Center for Composite Materials Research

FINAL REPORT

APPROACHES TO DESIGN AND EVALUATION OF SANDWICH COMPOSITES

By

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SUMMARY

This report describes research conducted under the grant NAG1-1956 during the period June 15, 1997 to October 31, 2000. This grant yielded a low cast manufacturing of composite sandwich structures technology and characterization interfacial and sub-interfacial cracks in foam core sandwich panels. The manufacturing technology is called the vacuum assisted resin transfer (VARTM). The VARTM is suitable for processing composite materials both at ambient and elevated temperatures and of unlimited component size. This technology has been successfully transferred to a small business fiber preform manufacturing company 3TEX located in Cary, North Carolina. The grant also supported one Ph.D, one M.S and a number of under graduate students, and nine publications and presentations.

INTRODUCTION

Composite sandwich structures have a number of advantages over the frame-stiffened metallic or composite structures. In addition to lightweight and high bending stiffness, they offer better torsion stiffness, excellent thermal and acoustic properties, sonic fatigue resistance, corrosion resistance, ballistic survivability, and lower cost. The improved core materials and co-cure processing almost eliminated the moisture and corrosion problems once plagued the applications of the sandwich composites. Currently sandwich composites are viewed as potential low cost technologies for manufacturing aircraft (F22 and joint fighter aircraft), ship structures, and sport equipment. During 70s through 90s sandwich composite structures were restricted because of moisture and corrosion problems. The damage tolerance technology of sandwich composites was not well established. For example, except the peel test (mode I), crack-lap shear (mode II) specimens, and recently, inclined beam specimen, there are no other proven fracture test specimens for sandwich composites. These problems are addressed in this research while developing a low cost manufacturing technology called vacuum assisted resin transfer (VARTM).

OBJECTIVES OF THE RESEARCH

Objectives of the research were:

1 Develop a vacuum assisted resin transfer molding processes capable of fabricating fiber reinforced composites at room as well as elevated temperature glass/vinyl ester and fabricate foam core sandwich panels.
2 Understand the interfacial problems that occur in co-cured sandwich panels
3 Develop a sandwich composite test specimen and test apparatus capable of simulating pure mode I, II, and combined I-II mode fracture. Then measure interfacial fracture tests under various states.

TECHNICAL APPROACH

The four objectives were accomplished through three tasks and they are:

1 Development of vacuum assisted resin transfer molding of sandwich panels.
2 Separation of energy release rate at interface and sub-interface cracks in sandwich panels
3 Measurement of fracture toughness of cracked foam core composite sandwich panels

RESEARCH ACCOMPLISHMENTS

Accomplishments made in of these tasks are summarized here and the details are presented in the Appendices.

Task 1: Development of vacuum assisted resin transfer molding of sandwich panels

Resin transfer molding (RTM) has been established as a cost efficient method for large volume production of high-performance composite components. High pressure and temperature and the matched tooling preclude RTM's use for large or one-of-a-kind components. Vacuum assisted resin transfer molding alleviates these cost concerns and can be used to fabricate large size components of acceptable quality where specific dimensional tolerances are not critical. The VARTM process is highly suitable for civil aviation aircraft, ship structures, automotive, and civil infra-structural applications. The basic principals of VARTM are described in Fig.1.

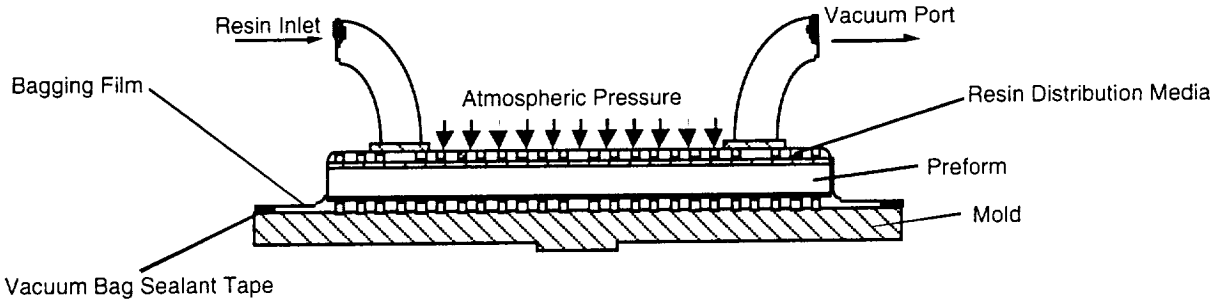

Fig. 1 Salient features of VARTM process.

The VARTM process employs room-temperature curable resins and vacuum pressure. In this research, a table-top (3'x2' component size) VARTM processing facility was developed which has the functionality to operate at room-temperature as well as elevated temperatures up to 300_ F. Electric strip-heaters in the base in combination with a heating blanket provide the elevated temperature capability. A programmable (PID) controller allows the reproduction and automation of necessary cure cycles. The complete setup is shown in Fig 2. The critical elements in the process are the carrier cloth, resin viscosity, and temperature control. Laminated panels of woven E-glass/vinyl ester (BGF 2532/Derakane 411-350) and carbon/vinyl ester (Fiberite W-5-322/Derakane 411-350) were successfully processed. A sandwich panel with face-sheets of glass/vinyl ester (BGF 2532/Derakane 411-350) and a PVC (DIAB H130) foam core was also fabricated.

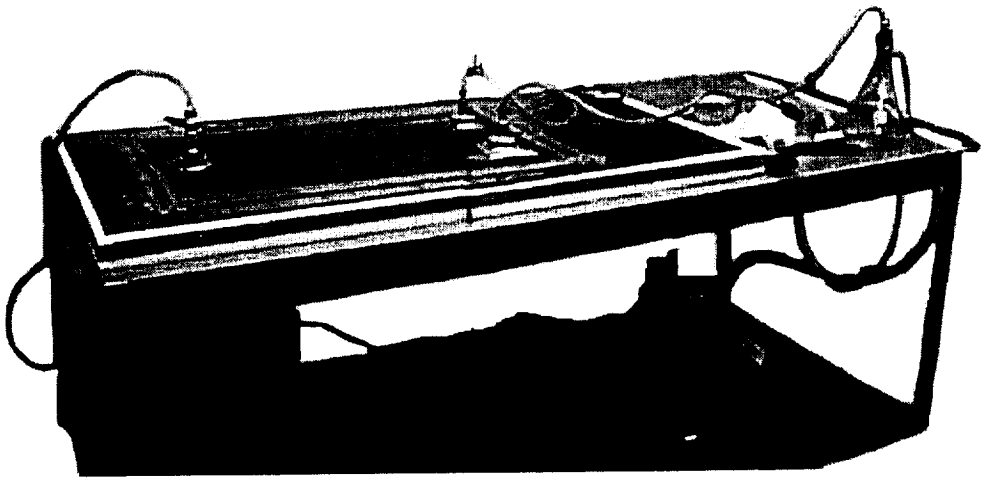

Fig. 2 Table-top setup of VARTM for RT and ET process

Fiber volumes for the glass and carbon laminates were determined to be 42% and 50%, respectively. Measured Tensile, Compression and in-plane Shear properties are listed in table. The glass values are in close agreement with those reported in literature. The low fiber volume can be attributed to the plain-weave architecture of the fabrics used. Fiber volume can be improved through the use of heavy woven roving or satin woven fabrics. Details of the process are presented in reference 1 and in Appendix A.

	Vinyl ester composite	
Fiber	E-glass	Carbon
Tensile		
Modulus, Msi	3.34	7.00
Poisson ratio	0.11	0.05
Strength, ksi	47.1	63.4
Compression		
Strength, ksi	51.6	38.0
Shear		
Modulus, Msi	0.58	0.51
Strength, ksi	12.2	11.2

Sandwich panels of different fabrics and core were produced using the tabletop VARTM facility. These panels were tested to measure mixed-mode fracture toughness. Results are in references 1 and 2 and in Appendices A and B.

Task 2: Separation of energy release rate at interface and sub-interface cracks in sandwich panels

A Classic problem of interfacial crack in a bi-material panels have been exhaustively studied in literature, yet no simple solution exists that provide guidelines to separate the energy release rates (G) at the crack tip. The mismatch of Poisson's ratio and/or the shear modulus across the cracked interface

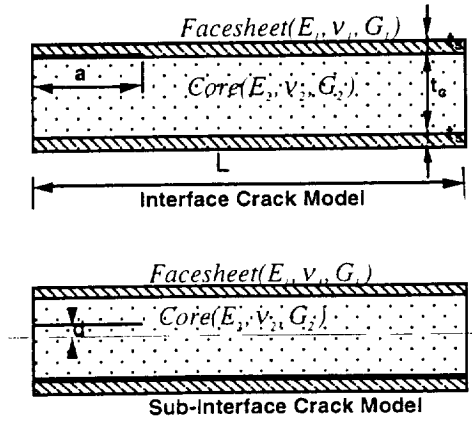

Fig. 3 Interface and sub-interface problems

causes oscillatory singular stresses.

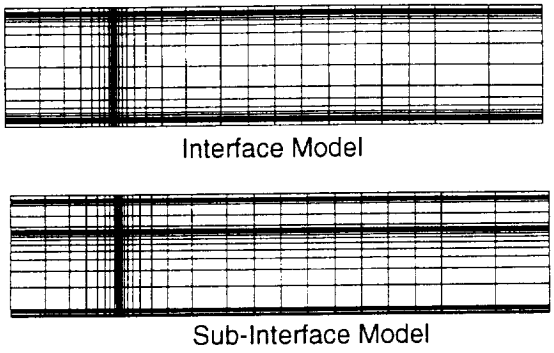

Fig. 4 Finite element models.

