Relation between Interfacial Fracture Toughness and Mode-mixity in Honeycomb Core Sandwich Composites

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ABSTRACT: A fracture mechanics approach is proposed to determine the residual strength of debonded honeycomb core composite sandwich panels. Asymmetric double cantilever beam sandwich specimens are tested in order to measure the core/face sheet interfacial fracture toughness. Graphite/epoxy composite laminates are used as face sheets, and the core is an aramid fiber/phenolic resin honeycomb structure. The experimentally measured critical loads, disbond lengths, and specimen dimensions are used in a finite element analysis to estimate the fracture (FE) toughness and the mode-mixity at the crack tip. The finite element results for the critical energy release rate agreed well with the experimentally measured values. It is found that the interfacial fracture toughness increases as the mode II component increases, and the difference can be as much as 70%. In order to demonstrate the importance of mode-mixity on damage tolerance, the design of a sandwich pressure vessel is considered. The allowable pressure for various size disbonds are calculated using the average fracture toughness as well as mode-mixity dependent fracture toughness. It is found that ignoring mode-mixity can lead to overestimation of the load carrying capacity of debonded sandwich panels by as much as 40%.

KEY WORDS: composite materials, delamination, debonding, finite element analysis, face sheet/core interface, interfacial fracture toughness, mode-mixity, sandwich construction.

INTRODUCTION

SANDWICH PANELS ARE susceptible to debonding of the face sheet from the core. This is similar to the phenomenon of delamination in laminated composites. Disbonds could develop due to poor manufacturing

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or during service, e.g., foreign object impact damage. Evaluation of damage and prediction of residual strength and stiffness of debonded sandwich panels is critical because the disbonds can grow in an unstable manner and can lead to catastrophic failure. The stiffness of sandwich structures depends very much on the integrity of the face sheet/core bonding. Even a small extent of disbond can significantly reduce the load carrying capacity, especially when the structure is under compressive loads [1,2]. Under compressive loads, the debonded face sheet can buckle and create conditions at the crack tip that is conducive for the unstable propagation of the disbond. Carlsson et al. [3] performed experiments to characterize the face sheet/core interface debonding and estimated the fracture toughness of sandwich structures. Later Viana and Carlsson [4] studied the effects of core density and core thickness on fracture toughness. Frostig and Sololinsky [5] and Frostig et al. [6] have developed analysis methods that are suitable for sandwich panels with debonded cores. Kardomateas [7,8] has developed methods for the analysis of delaminated composite beams, but they can be extended to the analysis of sandwich structures.

In this study, we will use interfacial fracture mechanics concepts to characterize the propagation of the disbond between the face sheet and the core. The objective of the present work is to perform fracture tests to determine the interfacial fracture toughness of the sandwich composite, and then demonstrate its application in predicting the performance of a sandwich structure containing a disbond. The interfacial fracture mechanics concepts necessary for the present study are briefly described. The asymmetric double cantilever beam tests are performed on sandwich specimens with different core thicknesses and disbond lengths. The finite element (FE) analysis of the specimens is performed to characterize the crack tip parameters and estimate the fracture toughness of the interface. The mode-mixity at the crack tip is determined from the detailed stress field in the vicinity of the crack tip, and the fracture toughness is expressed as a function of the mode-mixity. The experimentally determined fracture toughness values are compared with that of the FE analysis and the agreement was good. It is found that the interfacial fracture toughness increases as the mode 2 component increases, and the difference can be as much as 70%. Finally, the results are used to demonstrate the use of fracture mechanics in predicting the strength of a sandwich structure containing a disbond. It is found that consideration of mode-mixity is important for the accurate estimation of the residual load carrying capacity of a debonded sandwich structure. Ignoring the mode-mixity can over-predict the load carrying capacity of a sandwich structure as much as 41% and this can lead to catastrophic failure.

BIMATERIAL FRACTURE MECHANICS

The fracture at the interface between dissimilar materials is a critical phenomenon in many multi-material systems including sandwich construction. In these systems, the interfacial fracture cannot be characterized by a single fracture toughness parameter; rather it is a function of the relative amount of mode 2 to mode 1 at the interface [9,10]. The criterion for initiation of crack advance in the interface can be stated as

$$G = G_c(\psi), \quad \psi = \tan^{-1}\left(\frac{K_2}{K_1}\right) \tag{1}$$

In Equation (1) G is the energy release rate and G_c is the fracture toughness that depends on the mode-mixity parameter ψ, and K_1 and K_2, respectively are the mode 1 and mode 2 stress intensity factors. It must be noted that in bimaterial fracture, K_1 and K_2 are the real and imaginary parts of the complex stress intensity factor K. The toughness of interface $G_c(\psi)$ can be thought of as an effective surface energy that depends on the mode of loading.

