_2]_{3s}$ composite at room temperatures, and (b) temperature on $[+45^o{}_2/-45^o{}_2]_{3s}$ laminates for the hole size (D=0.5”).



No load and $\varepsilon = 0$ At 78MPa and $\varepsilon = 1.3\%$

At 27MPa and $\varepsilon = 2.17\%$ At 0.71MPa and $\varepsilon = 6.96\%$

Figure 3. Tensile damage of $[+45^o{}_2/-45^o{}_2]_{3s}$ specimen with a center hole (D = 0.5”) at room temperature.

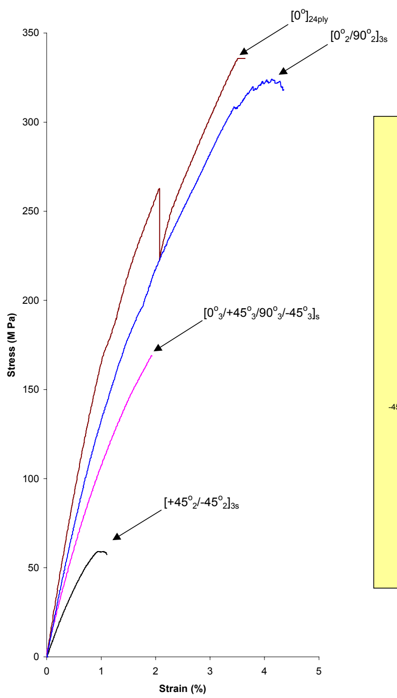


Figure 4. The effect of stacking sequence at room temperature with 0.5” diameter hole size under tensile loading.

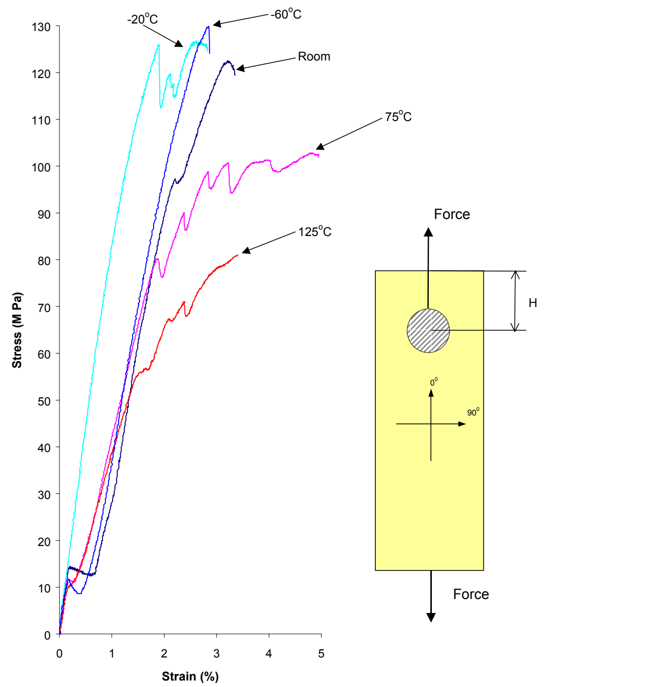
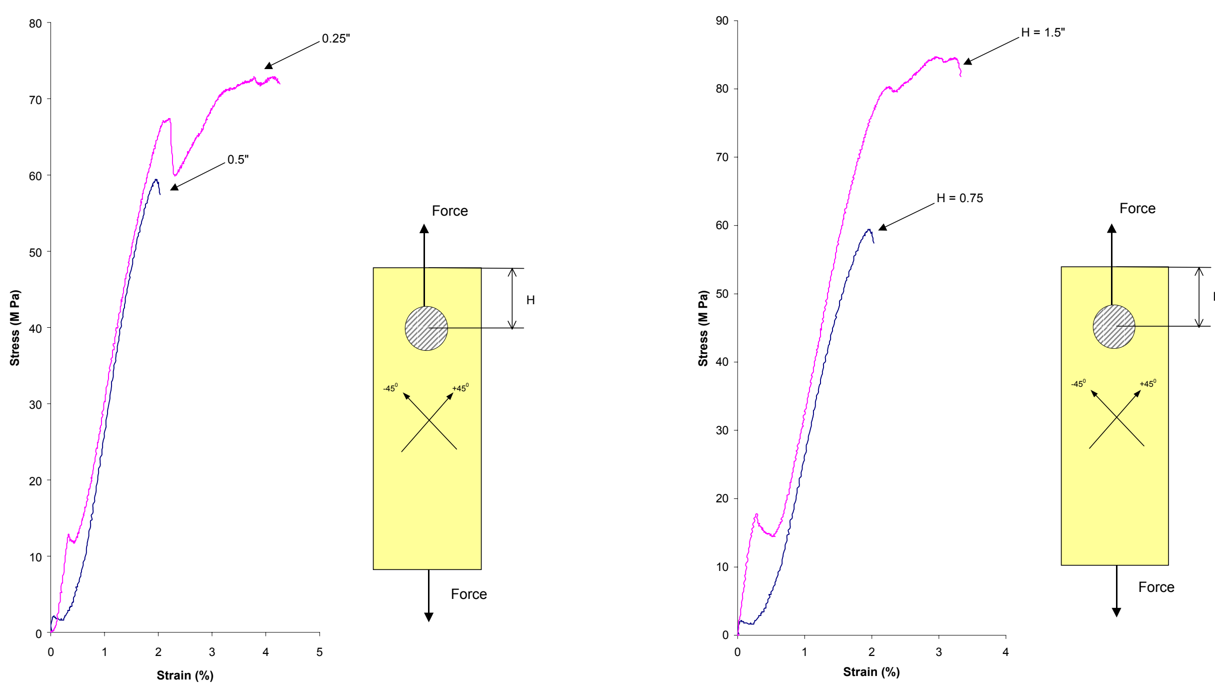