The sub-interface cracks (crack near the interface) also have similar oscillatory singular stresses. Therefore a conclusion could be that the G components for interfacial and sub-interfacial cracks could not be separated by superposition of pure modes. This research provided a practical solution to these problems in composite sandwich panels. Figure 3 describes interface and sub-interface crack geometries. The specimen length is 10-in, core thickness is 2-in, skin thickness is 0.14-in, and the crack length (a) is 2-in. Finite element models of the two problems are shown in fig. 4. The analysis was performed for opening and shearing mode loading conditions. A parametric study was conducted for a range of skin to core modular ratios (E_1/E_2 = 1 to 1,000), crack locations (from interface to mid-thickness), Poisson's ratio values, and crack tip element lengths (10 to 0.1% of the crack length). The total G, and G_I and G_{II} were calculated from the virtual crack closure technique.

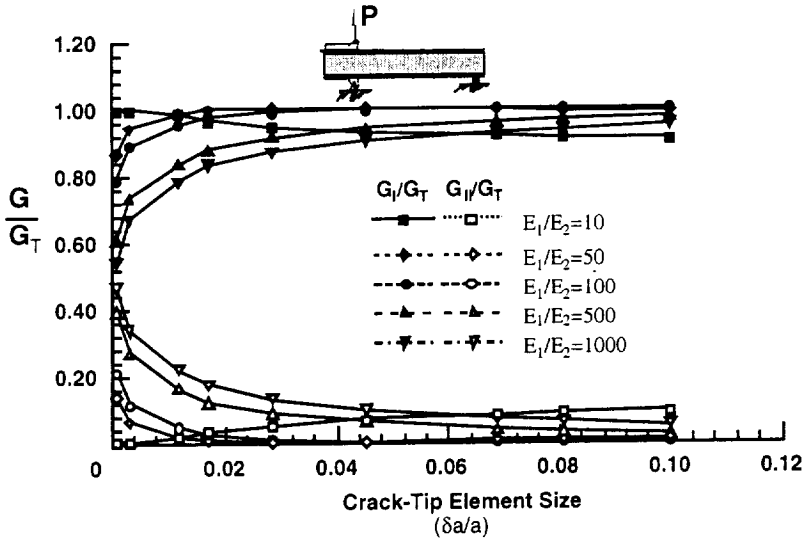

Fig. 5 Effect of crack tip element size on G components.

For interfacial and sub interfacial cracks, G_I and G_{II} varied with crack tip element size and finally reached a value one-half of the total G. This value was independent of E_1/E_2 and Poisson's ratio (see Fig 5). The same trend was shown for both opening and shearing mode loading for modular ratio greater than one. The G components were nearly constant for crack tip element lengths 4 to 10% of the crack length. Crack tip element size of 7% crack length was proposed for separating energy components. Based on these criteria, the foam core sandwich panels ($E_1/E_2 \geq 500$) had almost pure mode I for opening type loading and pure mode II for shearing type of loading. Fig 6 shows the G components for a sub-interface crack located at a distance 94% of half-thickness of the core from the mid-plane. The G components were independent of crack tip element size and these values were almost

same (<3% variation) as interfacial crack results. However, the G components were dependent on the crack tip element size for cracks located within the 3% of the core thickness or the face sheet thickness (which ever is the minimum) from the interface.

The crack tip element size of 7% of the crack length will give G components that can be considered constant for practical applications. Details are in reference 2 and in Appendix B.

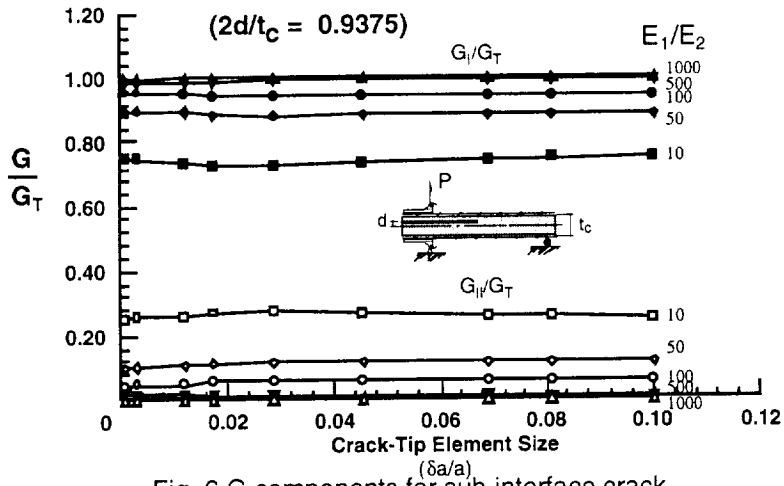

Fig. 6 G components for sub-interface crack

Task 3: Measurement of fracture toughness of cracked foam core composite sandwich panels

The VARTM facility built under this grant was used to fabricate sandwich panels. Panels consisted of Divinycell foam core (density 130 kg/m^3) and plain weave glass and carbon fabrics' face sheets. Test specimen had total thickness of 30.4 mm, width of 33mm and length of 304.8 mm. The face sheet and core thicknesses were 2.5 and 25.4 mm, respectively. Interfacial crack (length 50.8 mm) was made by a surgical knife. Test specimen and loading are shown in Fig 7. Displacement controlled test was conducted and the crack growth was monitored through an optical travelling microscope. The specimen was unloaded at every 5 mm of crack extension to measure compliance. The load and load-point displacements were recorded continuously. Test was stopped after about 25 mm of crack extension. Energy release rate (G) was calculated from area method and virtual crack closure technique (VCCT).

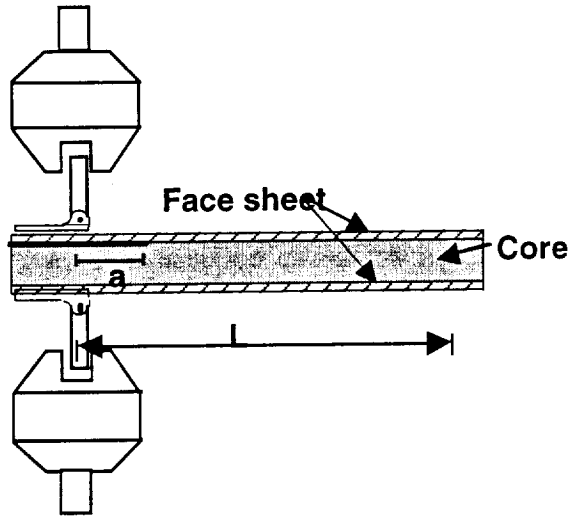

Fig. 7 Test specimen and loading

Figures 8 and 9 show the plot of energy release rates against crack extension for glass and carbon fabric face sheet beams. Open symbols are from the area method and closed symbols are from VCCT. The two methods' results agree reasonably, the difference was because of not including plastic deformation in the VCCT. Based on the preliminary results, the resistance to crack growth was found to be independent of face sheet material properties. The broken lines represent ±1 STD from the average. The average toughness was 1.88 kJ/m^2 for glass/vinyl ester and 2.0 kJ/m^2 for carbon/vinyl ester. The difference between the two toughness values was about 1 STD. The micrographic studies of the fractured specimen revealed that the interfacial foam was densified by resin. Amount of infiltration depends on the permeability and size of foam cells. The resin-densified foam will have higher toughness than the un-densified foam. The color variation near the interface represents the density variation. When the panel was made, a thin layer of foam was infiltrated by resin resulting in tougher material at the interface. Therefore, the crack propagated outside the densified foam (weaker region) instead of at the densified interface

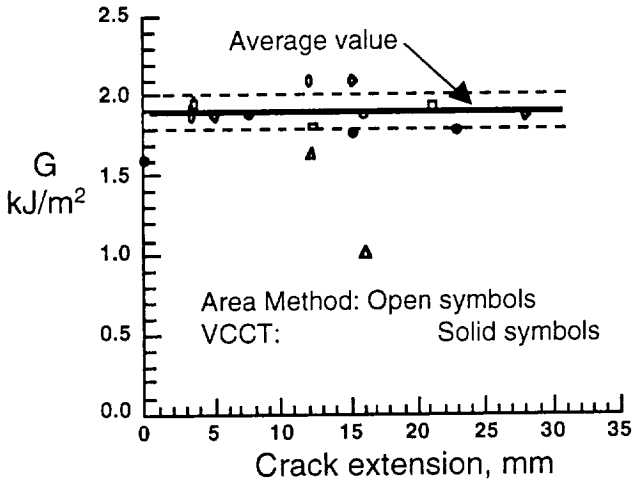

Fig. 8 Resistance of glass/vinyl ester sandwich beam.

VARTM or any other co-cured process of manufacturing foam core sandwich panels densifies the interface between face sheet and the core. As a result, the interface becomes stronger and tougher. More test studies are planned to establish the dependency of fracture toughness on the face sheet and core properties. Details of this study are presented in references 1 and 3, and in Appendices A and C

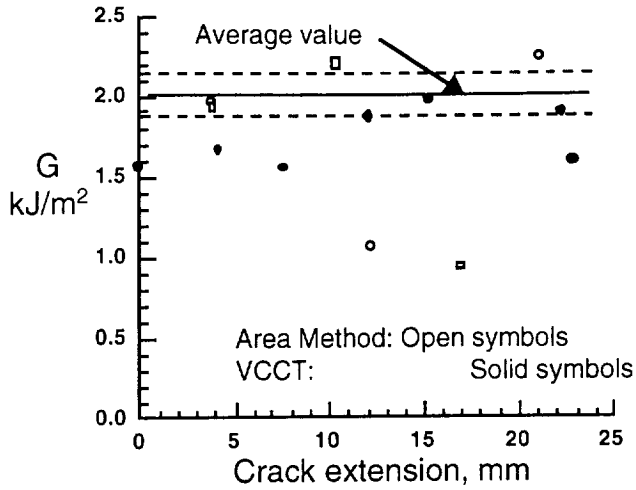

Fig. 9 Resistance of carbon/vinyl ester sandwich beam

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8 S. Smith, L. Emmanwori, R. Sadler, and K. Shivakumar, "Evaluation of Composite Sandwich Panels Fabricated Using Vacuum Assisted Resin Transfer molding," SAMPE 2000, Long Beach, CA May 21-25, 2000.