Hooke's law connecting the stresses and strains for a generally anisotropic material can be written in the following form:

$$\varepsilon_i = \sum_{j=1}^{6} s_{ij}\sigma_j, \quad \sigma_i = \sum_{j=1}^{6} c_{ij}\varepsilon_j \tag{2}$$

where $\varepsilon_i = [\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{33}, \gamma_{23}, \gamma_{31}, \gamma_{12}]^T$ and $\sigma_i = [\sigma_{11}, \sigma_{22}, \sigma_{33}, \tau_{23}, \tau_{31}, \tau_{12}]^T$ The superscript T denotes the transpose. The 6×6 matrices s and c are the conventional compliance and stiffness matrices, respectively.

We consider the face sheet and the honeycomb core as orthotropic materials. The principal axes of each material are taken to be parallel to the 1 and 2 axes. For an orthotropic solid, since $s_{16} = s_{26} = 0$, only four elastic constants, s_{11}, s_{22}, s_{12}, and s_{66} enter the plane problem formulation. The two non-dimensional parameters are defined as:

$$\lambda = \frac{s_{11}}{s_{22}}, \quad \rho = \frac{1}{2}(2s_{12} + s_{66})(s_{11}s_{22})^{-1/2} \tag{3}$$

It may be noted that $\lambda = 1$ when the material has transversely cubic symmetry, and $\lambda = \rho = 1$ when the material is transversely isotropic. The positive definiteness of the energy density requires that $\lambda > 0$, and $-1 < \rho < \infty$. For two orthotropic materials with aligned principal axes, we define the following parameters that will be useful later in defining the crack tip stress field [10]:

$$n = \left[\frac{1}{2}(1+\rho)\right]^{1/2} \tag{4}$$

$$H_{11} = \left[2n\lambda^{1/4}(s_{11}s_{22})^{1/2}\right]_1 + \left[2n\lambda^{1/4}(s_{11}s_{22})^{1/2}\right]_2 \tag{5}$$

$$H_{22} = \left[2n\lambda^{-1/4}(s_{11}s_{22})^{1/2}\right]_1 + \left[2n\lambda^{-1/4}(s_{11}s_{22})^{1/2}\right]_2 \tag{6}$$

$$\beta = \frac{\left[(s_{11}s_{22})^{1/2}+s_{12}\right]_2 - \left[(s_{11}s_{22})^{1/2}+s_{12}\right]_1}{(H_{11}H_{22})^{1/2}} \tag{7}$$

$$\varepsilon = (2\pi)^{-1}\ln\left(\frac{(1-\beta)}{(1+\beta)}\right) \tag{8}$$

The complex stress intensity factor K and the energy release rate G are given in terms of traction in the interface as

$$\left(\frac{H_{22}}{H_{11}}\right)^{1/2}\sigma_{22} + i\tau_{12} = (2\pi r)^{-1/2}Kr^{i\varepsilon} \tag{9}$$

$$K_1 = \sqrt{2\pi r}\left[\left(\frac{H_{22}}{H_{11}}\right)^{1/2}\sigma_{22}\cos(\varepsilon\ln r) + \tau_{12}\sin(\varepsilon\ln r)\right] \tag{10}$$

$$K_2 = \sqrt{2\pi r}\left[\tau_{12}\cos(\varepsilon\ln r) - \left(\frac{H_{22}}{H_{11}}\right)^{1/2}\sigma_{22}\sin(\varepsilon\ln r)\right] \tag{11}$$

$$G = \frac{H_{11}|K|^2}{(4\cosh^2\pi\varepsilon)} \tag{12}$$

We can obtain the stress components in front of the crack tip using FE analysis. Then using Equations (3) through (12) we can calculate the stress intensity factors K_1 and K_2, and finally G and ψ.

EXPERIMENTS

Asymmetric double cantilever beam (DCB) tests were conducted to determine the interfacial fracture toughness of the sandwich composite [11]. All specimens were fabricated using Toray Composites' unidirectional carbon fiber prepreg as the face sheet material (material designation A50TF266 S6 Class E, Fiber designation T800HB-12K-40B, matrix 3631) and a Euro-Composites aramid fiber ECA type honeycomb (1/8 in cell size; 4 lb/ft^3 density; 0.003 in wall thickness) as the core material. Four different core thicknesses, 25.4 mm (1 in.), 12.7 mm (0.5 in.), 9.525 mm (0.375 in.), and 6.35 mm (0.25 in.), were used. The sandwich panels of size 203×248 mm^2 (8 in. × 9(3/4) in.) were fabricated in an autoclave. No adhesive film was used in between the face sheet and the core. The epoxy from the prepreg was considered to be sufficient to provide the necessary bond strength. The face sheets consisted of 7 plies of T800/3631 graphite/epoxy composite with fiber orientation given by $[0, 90, 0, \overline{90}]_s$. The thickness of the face sheet was about 1 mm. The sandwich panel was machined to make individual 191×25.4 mm^2 (7.5 × 1 in.) specimens with an initial crack at the interface as shown in Figure 1. The disbond was created by inserting a nonporous Teflon film in between the face sheet and the core before curing the specimen in the autoclave.