Figure 5. The effect of temperature on $0^{o}_{2}/90^{o}_{2}]_{3s}$ laminates (D=0.5” and H =1.5”).



(a) (b)

Figure 6. MTS Stress-Strain curve for $[+45^{o}_{2}/-45^{o}_{2}]_{3s}$ joint specimens with varying (a) hole size and (b) the H value under tensile loading at room temperature.

A series of pictures of damage progression had been taken during the testing. Figure 3 shows the tensile damage of $[+45^o_2/–45^o_2]_{3s}$ composite specimen with center hole (D=0.5") at room temperature. For $[0^o]_{24\text{-}ply}$ and $[0^o_2/90^o_2]_{3s}$ specimens only the room temperature testing were conducted, because at the other temperatures the specimens did not break. Finally, Fig. 4 shows the effect of stacking sequence at room temperature. It can be concluded that, again, both the failure stress and stiffness are affected by the stacking sequence. Usually the higher values occur at $[0^o]_{24\text{-}ply}$ and the lower values at $[+45^o_2/–45^o_2]_{3s}$ configurations, whereas the remaining configurations fall somewhere in between.

For tensile testing of composite joints, even more parameters were varied; an enormous amount of data was obtained. Limited figures are shown in this paper. Once more the composite joint strips had four different lay-up configurations: $[0^o]_{24\text{-}ply}$, $[0^o_2/90^o_2]_{3s}$, $[+45^o_2/–45^o_2]_{3s}$ and $[0^o_3/+45^o_3/90^o_3/–45^o_3]_s$ with hole size 0.25", 0.375" and 0.5". The distance from the hole center to the edge of the strip H, also was varied. Two values of H were used: 0.75" and 1.5". The tests were conducted at room temperature, 75°C, 125°C, –20°C and –60°C. Figure 5 indicates that temperature has a significant effect both on the failure stress and stiffness of the joint. It was observed that both the failure stress and the stiffness of the joint increase with decreasing temperature. And as the temperature increases the stress-strain curve becomes more and more non-linear. Again like results were also found for other configuration of the composite specimens. Figure 6(a) shows the effect of hole size on the stress-strain curve. For the example shown, $[+45^o_2/–45^o_2]_{3s}$, and H = 0.75", both the strength and the stiffness of the joint decrease with increasing hole size. Figure 6(b) depicts the effect of the hole distance from the edge of the strip on the stress-strain curve. Again the example shown, we can conclude that the strength and the stiffness of the joint decrease with increasing H.