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TECHNOLOGY TRANSFER

The Vacuum Assisted Resin transfer Molding (VARTM) Technology developed under this funding was successfully transferred to 3TEX Inc, Cary, NC based small company for manufacturing engineered fabrics. Under a separate contract from 3TEX, CCMR of A&T fabricated and evaluated fabrics manufactured by 3TEX for automotive applications. Based on the results, 3TEX expressed interest learning the VARTM technology and expanding its business to composite manufacturing. 3TEX requested its engineers to be trained in VARTM and signed a MOU for mutual transfer of technologies. Trough this agreement, VARTM technology was transferred to 3TEX by training its Engineers. Technology consisted of two parts. First part was hands-on training, it was given at A&T on Aug 28-29, 2000. The second part was duplication of the process at 3TEX facility. CCMR staff traveled (October 18, 2000) to Cary and monitored and suggested improvements to the fabrication of composite panels. Currently, 3TEX has a full-fledged VARTM manufacturing facility and is supplying the products its customers. CCMR (A&T) charged $1,500 as the cost for training. The author acknowledges the partial funding provided by the Office of Naval Research in conducting this research.

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APPENDIX A
EVALUATION OF COMPOSITE SANDWICH PANELS FABRICATED USING VACUUM ASSISTED RESIN TRANSFER MOLDING

EVALUATION OF COMPOSITE SANDWICH PANELS FABRICATED USING VACUUM ASSISTED RESIN TRANSFER MOLDING

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ABSTRACT

Two composite laminated panels and one composite sandwich panel were fabricated using Vacuum Assisted Resin Transfer Molding (VARTM). One laminated panel was fabricated from woven E-glass and Vinyl-Ester resin, the other from woven Carbon and Vinyl-Ester resin. The sandwich panel was fabricated from woven E-glass, Vinyl-Ester resin and PVC foam. The measured fiber volume of the E-glass panel is 42%. The calculated fiber volume of the Carbon panel is 50%. Tension, compression, and shear tests were performed to evaluate the mechanical properties of the composite panels. The measured tensile modulus, ultimate tensile strength and Poisson's ratio of the E-glass panel are 23.03 GPa, 325 MPa, and 0.11, respectively. The measured shear modulus of E-glass panel is 3.86 GPa. The measured tensile modulus, ultimate tensile strength, and Poisson's ratio of the Carbon panel are 47.51 GPa, 436 MPa, and 0.04, respectively. The measured shear modulus of the Carbon panel was measured as 2.81 GPa. Three-point and four-point bending tests were conducted on sandwich beams machined from the sandwich panel. Predicted beam deflections based on the properties calculated from face-sheet and core properties were in close agreement with measured values for four-point bending, but they were not for three-point bending.

KEY WORDS: Vacuum Assisted RTM (VARTM), Composite Materials, Sandwich Construction, Mechanical Properties

1. INTRODUCTION

The advantages derived from the use of sandwich structures have been thoroughly documented in literature (1-4). The combination of composite face-sheets and a closed celled foam core yields a lightweight structure with high strength and flexural stiffness that is resistant to corrosion and moisture. Using Vacuum Assisted Resin Transfer Molding (VARTM), sandwich structures can be fabricated in a one step process that is not limited in shape or size. Removing the complicated process of bonding the face-

sheets to the core enhances the viability of sandwich structures. In the current study, VARTM was used to fabricate laminated composite panels as well as sandwich panels. Mechanical properties of the fabricated panels were measured and compared with values from literature.

2. MATERIAL PROCESSING

2.1 Materials Two different fiber reinforcements were selected for the laminated panels. The first, BGF 2532 by Burlington Glass Fabrics, is a plain-weave E-glass fabric that has an areal weight of 237 g/m^2. The second, W-5-322 by Fiberite, is a T-300 3K plain-weave carbon fabric that has an areal weight of 195 g/m^2. The matrix system used was the Dow Derakane 411-350 vinyl-ester epoxy. The sandwich panel was fabricated using BGF 2532, Derakane 411-350, and Diab Divinycell H130 PVC foam. Mechanical properties for the constituent materials are contained in Table 1.

Table 1. Constituent Material Properties*

	E-glass	T-300	Derakane 411	Divinycell H130
Density (g/cm^3)	2.57	1.75	1.12	0.13
Tensile Modulus (GPa)	72.5	231.7	3.38	0.14
Poisson's Ratio**	0.20	0.20	-	-
Shear Modulus (GPa)	30.0	8.9	1.41	0.05

* Properties as certified by manufacturer

** ν_{LT}

2.2 Vacuum Assisted Resin Transfer Molding

2.2.1 Laminated Panels A flat 13 mm thick aluminum plate measuring 762 mm wide by 1219 mm long was used as a mold surface for lay-up of the laminated panels. The mold surface was treated with mold release and then a peel ply, the fabric preform, a second peel ply and distribution media were stacked on the mold surface. The distribution media used is a 50% greenhouse shade cloth. The fabric preform consisted of either twenty plies of BGF 2532 or 16 plies of W-5-322, measuring 305 mm wide by 610 mm long. A vacuum sealant tape was placed around the perimeter of the mold surface and Nylon film was used to cover the stacked material creating a sealed mold. A vacuum pump was used to evacuate the sealed mold. After evacuating the preform, resin was infused into the preform. The resin supply was sealed after the preform was thoroughly wetted. After resin gelation the vacuum port was sealed. The preform was allowed to cure overnight at lab temperature (20 °C) and then removed from the vacuum bag. The panels were post-cured for 2 hours at 250 °C. The final

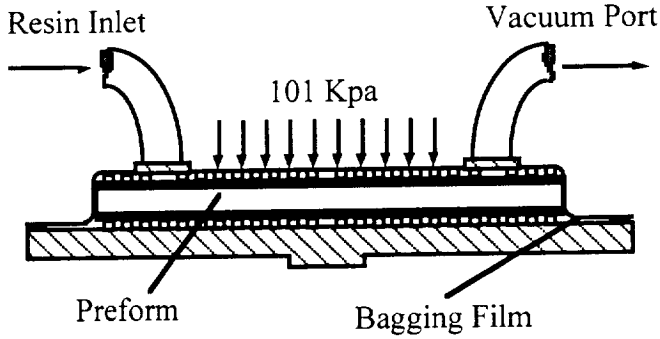

Figure 1. Vacuum Assisted Resin Transfer Molding

thicknesses obtained for the E-glass/Vinyl-Ester and Carbon/Vinyl-Ester panels are 4.3 mm and 3.8 mm, respectively. A schematic of the VARTM setup is shown in Fig. 1.

2.2.2 Sandwich Panel The same mold surface that was used for the laminated panels was used for fabrication of the sandwich panel. A layer of distribution media was placed on the mold surface followed by a peel ply, the preform, a peel ply, and a layer of distribution media. The sandwich preform consisted of 12 plies of BGF 2532, 25.4 mm Diab Divinycell H130 PVC foam, and 12 plies of BGF 2532. The plan-form area of preform was 305 mm x 610 mm. The preform was vacuum-sealed in the same manner as the laminated panel. Resin was infused on both the top and bottom surfaces of the preform. The sandwich preform was then allowed to cure overnight at lab temperature (20 °C) and then removed from the vacuum bag. The sandwich panel was post-cured for 2 hours at 250 °C. Final thickness obtained for the sandwich panel is 30.5 mm.

3. EVALUATION OF PANELS

Bulk density, fiber volume fraction, tensile, compressive and shear properties were determined for the two laminated panels. The specimen layout for the laminated panels is shown in Fig. 2. The sandwich panel was evaluated using three-point and four-point bending tests of sandwich beams machined from the sandwich panel. Specimen geometry will be covered in the sections that follow.

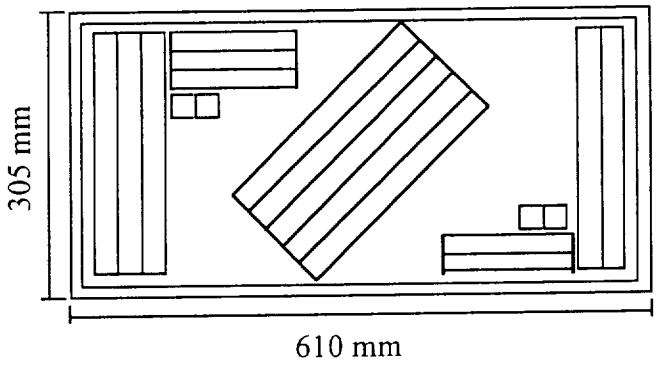

Figure 2. Specimen layout for laminated panels

3.1 Composite Density Composite density was calculated for each panel using four 25.4 mm x 25.4 mm specimen machined from each panel (see Fig. 1). Density was calculated using ASTM standard D792-86 (5). The average density of the E-glass/Vinyl-Ester panel was calculated to be 1.79 g/cm^3 with a standard deviation of 0.01 g/cm^3. The average density of the Carbon/Vinyl-Ester panel was calculated to be 1.40 g/cm^3 with a standard deviation 0.02 g/cm^3.