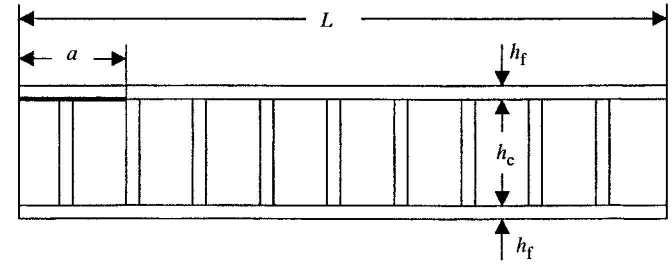

Figure 1. *A schematic of the honeycomb core composite sandwich panel with a disbond between the face sheet and core.*

The loading blocks were then glued to the specimens to finish the assembly. The loading blocks of dimensions $28 \times 20 \times 15$ mm^3 (1.1 × 0.8 × 0.6 in.) were cut from a rectangular steel bar. A 9.5 mm (3/8 in.) hole is drilled through the center of each loading block to allow for insertion of a loading pin. The nominal distance from the center of load application, or the center of the loading pin, to the crack tip was taken as 24 mm (0.95 in.). Actual dimensions were used in the finite element (FE) models discussed in the next section. The material properties of the graphite/epoxy composite, the core and steel are listed in Table 1. The properties of the face sheet and core materials were obtained from manufacturers' data.

The DCB test for sandwich is similar to that for delamination in composite laminates (ASTM D 5528-94a). The specimen is prepared with an initial disbond of length a within the interface where the fracture toughness is of interest, and it is loaded as shown in Figure 2. The load and displacement of the specimen are recorded and the crack is allowed to propagate a given length Δa. Finally, the specimen is allowed to return to an unloaded state. Using the load–displacement graph (Figure 3) and the

Table 1. Material properties (Moduli in GPa).

	E_1	E_2	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
Steel (isotropic)	206	–	0.3	–	–	–	–	–
T800/3631	162	7.58	0.34	0.34	0.25	4.41	4.41	3.03
Honeycomb core	0.021	0.193	0.31	–	–	0.044	0.007	0.068

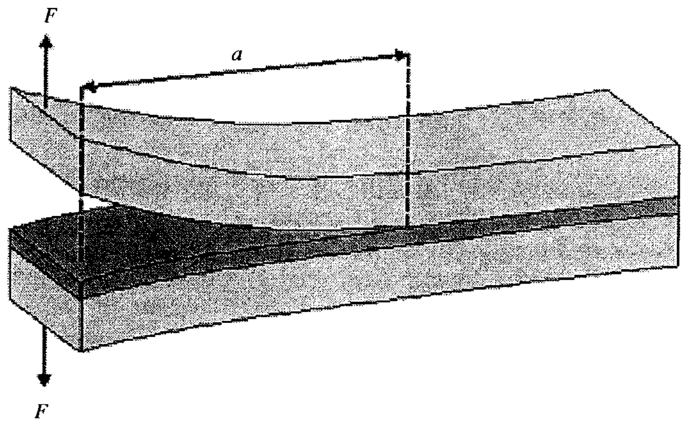

Figure 2. *Asymmetric double cantilever beam (DCB) specimen for sandwich composites.*

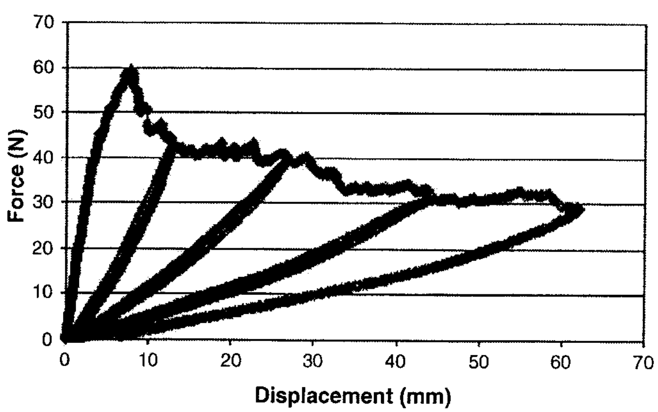

Figure 3. *Example of load vs displacement graph for a DCB test. The graph shows four loading-unloading cycles.*

crack propagation length, the energy required for propagating the crack of a given length and therefore the fracture toughness of the interface can be calculated. The fracture toughness (G_c) is given by

$$G_c = \frac{\Delta U}{B \Delta a} \tag{13}$$

where ΔU is the energy or work (area under the load versus displacement curve) required to propagate the crack, B is the specimen's width, and Δa is the crack extension length.

The tests were performed in a 12,000 lb MTI Phoenix machine with a 5000 lb interface load cell. The calibration and verification of both the displacement of the MTI machine and the load cell were conducted prior to testing.