FINITE ELEMENT MODEL

To explain and to simulate the observed behavior of S2 glass/toughened epoxy composite during testing a Finite Element model was developed, the ANSYS finite element commercial code was used. For $[+45^o_2/–45^o_2]_{3s}$ and $[0^o_3/+45^o_3/90^o_3/–45^o_3]_s$ specimens, a complete element mesh was needed to model for the finite element analysis. It was necessary for these two configurations due to the nature of the fiber orientation. For the remaining two configurations, a quarter of the model was used. Figure 7 shows the mesh for the $[+45^o_2/–45^o_2]_{3s}$ and $[0^o_3/+45^o_3/90^o_3/–45^o_3]_s$ specimens.

To predict the progress damage of the model, the ANSYS finite element commercial code and the Tsai-Wu criterion [6] were used. In the numerical analysis, a small displacement was provided, and then the resultant force was obtained. Figure 8 shows the comparison between the theoretical results and experimental data for four different configurations with a 0.5" diameter center hole. The results indicate that the failure model simulates the experimental data quite well. Figure 9 shows the damage patterns of $[0^o_3/+45^o_3/90^o_3/–45^o_3]_s$, in (a) 0° layer (average strain=1.2%) and (b) 90° layer (average strain=0.15%) specimens. In order to determent the failure mode for each layer, Tsai-Wu Criterion was adapted.