3.2 Fiber Volume Fraction

3.2.1 Areal Weight Method The same specimens that were used to determine density were used to determine fiber volume fraction. The mass of each of the fiber volume specimens for each panel was determined by weighing them on a precision balance. The volume of each specimen was calculated by dividing the mass of the specimen by the density of the composite. The dimensions of the specimen were measured using calipers and the plan-form area was calculated. Multiplying the areal weight of the fabric by the plan-form area of the specimen and the number of layers yields the mass of the fiber in the specimen. The volume of the fiber was calculated by

dividing the mass of fiber in the specimen by the density of the fiber. The ratio of the fiber volume in the specimen to the specimen volume is the fiber volume fraction. The fiber volume fraction calculated for the E-glass/Vinyl-Ester panel is 0.44 with a standard deviation of 0.01. The fiber volume fraction calculated for the Carbon/Vinyl-Ester panel is 0.50 with a standard deviation of 0.05.

3.2.2 Burn-out Method The fiber volume fraction can also be determined using the burn-out method (ASTM D2584-68) (5). The volume of the specimen is determined as described in section 3.1.1. The specimen is placed in a covered crucible, which is then placed in an oven capable of reaching temperatures sufficient to burn-off the matrix material. After the matrix has been burned-off, the fiber is removed from the crucible, rinsed with solvent to remove any ash, and weighed. The mass of the fiber obtained from the specimen is divided by the density of the fiber to obtain the fiber volume. Fiber volume fraction is calculated by taking the ratio of fiber volume to composite volume. Using this method the fiber volume of the E-glass/Vinyl-Ester panel was calculated to be 0.42 with a standard deviation of less than 0.01.

3.3 Mechanical Testing

3.3.1 Tensile Testing Five tension specimens were machined from each of the laminated panels. The specimen dimensions were 254 mm x 25.4 mm. The nominal thicknesses for the glass and carbon panels are 4.3 mm and 3.88 mm, respectively. Each specimen was tabbed with glass/epoxy tabs 1.6 mm thick. The tabs were 57 mm in length with a tab bevel of 10°. Tabs were bonded to the specimen using 3M Scotch Weld Structural Film Adhesive AF-163. Testing was conducted in accordance with ASTM standard D3039 (5). The crosshead displacement rate was 1.3 mm/minute. Longitudinal and transverse strain gauges were bonded on three of the five specimens

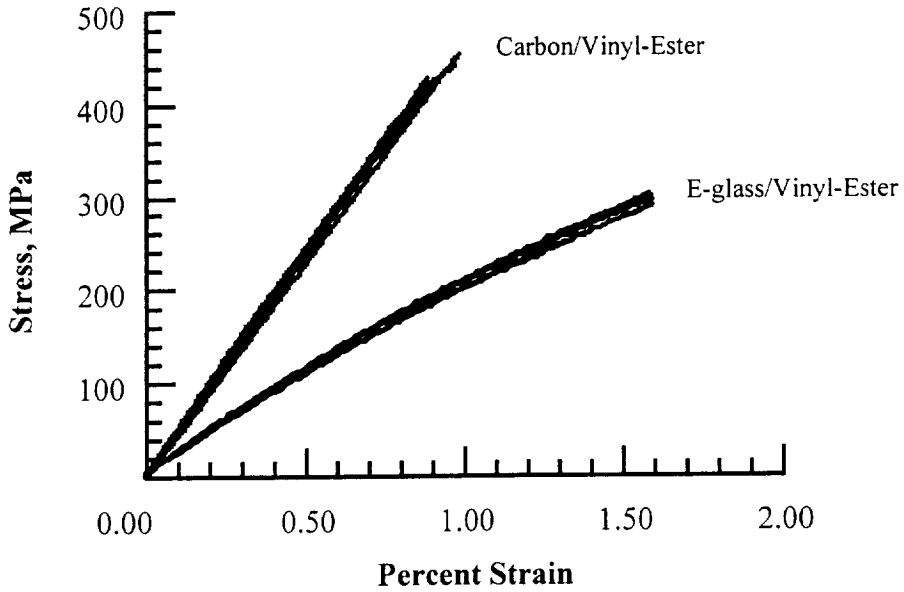

Figure 3. Tensile response of laminated panels

from each panel. The gauges were located at the center of the gauge section of the specimen. An extensometer was used to measure extension for two of the five specimens for each panel. The tensile response of both the glass and carbon panels is shown in Figure 3. Tensile modulus, ultimate strength, and Poisson's ratio for the two panels are reported in Table 2. The material properties for the E-glass panel were in close agreement with properties quoted for E-glass/Epoxy panels with similar fiber volume fraction (6). No data in literature was found for Carbon/Vinyl-Ester so no comparisons could be made.

3.3.2 Compression Testing Five IITRI Compression samples were machined from both the E-glass/Vinyl-Ester panel and the Carbon/Carbon/Vinyl-Ester panel. The specimens are 140mm x 19 mm. Each specimen was tabbed using the same process and materials used for the tensile specimens. The tabs are 64 mm in length with tab bevel of 14°. The gauge length of the specimen is 13 mm. The tests were run in displacement control with a crosshead displacement rate of 1.3 mm/min. The tests were conducted in accordance with ASTM standard D3410-87 (5). No strain data was recorded. Therefore, only ultimate strength is reported in Table 2.

3.3.3 Shear Testing Five shear specimens were machined from the laminated panels. These specimens were cut at 45° to the warp and weave direction of the reinforcing fabric. The specimens are 254 mm x 25.4 mm. The specimens were tabbed in the same manner as the tensile test specimen. Axial and transverse strain gauges were applied to all specimens. Shear stress and shear strain can be determined from axial measurements using

$$\tau = \frac{\sigma}{2} \qquad [1]$$

and

$$\gamma = \varepsilon_1 - \varepsilon_2. \qquad [2]$$

In the previous expression, τ is the shear stress, σ is the stress due to the applied load, γ is the shear strain, and ε_1 and ε_2 are the longitudinal and transverse strains measured by the strain gauges (6). The shear response of the laminated panels is shown in Figure 4. The shear modulus and ultimate shear strength calculated from Fig. 4 are reported in Table 2.

Table 2. Mechanical Properties of laminated panels*

	E-glass/Vinyl-Ester (42% fiber volume)	**Carbon/Vinyl-Ester** (50% fiber volume)
Tensile Modulus, GPa	23.0 (0.1)	47.5 (1.2)
Ultimate Tensile Strength, MPa	324.5 (7.2)	436.4 (13.3)
Poisson's Ratio	0.11 (0.01)	0.04 (0.01)
Ultimate Compressive Strength, MPa	355.7 (12.1)	262.1 (20.1)
Shear Modulus, GPa	3.86 (0.14)	2.81 (0.14)
Ultimate Shear Strength, MPa	83.9 (2.2)	77.5 (3.3)

*Numbers in parenthesis are standard deviations for the test values

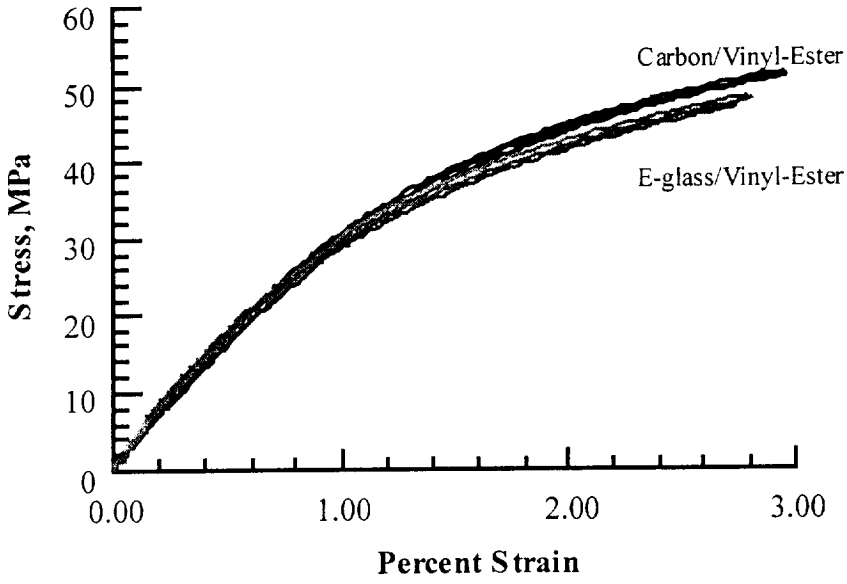

Figure 4. Shear response of laminated panels

3.3.4 Sandwich Beam Testing

Six beam specimens were machined from the E-glass/Vinyl-Ester, PVC Foam core sandwich panel. The nominal height of the sandwich, h, is 30.5 mm. The nominal width of the specimens, b, is 49 mm. The length of the specimen, L, is 305 mm. The core thickness, c, is 25.4 mm. Half of the specimens were used for three-point bending tests and the other half were used for four-point bending tests. A schematic of the test configurations is shown in Fig. 5. The span, a, of the test was 254 mm.