Four specimen core thicknesses (h_c), 6.35, 9.525, 12.7, and 25.4 mm (1/4, 3/8, 1/2, and 1 in.) were tested. The crosshead deflection rate was kept at a constant rate of 1 mm/min (0.04 in./min) to retain quasi-static conditions for all tests. Five specimens of each core thickness were tested. Each specimen was cyclically loaded and unloaded four times without disturbing the specimen setup. A typical cycle was loaded to propagate the crack a distance between 12.7 and 25.4 mm (0.5 and 1 in.). However, in some instances the crack grew past the 25 mm mark. When the crack propagation reached the designated length, the MTI machine was unloaded at 1 mm/min and the crack was marked on both sides of the specimen by hand using a bright light source to better identify the crack tip. After the final loading cycle was completed for a specimen, the specimen was removed from the MTI machine and the extent of crack propagation (a_1, a_2, etc.) was averaged between the lengths measured on each side of the specimen.

Force–displacement diagrams were plotted for each cycle. The G_c value was computed using the specimen's width, the crack propagation length, and the strain energy/work loss for each cycle when a specimen was loaded (Equation (13)). The results of all tests are summarized in Table 2, based on core thickness and order tested. G_{c1} indicates the G_c value for the initiation for the disbond made from the nonporous Teflon film (NPTF), while the G_c values with number subscripts indicate sequential loading cycles of naturally made cracks.

From the experimental results presented in Table 2, it is clear that the interfacial fracture toughness is not constant for the material system, but varies with the crack length and the core thickness. One explanation for this behavior is that the mode-mixity may play a role in affecting the G_c values among the varying core thicknesses. Briefly stated, interfaces

Table 2. Average values for G_c (N/m) for different crack lengths and core thicknesses. G_{c1} is for the first loading cycle and represents the initiation fracture toughness. Other G_c values are for subsequent loading cycles.

h_c(mm)	Average G_{c1}	Average G_{c2}	Average G_{c3}	Average G_{c4}
25.4	609	443	578	629
12.7	566	711	863	956
9.525	679	708	767	818
6.35	702	904	965	1050

subject to higher percentage mode 2 stresses will have higher critical fracture toughness values. A FE analysis was conducted to determine the relationship of G_c to mode-mixity.

FINITE ELEMENT ANALYSIS

Using the material properties given in Table 1 and Equations (3) through (8), we can obtain the following material parameters,

$$H_{11} = 2.3679 \times 10^{-4}, \quad H_{22} = 7.8737 \times 10^{-5},$$
$$\varepsilon = -0.013, \quad \left(\frac{H_{22}}{H_{11}}\right)^{1/2} = 0.5766 \tag{14}$$

The FE method was used to analyze the test specimens. The goal of the analysis is to obtain the detailed stress field in front of the crack tip and use the information to calculate the complex stress intensity factor K, the energy release rate G and mode-mixity parameter ψ. The FE models were created using the ABAQUS® [12] finite element program plane strain elements. The materials were assumed to be linearly elastic, and the material properties used can be found in Table 1. Both face sheets and the core are modeled as orthotropic materials. The face sheet was separated into individual layers of 0 and 90°. The FE model is shown in Figure 4. The boundary condition at A are $u_{A1}=0$, and at B are $u_{B1}=0$, and $u_{B2}=0$, where the subscripts 1 and 2 refer to displacements in the respective directions. The detailed mesh in the vicinity of the crack tip is shown in Figure 5.

Using the crack length and the corresponding critical load, the interface stresses σ_{11} and shear stresses τ_{12} were calculated at each node in front of the crack for a distance of one laminate thickness (1 mm). The mode 1 (K_1) and mode 2 (K_2) stress intensity factors were calculated at each node using

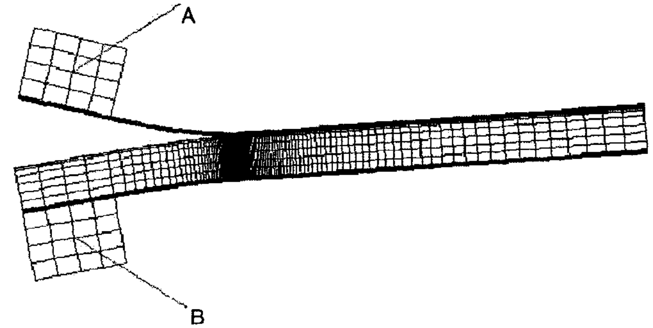

Figure 4. Finite element model of the asymmetric DCB sandwich specimen.