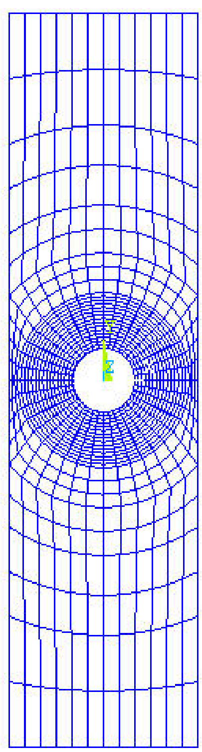
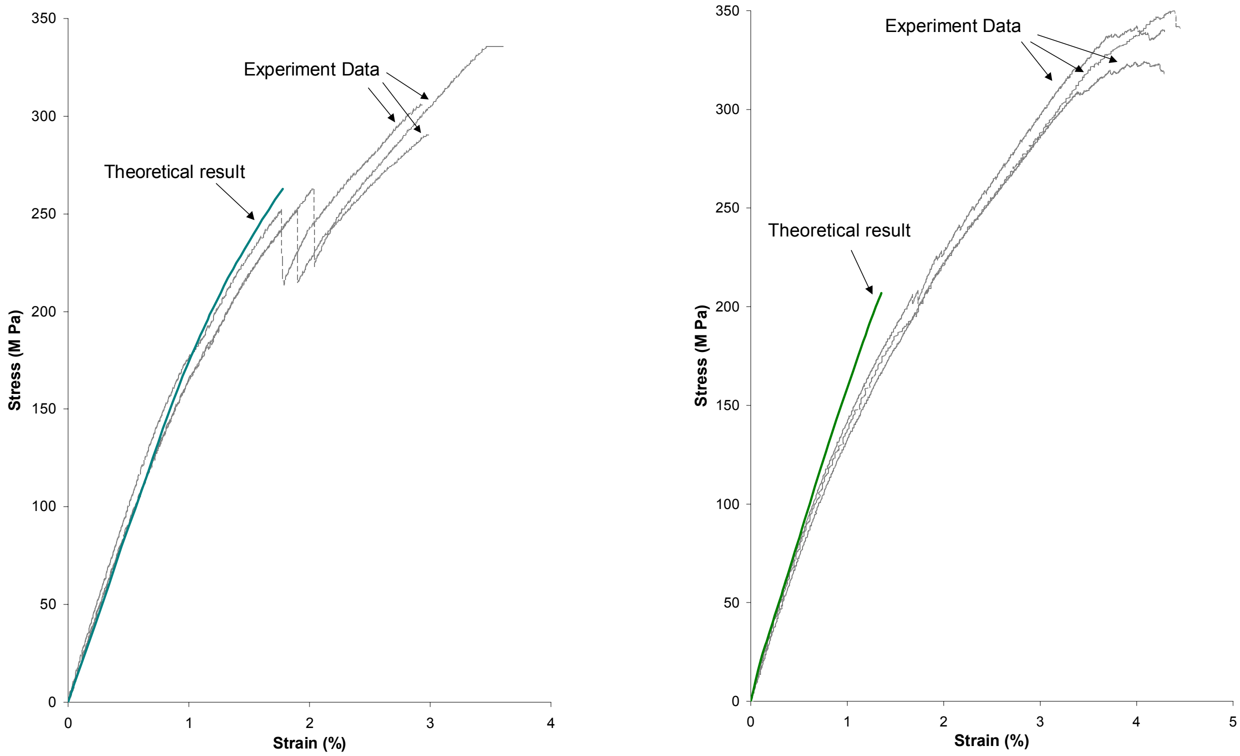
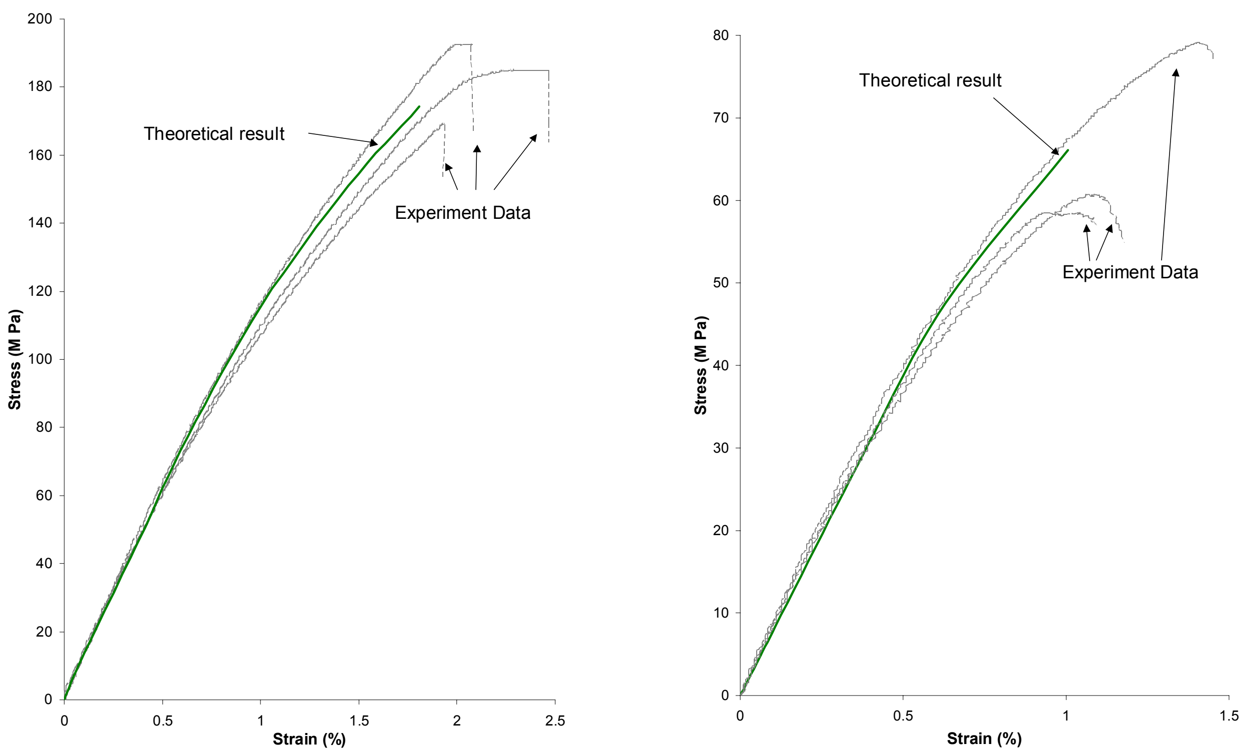


Figure 7. Mesh for the multidirectional and angle-ply composites.