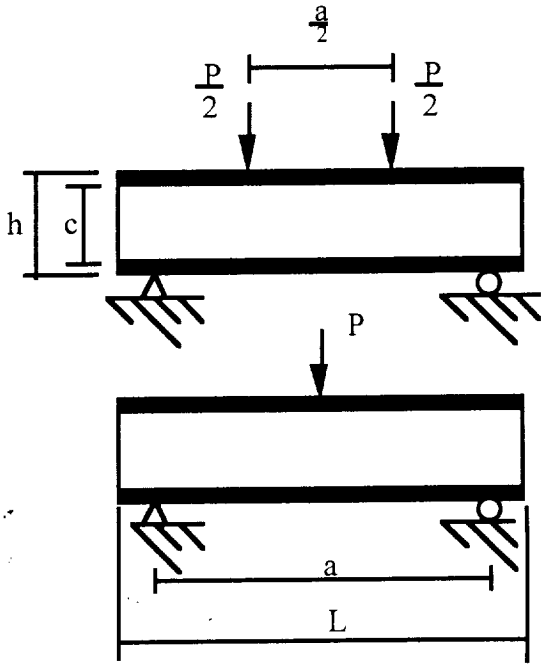

Figure 5. Three-Point and Four-Point bending tests

3.3.4.1 Three-Point Bending Tests

Three sandwich beam bending specimens were tested. The crosshead displacement rate was 1.3 mm/min. The bottom surface deflection of the mid-span of the beams was recorded using an LVDT. The plot of normalized load (P/b) vs. mid-span deflection is shown in Fig.6. The deflection at the mid-span of a sandwich beam with thin face-sheets and a weak core loaded in three-point bending is given by

$$w = \frac{P}{b}\left(\frac{a^3}{48D} + \frac{a}{4N}\right). \quad [3]$$

Where w is the deflection at the mid-span location and a is the span. The bending stiffness, D, and the shear stiffness, N, for a sandwich beam with thin face-sheets and a weak core can be calculated if the material properties of the face-sheets and core are known (5). The expressions for D and N are

$$D = \frac{E_f(h^3 - c^3)}{12(1-\nu_f)} \quad [4]$$

and

$$N = \frac{G_c\,(h+c)^2}{4c}. \quad [5]$$

In these previous expression the subscript f denotes properties of the face-sheets and the subscript c denotes properties of the core. The bending stiffness of the sandwich beam was calculated to be 19.7 x 10^3 KN-mm. The shear stiffness of the sandwich beams was calculated to be 1.56 KN/mm. Predicted deflections for the midpoint were calculated using these values for bending stiffness and shear stiffness in Eq. 3.

These values are also plotted in Fig. 6. There is 50% difference in the slope of the

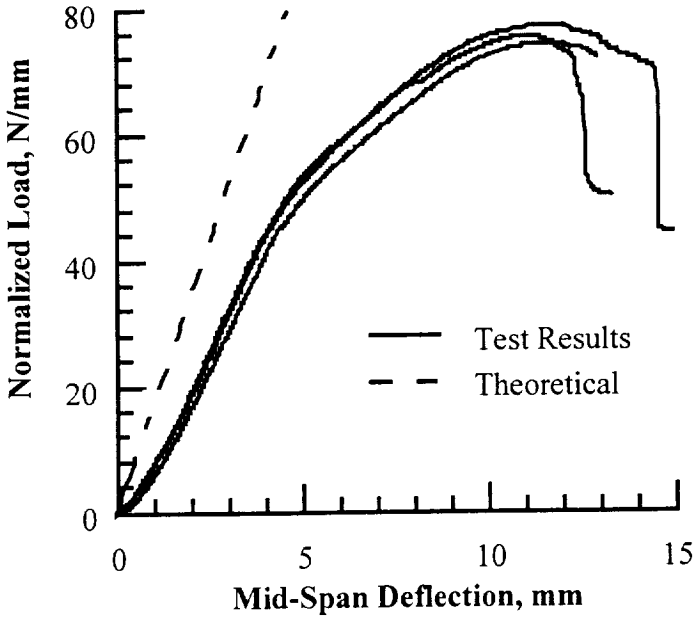

Figure 6. Three-point bending response of composite sandwich beams predicted and measured values. The thin face-sheet and weak core assumption may not apply for this loading case.

3.3.4.2Foure-Point Bending Tests Three sandwich beam bending specimens were subjected to four-point bending loading. The crosshead displacement rate was 1.3 mm/min. The bottom surface deflection of the mid-span of the beams was recorded using a LVDT. The plot of normalized load (P/b) vs. mid-span deflection is shown in Fig. 7. The analytical expression for the mid-span deflection of a sandwich beam in four-point bending is given by

$$w = \frac{P}{b}\left(\frac{11a^3}{768D} + \frac{a}{8N}\right). \qquad [6]$$

The expressions for bending and shear stiffness remain Eqs. 4 and 5, respectively. The theoretical mid-span deflections are plotted in Fig. 7 for comparison with experimental test results. The slope of the predicted deflection and the measured deflections are within 10%. The thin face-sheet and weak core assumption seems valid in this loading configuration.

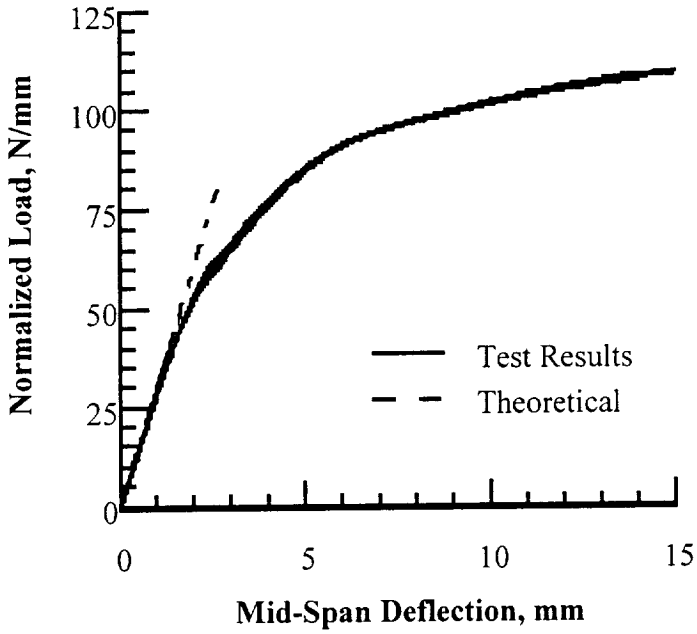

Figure 7. Four-point bending response of composite sandwich beams

4. CONCLUDING REMARKS

Two composite laminated panels and one composite sandwich panel were fabricated using Vacuum Assisted Resin Transfer Molding (VARTM). One laminated panel was fabricated from woven E-glass and Vinyl-Ester resin, the other from woven Carbon and Vinyl-Ester resin. The sandwich panel was fabricated from woven E-glass, Vinyl-Ester resin and PVC foam. The measured fiber volume of the E-glass panel is 42%. The calculated fiber volume of the Carbon panel is 50%. Tension, compression, and shear

tests were performed to evaluate the mechanical properties of the composite panels. The measured tensile modulus, ultimate tensile strength and Poisson's ratio of the E-glass panel are 23.03 GPa, 325 MPa, and 0.11, respectively. The measured shear modulus of E-glass panel is 3.86 GPa. The measured tensile modulus, ultimate tensile strength, and Poisson's ratio of the Carbon panel are 47.51 GPa, 436 MPa, and 0.04, respectively. The measured shear modulus of the Carbon panel was measured as 2.81 GPa. Three-point and four-point bending tests were conducted on sandwich beams machined from the sandwich panel. Predicted beam deflections based on the properties calculated from face-sheet and core properties were in close agreement with measured values for four-point bending, but they were not for three-point bending. Further work is necessary to assess the damage tolerance of sandwich panels fabricated using VARTM.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Dr. Yapa Rajapakse (Grant # N00014-99-1-0445) of Office of Naval Research (ONR) and Dr. I. S. Raju (NAG1-1956) of NASA Langley Research Center for supporting this research.

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APPENDIX B
EVALUATION OF THE INTERFACIAL FRACTURE TOUGHNESS OF VARTM SANDWICH PANELS USING THE MODE-I CRACKED SANDWICH BEAM SPECIMEN

EVALUATION OF THE INTERFACIAL FRACTUER TOUGHNESS OF VARTM SANDWICH PANELS USING THE MODE-I CRACKED SANDWICH BEAM SPECIMEN

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Abstract

Two composite sandwich panels were fabricated using vacuum assisted resin transfer molding (VARTM). One panel was fabricated with face-sheets of woven E-glass/vinyl-ester, the other with woven carbon/vinyl-ester face-sheets. Both panels had closed cell PVC cores with a density of 130 g/cm^3. Three-point and four-point bend specimens were machined from the panels and tested to evaluate the quality of the sandwich panels. The load-deflection response of the sandwich beams was in close agreement with sandwich beam theory. Mode-I cracked sandwich beam (CSB) specimens were also machined from the panels. Fracture tests were preformed to evaluate the fracture toughness of the interface between the face-sheet and core. Load-displacement curves were obtained for loading and unloading of the specimens during crack growth. Three increments of crack growth were monitored. Energy-release rates (ERR) were calculated using the area method and from a finite-element analysis using the virtual crack closure technique (VCCT). The energy-release rates remained constant for the 25.4 mm of crack growth monitored. For the E-glass/PVC sandwich the fracture-toughness values calculated using the area method and the VCCT were 1.88 kJ/m^2 and 1.75 kJ/m^2, respectively. The values for the carbon/PVC sandwich were 2.00 kJ/m^2 and 1.68 kJ/m^2, respectively.

Introduction

Sandwich structures offer advantages in stiffness, weight, and insulation over most structural configurations. Using vacuum assisted resin transfer Molding (VARTM), sandwich structures can be fabricated in a low-cost one step process. This combination of cost-effectiveness and structural efficiency makes VARTM sandwich structures very attractive for many applications.

Over the last twenty years a great deal of research has been directed into understanding the failure and fracture of laminated composites and of composite sandwich structures. Small defects in the interface region between the face-sheet and core can result in catastrophic failure of sandwich structures under certain loading conditions. This particularly the case for VARTM sandwich structures where the process may not generate uniform adhesion of face-sheet to core.

One specimen that has received considerable attention in literature is the Mode-I Cracked Sandwich Beam (CSB) proposed by Prasad and Carlsson[1,2] and later reinvestigated by Cantwell and Davies[3]. The Mode-I CSB configuration is shown if Fig. 1. The objective of this work is to evaluate the interfacial fracture toughness of a VARTM sandwich beam using the CSB fracture specimen.

