Using the Climbing Drum Peel (CDP) Test to Obtain a G_{IC} value for Core/Facesheet Bonds

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ABSTRACT: A method of measuring the Mode I fracture toughness of core/facesheet bonds in sandwich structures is desired, particularly with the widespread use of models that need this data as input. This study examined if a critical strain energy release rate, G_{IC}, can be obtained from the climbing drum peel (CDP) test. The CDP test is relatively simple to perform and does not rely on measuring small crack lengths such as required by the double cantilever beam (DCB) test. Simple energy methods were used to calculate G_{IC} from CDP test data on composite facesheets bonded to a honeycomb core. Facesheet thicknesses from 2 to 5 plies were tested to examine the upper and lower bounds on facesheet thickness requirements. Results from the study suggest that the CDP test, with certain provisions, can be used to find the G_{IC} value of a core/facesheet bond.

KEY WORDS: honeycomb, fracture toughness, mode I delamination, double cantilever beam, climbing drum peel

INTRODUCTION

Sandwich structures, particularly with honeycomb core, have been used in the aircraft industry for years. Due to the criticality of weight concerns for space vehicles honeycomb sandwich construction is extremely attractive. A drawback of these structures can be a poor core/facesheet bond. Under mode I (opening-mode) stresses on the structure, if not well bonded, the facesheet can peel away from the core and since there are no mechanical fasteners or other "crack stoppers" this failure can debond very large areas causing catastrophic failure. The X-33 liquid hydrogen tank is a well-publicized case of this type of failure [1].

In order to obtain a mode I fracture toughness value (G_{IC}) for the facesheet peeling from the core, a test method needs to be utilized to obtain a meaningful number, not only for comparison, but for analysis purposes. This value is termed "critical strain energy release rate" and is simply the energy needed to create a unit of peeled surface area. No standard currently exists for determining the mode I toughness (critical strain energy release rate) of a core/facesheet bond. For sandwich structures, ASTM Standard D 1781 exists for quality control and relative comparisons and is not meant to be used to find a fracture toughness value [2]. In a paper by Okada and Kortschot [3] it was contended that a critical strain energy release rate could be calculated from the climbing drum peel (CDP) test. The most widely used method for determining G_{IC} for a facesheet peeling from a core is the double cantilever beam (DCB) test which follows the general outline for determining the critical strain energy release rate of a solid laminate which is given in ASTM Standard D 5528 [4]. Adaptations must be made since a sandwich structure and not a solid laminate is being tested. Various techniques to accomplish this can be found in the literature [5-14]. For the majority of these studies, the compliance calibration method was used to reduce the data and obtain a G_{IC} number.

This work is an extension of Reference [3] but with more emphasis on direct comparisons of the Climbing Drum Peel and the Double Cantilever Beam fracture toughness values and less emphasis on the details of the debond mechanisms.

ANALYSIS

Climbing Drum Peel (CDP)

Examining the mechanics of the climbing drum peel test can give a relation between displacement of the load frame's crosshead and the length of the facesheet that has been peeled. From this relation, energy methods can be used to determine the energy needed to produce the given length of peel. Figure 1 defines the notation that will be used. The following notation used in Figure 1 is:

d = load frame displacement
t_f = thickness of the facesheet being peeled
r_1 = inner radius of drum + one half facesheet thickness
r_2 = outer radius of drum + one half strap thickness
D_1 = length of facesheet peeled
D_2 = total displacement of the drum
θ = angle through which drum rotates

For a CDP test, ASTM Standard D 1781 only gives results as a *peel torque* defined as:

$$\tau = \frac{(P_2 - P_1)(r_2 - r_1)}{w} \tag{1}$$

Where P_1 and P_2 will be defined in Figure 2 and w is the width of the specimen..