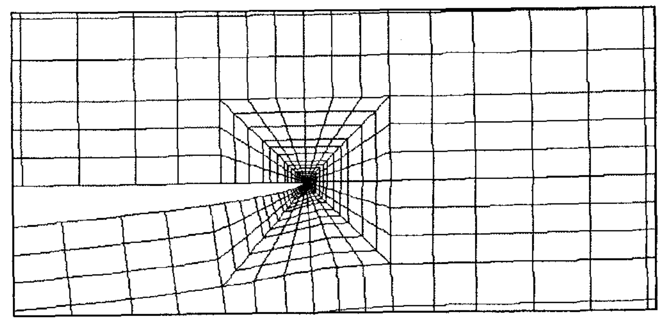

Figure 5. Details of the finite element mesh near the crack tip.

Equations (10) and (11). Then using K_1 and K_2, the mode-mixity parameter ψ was determined from Equation (1). The critical energy release rate or fracture toughness was calculated using Equation (12). The G_c values and mode-mixity parameters ψ obtained from the FE analysis are shown in Table 3.

The variation of G_c with crack length is shown in Figure 6, and it can be noted that no definite correlation can be found. The average value of G_c for all tests was equal to 747 N/m. The variation of G_c with mode-mixity ψ for all specimens (for all core thicknesses and crack lengths) is shown in Figure 7.

From the trend shown in Figure 7, one can approximately fit a linear relation for the fracture toughness as a function of mode-mixity. A least square fit yields

$$G_c(\psi) = 38.524\psi - 123.12 \tag{15}$$

Table 3. G_c values from experiments and FE analysis, and corresponding mode mixity parameter ψ. Face sheet thickness is 1.07 mm (0.042 in.).

Core thickness (mm)	P_{cr}(N)	Crack length (mm)	Experimental G_c (N/m)	FE analysis G_c (N/m)	Mode-mixity ψ (degrees)
25.4	60.9	24	609	632	16.5
25.4	36.7	39	443	415	17.5
25.4	33.5	56	578	571	18.0
25.4	23.5	84	629	546	18.5
12.7	56.9	24	566	650	22.4
12.7	41.6	41	711	616	23.9
12.7	38.5	56	863	911	24.5
12.7	34.3	73	956	1172	24.9
9.525	52.2	24	679	620	23.5
9.525	38.4	43	708	713	25.0
9.525	31.7	59	767	846	25.5
9.525	28.6	78	818	1023	25.9
6.35	55.7	24	702	779	22.6
6.35	46.0	40	904	881	23.7
6.35	40.9	56	965	1142	24.1
6.35	34.0	82	1047	1221	24.5
		Average	747	796	

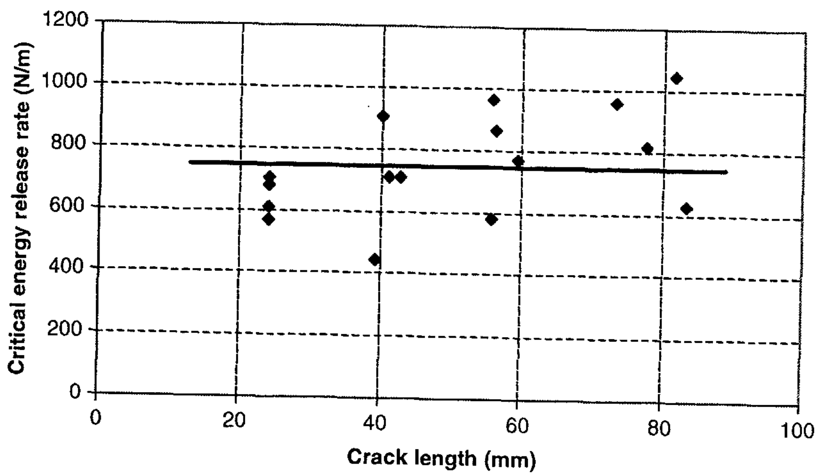

Figure 6. Critical energy release rate as a function of crack length, the solid line represents the average.

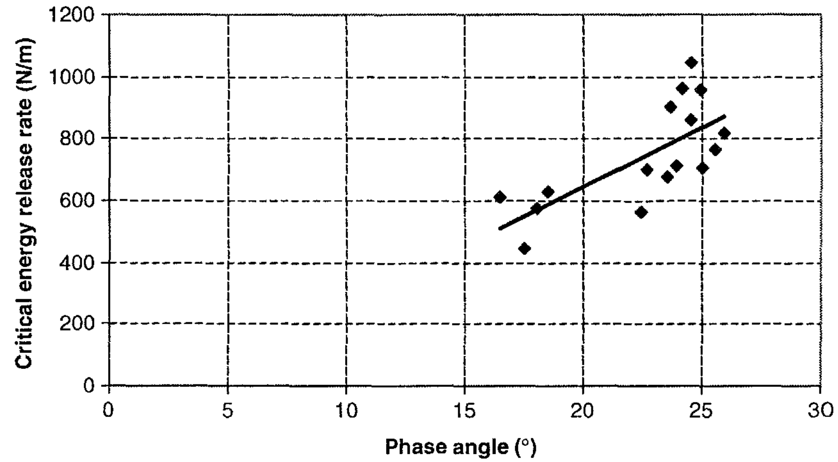

Figure 7. Critical energy release rate as a function of mode-mixity.

where G_c is in Newtons per meter and ψ is in degrees. If we assume that the interfacial fracture toughness is a constant for the particular material system, then the average fracture toughness $\bar{G}_c$ takes the value 747 N/m. It may be noted that according to the linear variation G_c equals to 747 N/m when $\psi = 22.58°$, i.e., $\bar{G}_c = G_c(22.58°)$. It should be mentioned that the relation in Equation (15) is empirical and hence is valid only in the range of mode-mixity values tested.