Material Processing

Two different fiber reinforcements were selected for the sandwich panels. The first, BGF 2532, is an 1K plain-weave E-glass fabric with an areal weight of 237 g/m^2. The second, W-5-322, a 3K plain-weave T-300 carbon fabric that has an areal weight of 195 g/m^2. The matrix system used was the Dow Derakane 411-350 vinyl-ester epoxy. The core of the sandwich panels was Diab Divinycell H130 PVC foam.

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Vacuum Assisted Resin Transfer Molding

A flat 13-mm thick aluminum plate measuring 762 mm wide by 1219 mm long was used as a mold surface for lay-up of the sandwich panels. The mold was treated with a release agent and the sandwich preform (Fig. 2) was placed onto the surface. The sandwich preform consisted of either 10 plies of BGF 2532 or 8 plies of W-5-322 stacked on top and bottom of a rigid, closed cell, PVC foam core. The preform measured 305 mm wide by 610 mm long. Peel plies were used on top and bottom of the preform. A vinyl greenhouse 50% shade cloth was stretched over the top peel ply to act as a distribution media. Vacuum sealant tape was placed around the perimeter of the mold surface and nylon film was used to cover the stacked material creating a sealed vacuum bag. A vacuum pump was used to evacuate the sealed bag. After evacuating the preform, resin was infused into the preform at one end of the panel and allowed to flow across the distribution media to the vacuum port. The resin supply tubing was sealed after the preform was thoroughly wetted and the vacuum pump was shut down and the vacuum port sealed. The consolidated preform was allowed to cure overnight at lab temperature (20 °C) and then removed from the vacuum bag. The panels were post-cured for 2 hours at 100 °C. The final thickness obtained for both sandwiches was 30.5 mm. This corresponds to skin thickness of 2.5 mm.

Material Characterization

To obtain the material properties for the face-sheets of the sandwich panels, laminated panels of both E-glass/vinyl-ester and carbon/vinyl-ester were consolidated using VARTM. Fiber volume fractions of 0.42 and 0.50 were obtained for the E-glass and carbon panels, respectively. The material properties obtained for these panels are listed in Table 1. The core materials for the sandwich panels, Divinycell H130 closed cell foam, has a tensile modulus of 0.14 GPa, a Poisson's ratio of 0.4, and a shear modulus of 0.05 GPa.

Bending stiffness and shear stiffness of the sandwich panels can be calculated from the properties of the face-sheets and core. Once bending stiffness and shear stiffness are determined the deflection of a sandwich beam can be calculated for a given loading using sandwich beam theory. Three-point and four-point bend specimens were machined from the sandwich panels. The span of the beams was 254 mm and the width of the beams was 50.4 mm. Assuming the face-sheets carry all bending and the core carries all shear loads, the deflection at the midpoint of a three-point and four-point sandwich beams can be written

$$w = \frac{P}{b}\left(\frac{a^3}{48D} + \frac{a}{4N}\right). \quad (1)$$

and

$$w = \frac{P}{b}\left(\frac{11a^3}{768D} + \frac{a}{8N}\right). \quad (2)$$

Where w is the mid-point deflection, a is the span, P is the applied load, b is the width of the beam. The terms D and N are the bending and shear stiffness. The equations for the bending and shear stiffness of a sandwich are

$$D = \frac{E_f(h^3 - c^3)}{12(1-\nu_f)} \quad (3)$$

and

$$N = \frac{G_c\,(h+c)^2}{4c}\,. \quad (4)$$

In Eqs. 3 and 4, E_f is the modulus of the face-sheet, ν_f is Poisson's ratio for the face-sheet, h is the height of the sandwich, c is the height of the core, and G_c is the shear modulus of the core. Figures 3 and 4 show the bending response of E-glass/PVC and carbon/PVC sandwich beams. The measured deflection at the midpoint of the beams was in agreement with the values predicted by sandwich beam.

Cracked Sandwich Beam Fracture Test

Three Mode-I CSB specimens were machined from each of the sandwich panels. The nominal thickness or height of the sandwich panels was 30.5 mm. The width of the sandwich specimens, b, was 33.0 mm. The total length of the specimens was 305 mm.

Specimen Preparation

After machining the CSB specimens to their final dimensions aluminum piano hinges were adhesively bonded to the face-sheets. These hinges act as load points for the CSB specimen. The hinges are mounted 25.4 mm from one end of the specimen. The mounting procedure involves abrading surfaces of both the face-sheet and the hinge. The abraded areas are rinsed with acetone and allowed to air dry. While drying the adhesive is prepared. The hinges are bonded to the face-sheets using 3M DP-460 two-part epoxy adhesive. To maintain bond-line thickness 5% by weight 1 μ glass beads are added to the adhesive. The

glass beads are mixed into epoxy at the same time parts A and B are combined. The epoxy is mixed and spread onto the aluminum hinges, which are then aligned on the specimens and clamped in place. The adhesive is cured at 60 °C for 2 hours. A delamination is cut into the interface region using a thin saw blade to approach initial crack length and then a surgical knife is used to reach the desired length. White paint is applied to one surface of the interface and marks are place at 2.5-mm intervals along the interface region.

Test Procedure

The fracture tests were carried out on a 50 kip MTS load cell. The testes were conducted in displacement control with a crosshead displacement rate of 1.3 mm/min. Load and crosshead displacement was recorded throughout the test. The specimen is mounted in the grips of the load frame. An optical tracking microscope is used to locate the crack tip and the crack tip location is recorded. The test is then started and the crack is monitored for growth as the crosshead opens the delamination. The crack is allowed to grow steadily until it extends approximately 8 mm. The crosshead is stopped and the crack growth is recorded using the optical microscope to locate the new crack tip. The crosshead displacement is reversed and the unloading data is recorded. This procedure is repeated three times for each specimen resulting in approximately 25 mm of crack growth.

Computation of Fracture Toughness

Two methods are used to determine the fracture toughness of the interface region. The methods are the area method and the virtual crack closure technique. These methods are described in the sections to follow.

Area Method

Figure 5 shows a typical set of curves obtained from a fracture test. The critical loads, or the load where crack growth begins, are noted for each load-unload cycle. Using these points the area between the curves can be approximate. This area corresponds to the energy-released as the crack grows. The energy-release rate can be calculated using the relationship

$$\mathrm{ERR} = \frac{\Delta E}{b\,\Delta a}. \qquad (5)$$

In this expression ΔE is the area of the triangular region defined by the origin and the critical loads, Δa is the crack extension noted during the test for the load-unload cycle, and b is the width of the sandwich. This value is taken as the average energy released for the crack extension and is plotted against one half Δa. The procedure is repeated for each set of curves obtained during the test.

Finite Element Analysis and VCCT

A finite-element model was created for the CSB specimen configuration for each crack length. The finite-element mesh used to evaluate the cracked sandwich beam is shown in Figure 6. This model consisted of 720 nodes and 785 elements. A 4-node linear strain element was used. The boundary conditions are shown in the idealization of the model.

To determine the interfacial fracture toughness the critical load noted during the test is applied to the model for each crack length. A finite-element analysis is conducted and the load at the crack tip along with the opening displacement behind the crack tip are used to calculate the energy-release rate[4]. The value of energy-release rate is plotted for each crack length.

Results and Discussion

A load-displacement curve is shown in Figure 7 for one specimen of each sandwich panel. Each plot contains the data from three load-unload cycles. The critical loads and crack extensions for the E-glass/PVC sandwich are in Table 2. The critical loads and crack extensions for the carbon/PVC sandwich are in Table 3. The interfacial fracture toughness values calculated for the E-glass/PVC and carbon/PVC sandwich specimens are shown in Figs. 8 and 9 and Tables 4 and 5, respectively. The closed symbols in the figures are the values computed using the VCCT method. The open symbols are the values obtained using the area method.

Examining Figures 8 and 9 it appears that the lowest point in Figure 8 and the lowest two points on Figure 9 do not fit the trend of the data. The remaining points show nearly constant energy-release rate with crack extension. Excluding the three suspect points the average ERR calculated for the E-glass/PVC sandwich using the area method is 1.88 kJ/m^2 with a standard deviation of 0.06. The average ERR value for the same panel calculated using the VCCT method is 1.75 kJ/m^2 with a standard deviation of 0.11. The values are within one standard deviation of one another. The average ERR obtained for the carbon/PVC sandwich using the area method is 2.00 kJ/m^2 with a standard deviation of 0.13. The VCCT extracts an average value of 1.68 kJ/m^2 with a standard deviation of 0.18. The ERR values are nearly the same for both panels.

Concluding Remarks

The interfacial fracture toughness of two VARTM sandwich panels was evaluated. The panels had identical dimensions and core materials, but had different face-sheet materials. Cracked sandwich beam specimens from both panels were tested in the Mode-I loading configuration. Load and displacement were measured for various amounts of crack growth. Energy-release rates were calculated using the area method and the virtual crack closure technique. Results from the two methods were in agreement. The interfacial fracture toughness of the E-glass/PVC sandwich panel was computed as 1.88 kJ/m^2 using the area method and 1.75 kJ/m^2 using the VCCT. The values of interfacial fracture toughness computed for the carbon/PVC sandwich were 2.00 kJ/m^2 and 1.68 kJ/m^2, respectively. The resistance to crack growth was nearly constant for 25 mm of crack extension for both sandwich panels. The data indicates that the interfacial toughness of the sandwich is dependent on the core material and independent of the face-sheet material. The data also indicates that the crack resistance value remains constant after crack initiation.