From the figure it can be seen that the total displacement of the drum is equal to the amount of facesheet peeled plus the amount of load frame displacement. In equation form:

$$D_2 = D_1 + d \tag{2}$$

Since the arc length of a segment of a circle is given by $r\,\theta$;

$$D_1 = r_1\,\theta \quad \text{and} \quad D_2 = r_2\,\theta \tag{3}$$

Substituting in the second of equation (3) into equation (2) gives:

$$D_2 = \frac{r_2}{r_1} D_1 \tag{4}$$

Putting (4) into (2) gives:

$$D_1 = \frac{r_1 d}{r_2 - r_1} \tag{5}$$

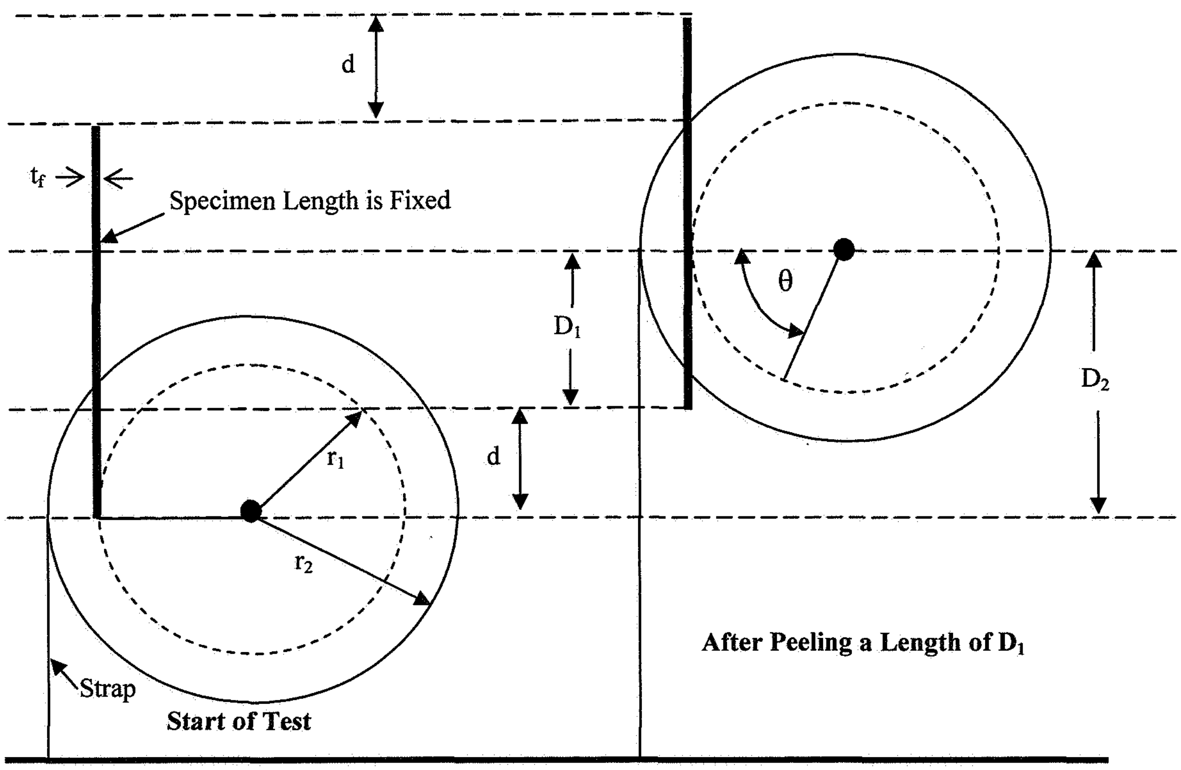

Figure 1. *Schematic of the CDP test at the start (left) and after peeling a length, D_1, of facesheet (right).*

This gives the length of facesheet peeled as a function of displacement and the two radii of the drum. A sketch of a load-displacement plot from a CDP test is given in Figure 2. In this sketch, P_1 is the load needed to overcome the drum rolling up the facesheet when no debonding is taking place and P_2 is the total load needed to roll up the drum plus the extra load needed to peel the facesheet off of the core. The saw tooth pattern as the drum peels the facesheet is due to the "stick-slip" behavior of the honeycomb as rows of cells are encountered.