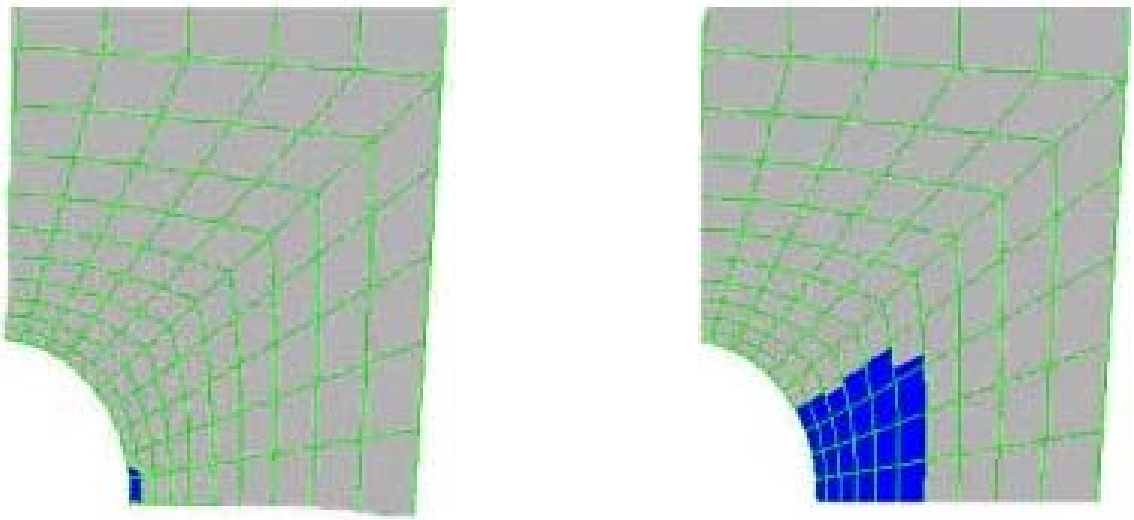
(a) (b)

Figure 8. Comparison between the theoretical results and experimental data for (a) $[0^o]_{24\text{-ply}}$, (b) $[0^o{}_2/90^o{}_2]_{3s}$ strips with a center hole (D=0.5”).



(c) (d)

Figure 8. Comparison between the theoretical results and experimental data for (c) $[0^o{}_3/+45^o{}_3/90^o{}_3/–45^o{}_3]_s$ and (d) $[+45^o{}_2/–45^o{}_2]_{3s}$ strips with a center hole (D=0.5”). (*continued*)



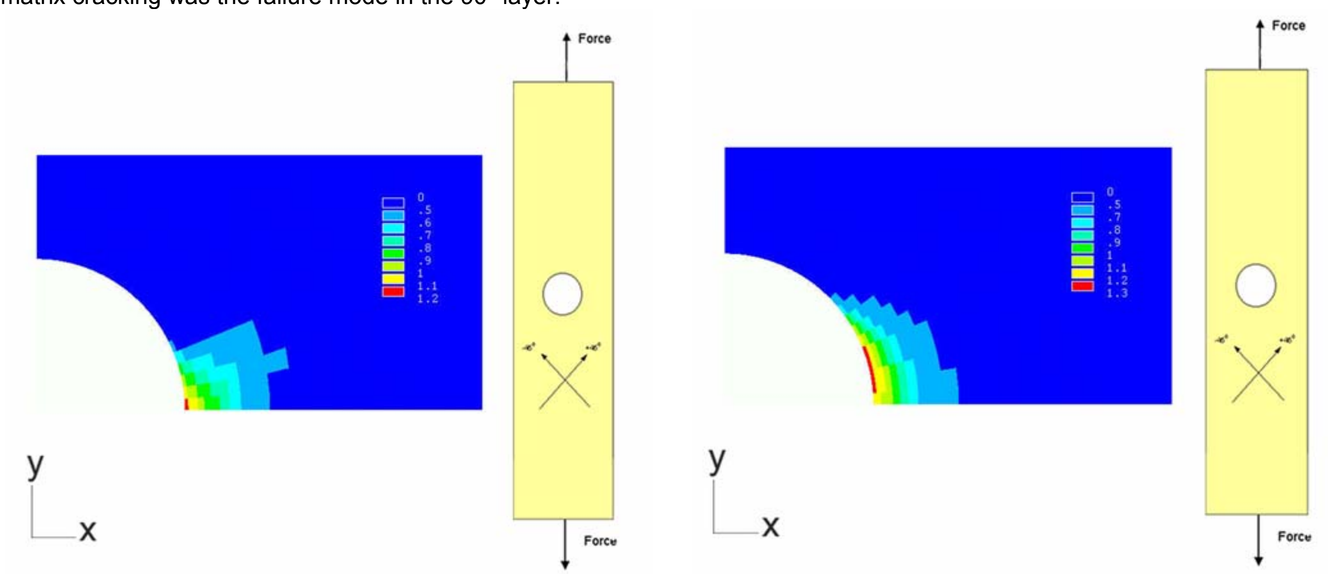
(a) (b)