Acknowledgments

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Table 1. Mechanical Properties of laminated panels

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Ultimate Tensile Strength, MPa	324.5	436.4
Poisson's Ratio	0.11	0.04
Ultimate Compressive Strength, MPa	355.7	262.1
Shear Modulus, GPa	3.86	2.81
Ultimate Shear Strength, MPa	83.9	77.5

Table 2. Critical loads and crack extensions for the glass/PVC sandwich specimens

MIG1		**MIG2**		**MIG3**	
Pcr	Δa	Pcr	Δa	Pcr	Δa
182.47	-	163.51	-	156.89	-
174.18	7.26	157.76	10.16	153.79	6.985
145.95	10.16	135.55	10.16	140.78	5.08
128.84	7.62	122.35	7.62	133.97	7.925

Table 3. Critical loads and crack extensions for the carbon/PVC sandwich specimens

MIC1		**MIC2**		**MIC3**	
Pcr	Δa	Pcr	Δa	Pcr	Δa
227.57	-	218.83	-	235.74	-
211.82	7.874	211.58	8.255	235.035	7.62
197.84	5.08	200.9	7.62	217.74	9.195
189.91	8.001	137.014	12.7	177.845	8.58

Table 4. Energy-release rates calculated for the glass/PVC sandwich specimens

MIG1		**MIG2**		**MIG3**		**VCCT**	
Δa	ERR	Δa	ERR	Δa	ERR	Δa	ERR
3.63	1.95	5.08	1.87	3.49	1.97	0	1.586
12.34	1.8	15.24	2.09	12.07	1.64	7.62	1.881
21.23	1.93	27.94	1.88	16.03	1.02	15.24	1.762
						22.86	1.779

Table 5. Energy-release rates calculated for the carbon/PVC sandwich specimens

MIG1		**MIG2**		**MIG3**		**VCCT**	
Δa	ERR	Δa	ERR	Δa	ERR	Δa	ERR
3.937	1.9336	4.1275	1.678	3.81	1.9675	0	1.573
10.414	2.2057	12.065	1.879	12.218	1.0648	7.62	1.557
16.96	0.9469	22.225	1.9178	21.1	2.249	15.24	1.988
						22.86	1.607

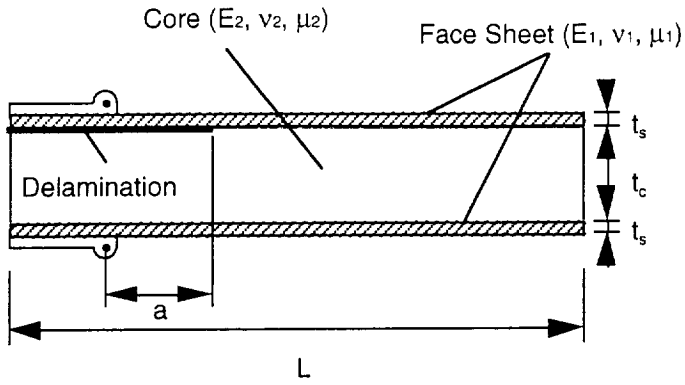


Figure 1. Mode-I Cracked sandwich beam (CSB) fracture specimen

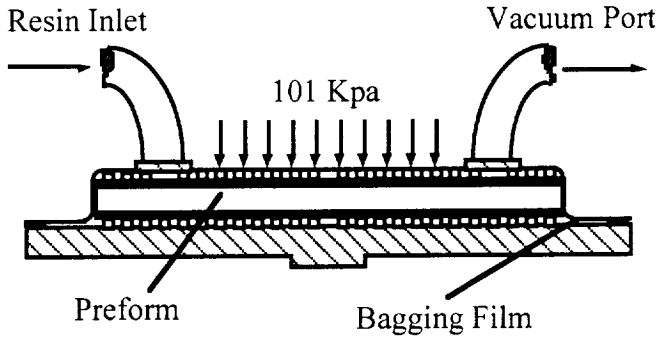
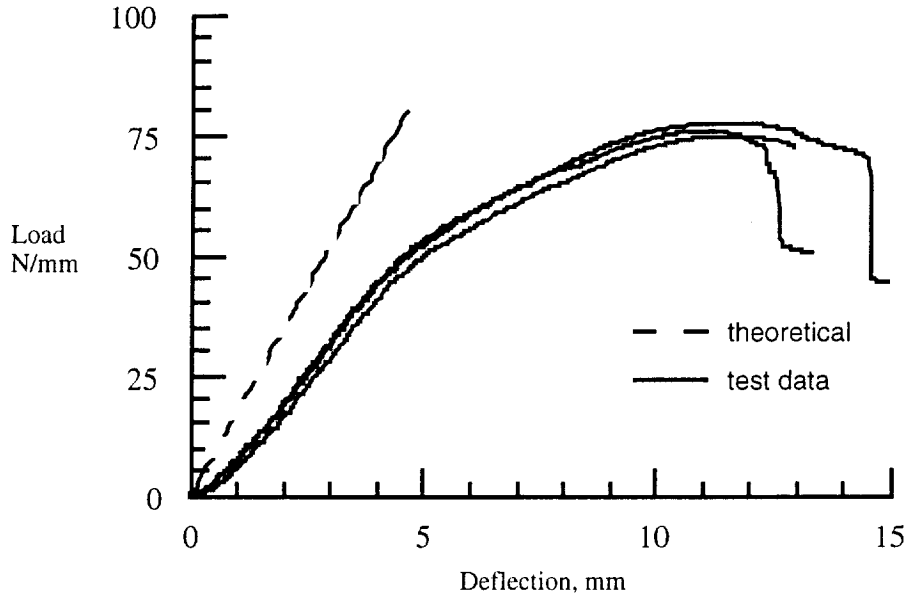
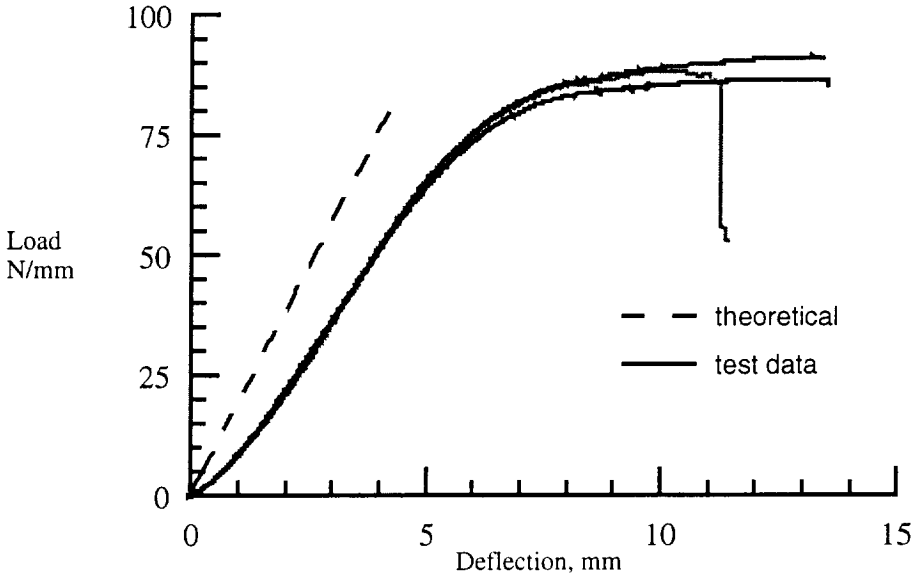