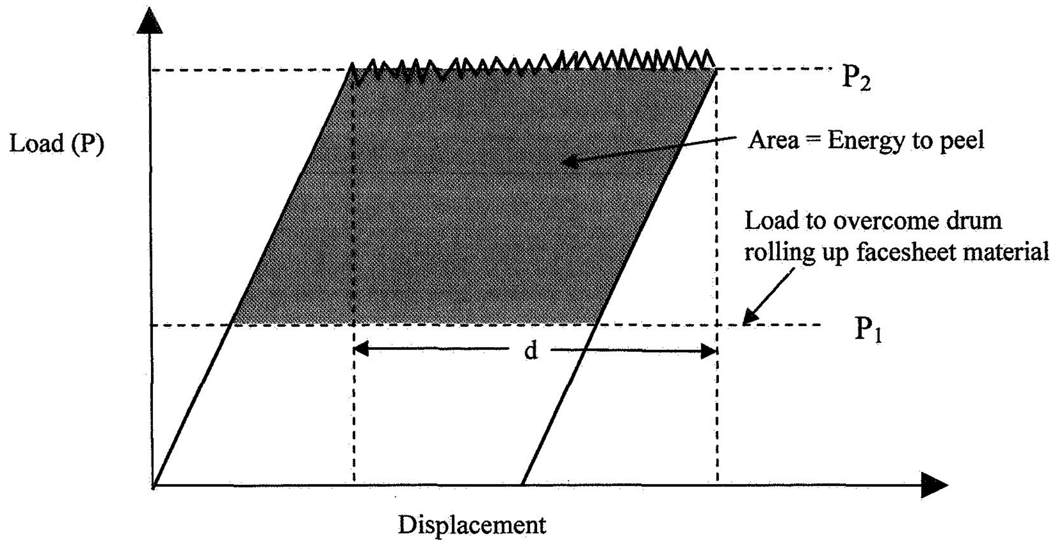

Figure 2. *Sketch of CDP load versus displacement data.*

Figure 2 shows the energy needed to peel the facesheet from the core as the area of the parallelogram under the curve between P_1 and P_2. Dividing this area by the surface area created on the peeled specimen gives the critical strain energy release rate. In equation form:

$$G_{IC} = \frac{(P_2 - P_1)d}{w D_1} \tag{6}$$

Where w is the specimen width.
Combining equations (5) and (6) gives:

$$G_{IC} = \frac{(P_2 - P_1)d(r_2 - r_1)}{w r_1 d} = \frac{(P_2 - P_1)(r_2 - r_1)}{w r_1} \tag{7}$$

Equation (7) is the peel torque divided by r_1. Analytically this is the critical strain energy release rate as determined from a climbing drum peel test.

Double Cantilever Beam (DCB)

A brief description of the DCB test follows, as it was used to validate the empirical data obtained from the CDP tests. A schematic of the DCB test and the notation used is shown in Figure 3.

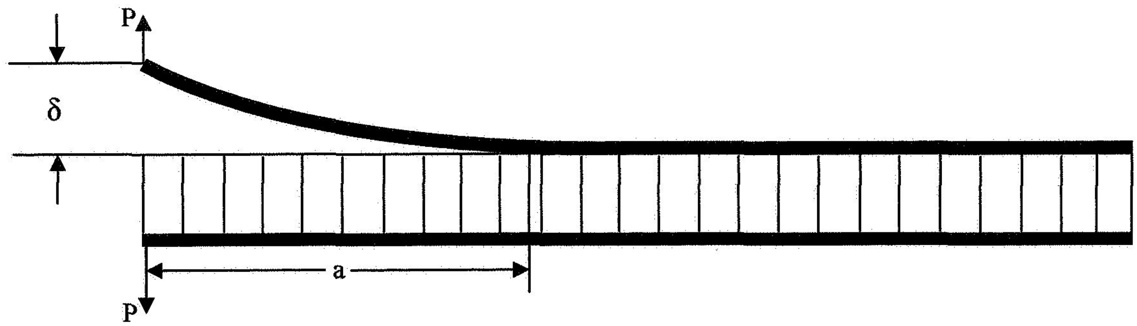

Figure 3. Schematic of the DCB test.