DESIGN EXAMPLE

To demonstrate the usefulness of fracture mechanics approach for debonded sandwich structures, we consider the problem of a pressure vessel similar to the liquid hydrogen tank of the X-33 reusable flight demonstration vehicle. The problem here is to determine the maximum gas pressure inside the core that will not cause a disbond of given length to propagate. Furthermore, we will illustrate the importance of considering the mode-mixity in the analysis. This failure mode occurred in X-33 vehicle fuel tank made using a sandwich design of a polymer matrix composite face sheets and honeycomb core.

In the present example, the problem of a pressurized disbond in a one-dimensional (1-D) sandwich plate is considered. The material properties are the same as in the previous section. The load and boundary condition are shown in Figure 8. Due to symmetry only the right half of the 1-D plate is modeled. The disbond is subjected to a uniform internal pressure. The FE model and a sample deformation shape are shown in Figure 9.

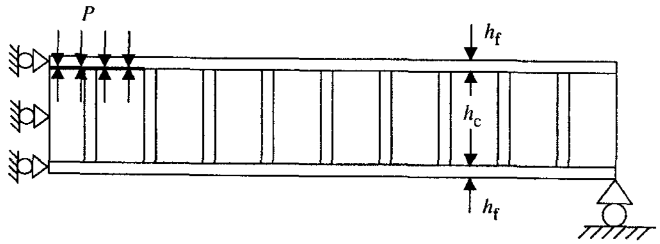

Figure 8. Half structural model of face sheet/core debonding in an one-dimensional sandwich panel with pressure load.

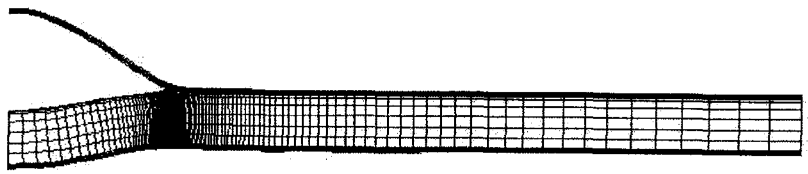

Figure 9. Finite element model and deformation shape (12.7 mm core).

In order to obtain the maximum allowable pressure for a given disbond length, the energy release rate has to be calculated for a unit applied pressure p. The energy release rate, G, is proportional to the square of the applied load or

$$G = cp^2 \tag{16}$$

where c is a constant and p is the applied pressure. One should note that the stress intensity factor is proportional to the load and G is proportional to the square of the stress intensity factor. The critical pressure $p_{\max}$ can be obtained using

$$p_{\max} = \sqrt{\frac{G_c}{G_0}} \tag{17}$$

where G_c is the interfacial fracture toughness of the sandwich material system obtained from testing and G_0 is the energy release rate corresponding to the unit pressure obtained from Equation (12).

The fracture toughness G_c can be obtained from the experimental results in two ways. If we ignore the effect of mode-mixity parameter ψ and assume that the interfacial fracture toughness is a constant for the material system, then we can use the average fracture toughness $\bar{G}_c$ in Equation (17).

***Table 4.** G_0 (Energy release rate for unit pressure), mode-mixity ψ, and maximum allowable pressure p_{max} based on two approaches for various disbond lengths. Face sheet thickness is 1.07 mm (0.042 in.).*

h_c (mm)	a(mm)	G_0 (N/m)	ψ (°)	$p^{(1)}_{max}$(MPa)	$p^{(2)}_{max}$(MPa)
25.4	12.7	7.37E-10	12.9	1.0066	0.7134
25.4	19.1	2.21E-09	13.3	0.5812	0.4196
25.4	25.4	5.16E-09	14.2	0.3805	0.2865
25.4	38.1	2.14E-08	15.4	0.1869	0.1486
25.4	50.8	6.01E-08	16.2	0.1115	0.0915
12.7	12.7	7.37E-10	14.5	1.0066	0.7676
12.7	19.1	2.21E-09	17.1	0.5812	0.4932
12.7	25.4	6.26E-09	19.0	0.3453	0.3113
12.7	38.1	2.65E-08	21.1	0.1678	0.1612
12.7	50.8	7.70E-08	22.3	0.0985	0.0977
9.525	12.7	7.37E-10	15.3	1.0066	0.7959
9.525	19.1	2.58E-09	18.3	0.5381	0.4753
9.525	25.4	6.63E-09	20.2	0.3355	0.3141
9.525	38.1	2.95E-08	22.3	0.1592	0.1579
9.525	50.8	8.62E-08	23.4	0.0931	0.0950
6.35	12.7	7.37E-10	15.5	1.0066	0.8027
6.35	19.1	2.58E-09	18.3	0.5381	0.4747
6.35	25.4	7.37E-09	19.9	0.3183	0.2952
6.35	38.1	3.21E-08	21.6	0.1526	0.1486
6.35	50.8	9.47E-08	22.5	0.0888	0.0886