Figure 2. Vacuum assisted resin transfer molding

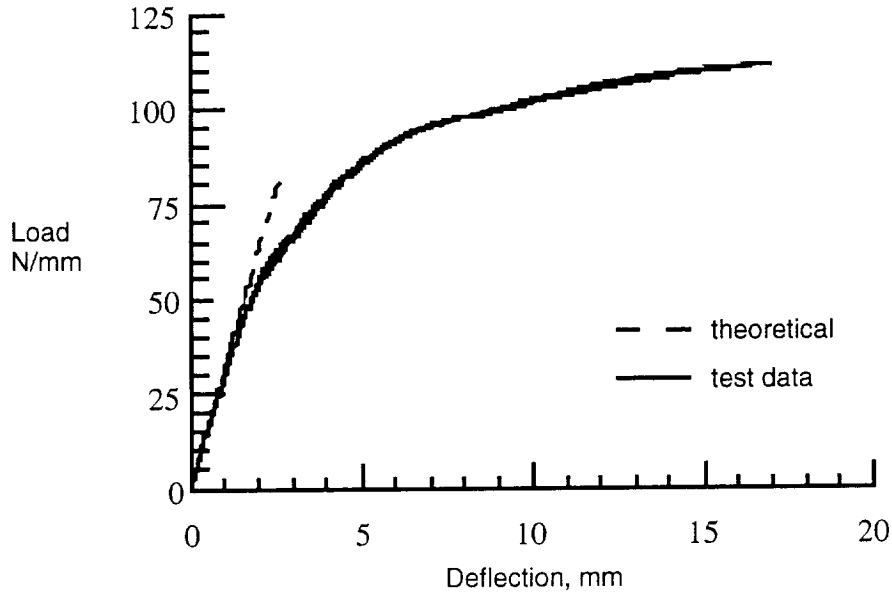


(a) glass sandwich panel

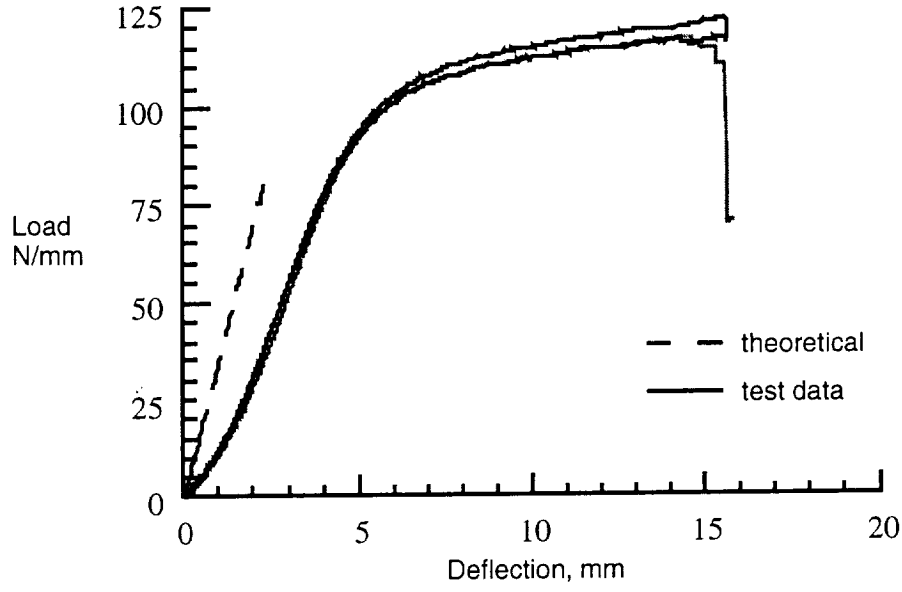


(b) carbon sandwich panel

Figure 3. Three-point bend response of VARTM sandwich panels



(a) glass sandwich panel



(b) carbon sandwich panel

Figure 4. Four-point bend response of VARTM sandwich panels

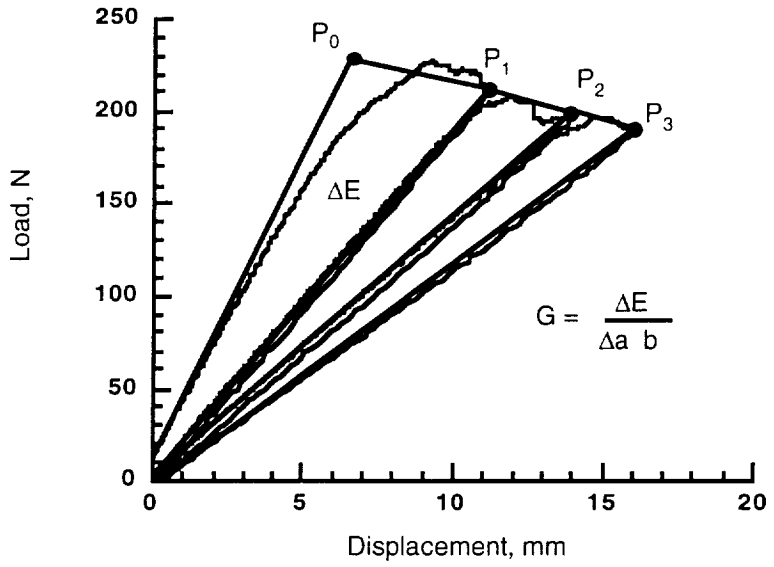


Figure 5. Typical load displace ment curve

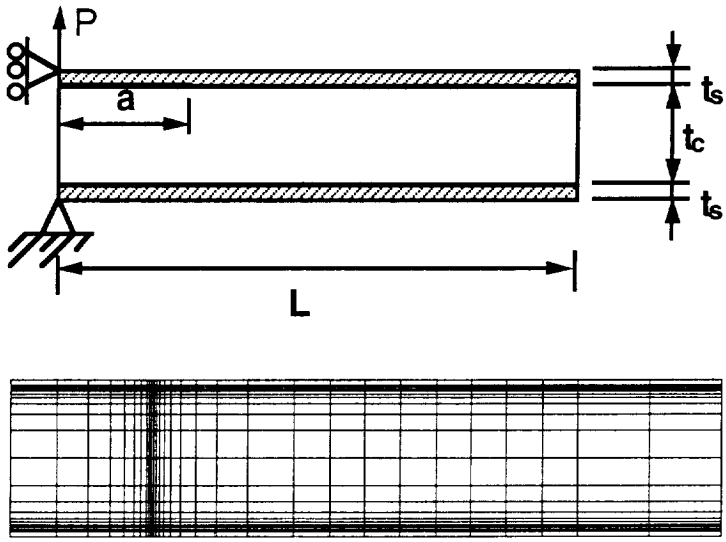


Figure 6. Finite-element idealization and finite-element mesh

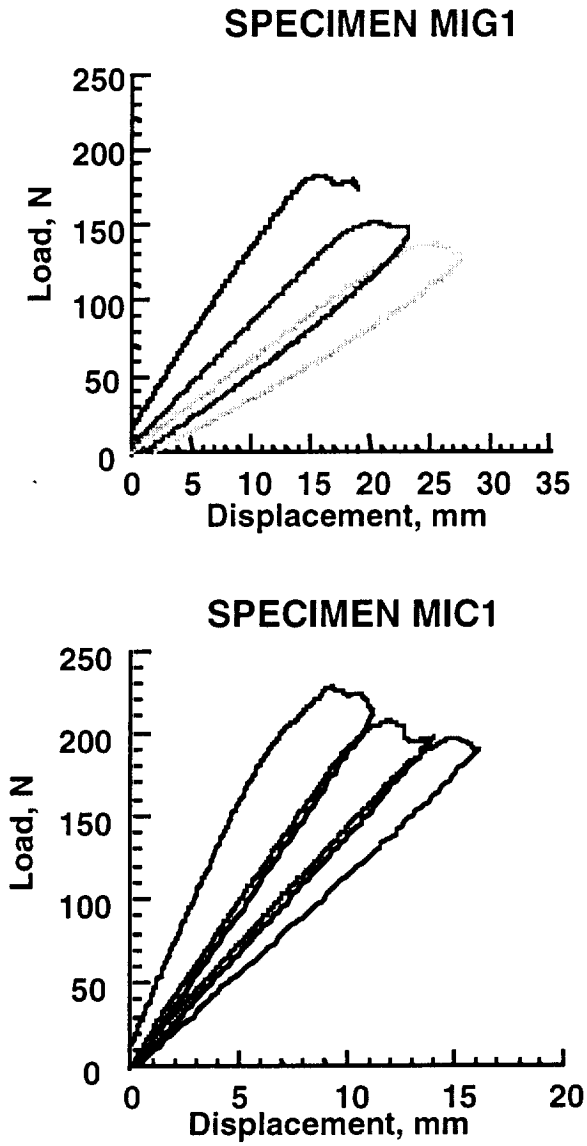


Figure 7. Load-displacment curves for CSB fracture test

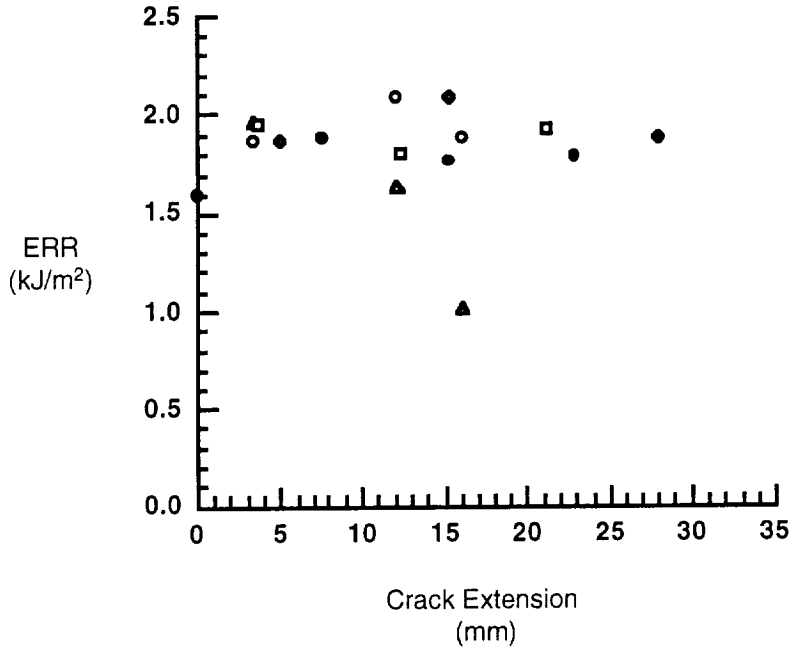


Figure 8. Resistance curve for the glass/PVC sandwich panel

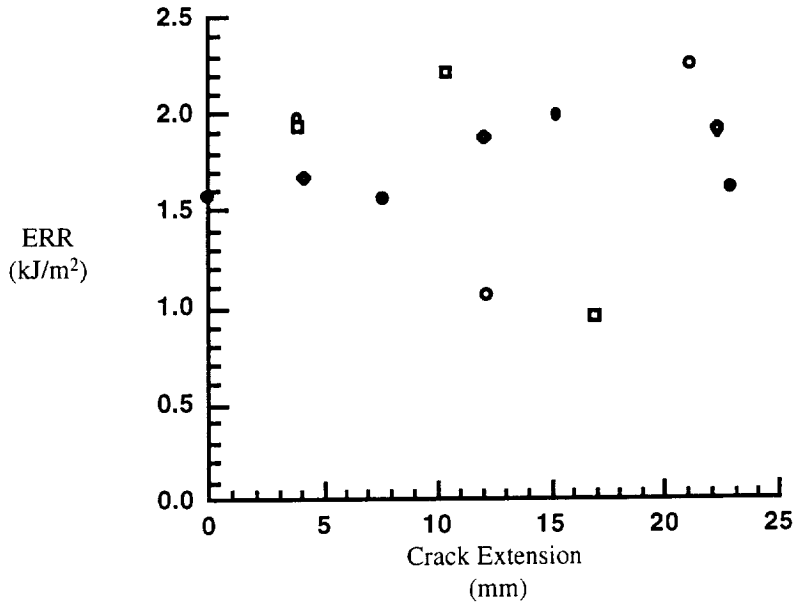


Figure 9. Resistance curve for the carbon/PVC sandwich panel