Figure 9. Predicted damage pattern of $[0^o{}_3/+45^o{}_3/90^o{}_3/-45^o{}_3]_s$, in (a) 0^o layer (average strain=1.2%) and (b) 90^o layer (average strain=0.15%) specimens.

From Tsai-Wu Criterion,

$$\frac{\sigma_1^2}{XX'} + \sigma_1\left(\frac{1}{X} + \frac{1}{X'}\right) = e_f \qquad (1)$$

where σ_1 is the stress along the fiber direction, X and X^t are the tensile and compressive strength. If $e_f \geq 1$ (fiber breakage), $e_f \leq 1$ (matrix cracking). For 0^o layer, the X and X^t are assumed to be the same, and the stress σ_1, is obtained from the ANSYS result. The value of e_f was calculated and it was found that $e_f \geq 1$, therefore the layer was failed by fiber breakage. As for 90^o layer, the same scheme was used to obtain the failure mode of the layer. The e_f value was found less than 1, consequently matrix cracking was the failure mode in the 90^o layer.



(a) (b)

Figure 10. Value of the failure constant in (a) $+45^o$ and (b) -45^o layers for $[+45^o{}_2/-45^o{}_2]_{3s}$ composite strips (D=0.5", Average strain=0.33%).

Figure 10(a) shows the distribution of the stress components contours in the $[+45^o{}_2/-45^o{}_2]_{3s}$ composite strips for σ_x, σ_y, τ_{xy} in the $+45^o$ layers, while Fig. 10(b) shows the stress contours in the -45^o layers. Due to symmetry, only one quarter of the strip is shown. For each stress intensity a different color is used, with red the depicting the highest intensity for tensile stresses. The value of the failure constant is shown in Fig. 10 for various lay-up configurations, and strain level. For the failure constant a value larger than one indicates failure. From the figure one may conclude that failure may initiate from different locations on the hole boundary, and from different layer. For example, in Fig. 10 it can be seen that the direction for increasing value of the failure constant is approximately 45^{o}, which corresponds to the experimental failure direction.

CONCLUSIONS

The testing of composite strips with a hole and composite joints has provided extremely important information, which can be used in the design of such composite structures. It was observed that hole size, stacking sequence, temperature greatly affect the strength and stiffness of these composites. A finite element model to simulate the observed failure behavior in experiments has been developed using the ANSYS computer program.

The following conclusions can be drawn:

- The stress-strain curve is linear and then non-linear; the non-linear portion is due to damage in the composite
- The stacking sequence (lay-up configuration) significantly affects the strength and stiffness of the composites
- The stiffness of the strip increases with decreasing hole size
- The failure stress increases with decreasing hole size
- Temperature has a very significant effect on the strength and stiffness of a composite joint. In general, as the temperature increases, the strength and the stiffness of the joint are reduced. Also, the stress-strain curve becomes more non-linear
- Pin hole size also affects the strength and stiffness of the joint. Larger hole sizes, reduce both the strength and the stiffness.
- As expected, the distance of the hole from the edge of the strips also affects the behavior of the joint.
- Tsai-Wu tensor failure theory can be used to study the failure of composite strip with a hole, or composite joints. The location of failure initiation and direction of failure can be predicted using the Finite Element model.

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