On the other hand, one can consider the effect of mode-mixity parameter and express G_c as a function of ψ. In that case ψ has to be evaluated for each case, and the G_c to be used in Equation (17) will depend on the ψ for the particular case. The values of G_0, ψ, and the maximum allowable pressure for various disbond lengths are shown in Table 4.

In Table 4, $p^{(1)}_{\max}$ is the allowable pressure based on constant interfacial fracture toughness and $p^{(2)}_{\max}$ is calculated assuming the fracture toughness is a function of mode-mixity ψ (Equation 15).

The values of G_0, energy release rate for unit pressure, as a function of disbond length for different core thicknesses are shown in Figure 10. The variation of G_0 with respect to a is, in general, power-law type as expected. The energy release rate decreases as the core thickness increases. This is because the stiffness of the specimen increases with core thickness, which in turn reduces G_0.

The maximum allowable pressure for various crack lengths in panels of different core thicknesses is shown in Figures 11–14. The trend is similar in all figures. The constant G_c approach overestimates the maximum allowable pressure that can be applied. When mode-mixity is taken

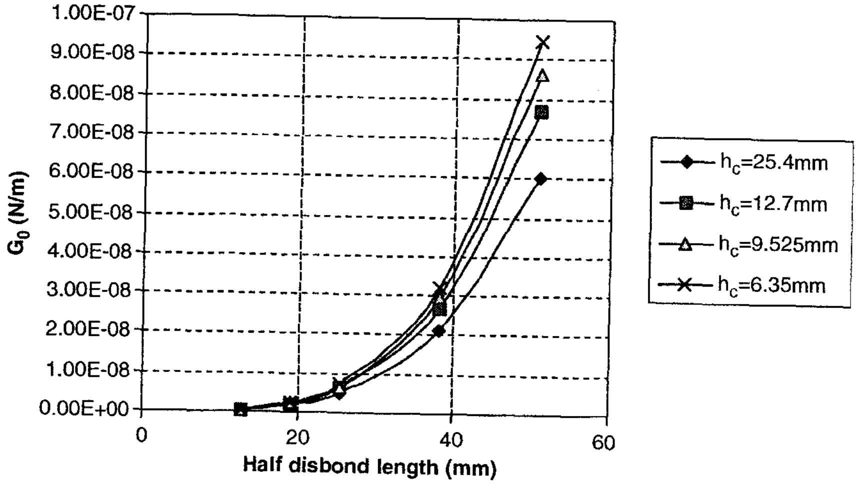

Figure 10. *Energy release rate for unit pressure.*

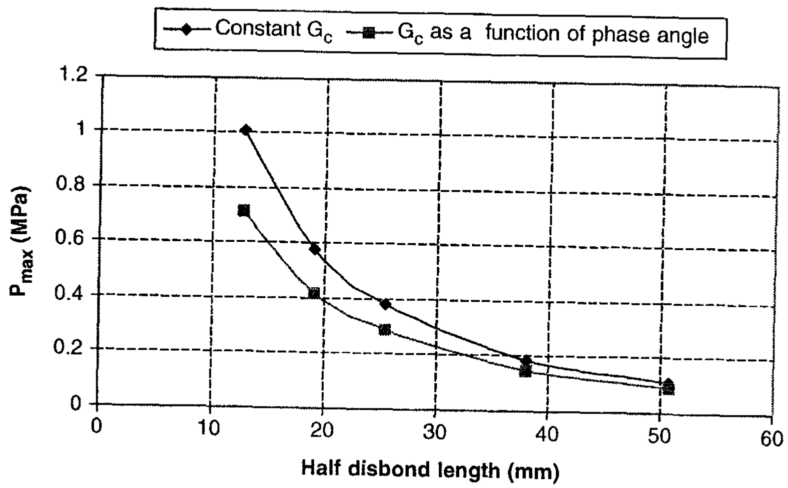

Figure 11. *Allowable pressure for various disbond lengths for 25.4 mm thickness core.*

into consideration, the allowable pressure decreases significantly for small disbond lengths ($10\,\text{mm} < a < 30\,\text{mm}$). Thus ignoring mode-mixity dependence on the interfacial fracture toughness can lead to overestimation of the strength of the sandwich structure and may lead to catastrophic failures. The maximum difference between the two approaches occurs for short disbond lengths in thick-core sandwich panels. The percentage difference

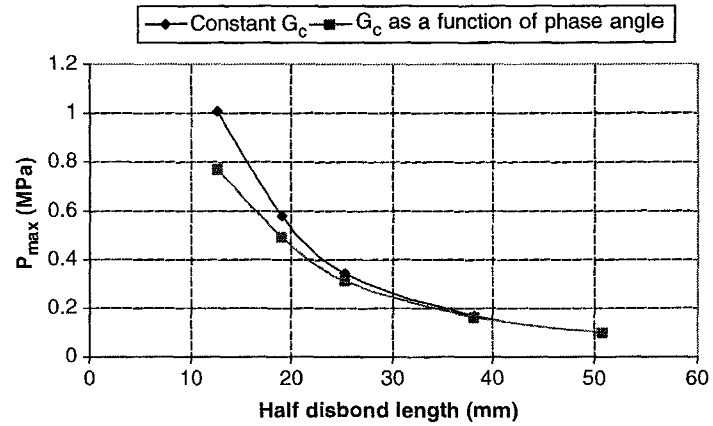

Figure 12. *Allowable pressure for various disbond lengths for 12.7 mm thickness core.*

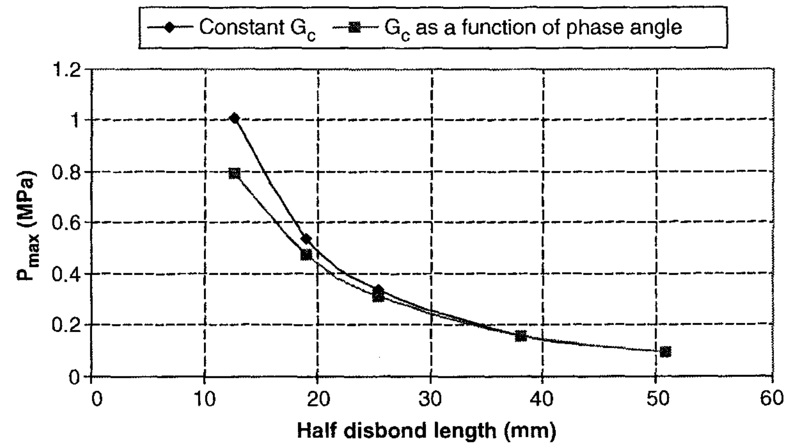

Figure 13. *Allowable pressure for various disbond lengths for 9.525 mm thickness core.*

between the two allowable pressures for $a = 12.7\,\text{mm}$ and $h_c = 25.4\,\text{mm}$ is about 41%.

SUMMARY

Asymmetric DCB fracture tests were performed on sandwich specimens in order to determine the interfacial fracture toughness. The experimental critical loads, and specimen dimensions, and properties were used in a finite element analysis (FE) to determine the detailed crack-tip stress fields corresponding to the experimental conditions. The FE results include the

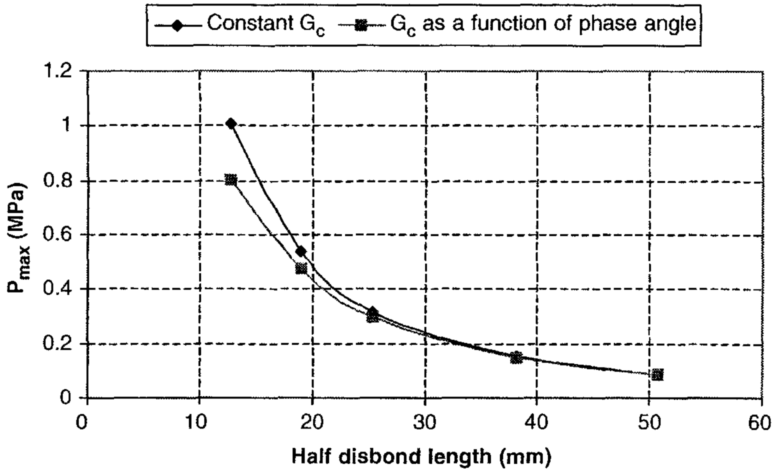

Figure 14. *Allowable pressure for various disbond lengths for 6.35 mm thickness core.*

mode 1 and 2 stress intensity factors, the energy release rate and mode-mixity parameter. The FE results for fracture toughness agreed well with the experimental values. The fracture toughness is found to increase with the mode-mixity. From the FE results, a linear empirical relation was determined between the fracture toughness and the mode-mixity parameter. The results were used to demonstrate the importance of considering the mode-mixity in the design of sandwich structures from a damage tolerance point of view. It is shown that assuming the interfacial fracture toughness as a constant for the material system will lead to overestimation of the strength of the structure which can lead to catastrophic failure.

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