The following notation is used in figures 3 and 4:
δ = Opening displacement
P = Load
a = debond length

A sketch of typical load-displacement data is given in Figure 4. The shaded area under the curve represents energy required to bend and peel the facesheet. The test can be paused at any time as the disbond is growing for load, displacement and debond length data acquisition. However in this study, energy methods were used which only rely on the final disbond length. Thus, intermittent points were not necessary. As in the CDP test, a saw tooth pattern is developed as the disbond encounters and peels off of rows of cells.

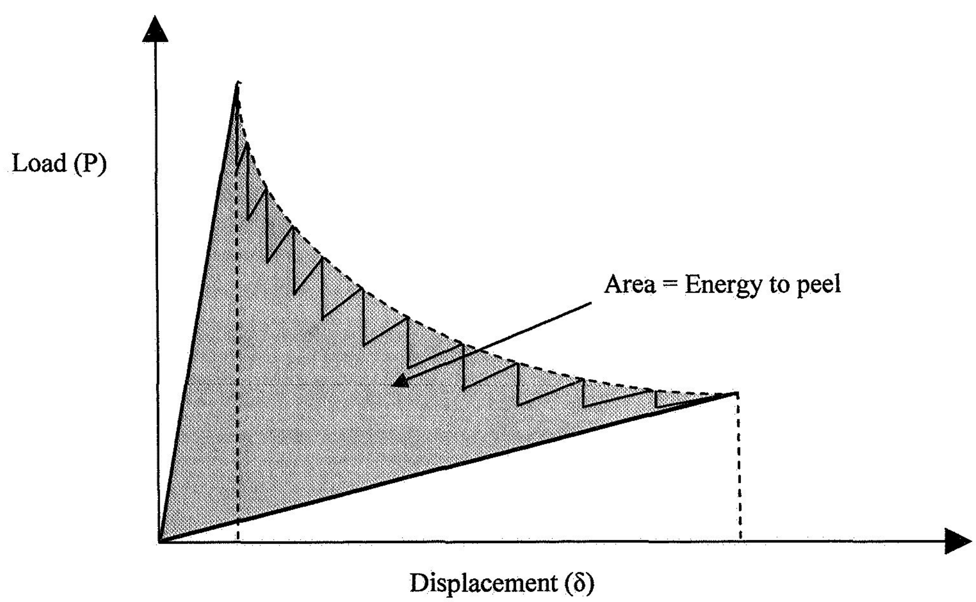

Figure 4. Sketch of load-displacement data for a DCB test.

The area under the curve (energy put into peeling) divided by the surface area created (disbond length times width) gives an estimate of the critical strain energy release rate. The area under the curve was found by integrating a polynomial curve fit of the test data.

EXPERIMENTAL

Materials and Specimen Preparation

The core used in this study was 1.27 cm (0.5 in.) thick glass/phenolic honeycomb with cell sizes of 4.76 mm (3/16 in.). Two core densities were used, 64.2 kg/m^3 (4.0lb/ft^3) and 128.4 kg/m^3 (8.0lb/ft^3). The facesheets consisted of carbon/epoxy plain weave with various thicknesses. An epoxy film adhesive of areal weight 300 g/m^2 was used between the facesheets and core in a co-cure process. The film adhesive was not so strong as to fail the honeycomb material before peeling at the core/facesheet bondline. The sandwich panels were processed in a platen press as square 35.6 cm (14 in.) panels from which specimens could be cut.

For the CDP test specimens, the cured sandwich panel was cut into 7.62 cm × 30.38 cm (3 in. × 12 in.) beams. At the top of the specimen, 2.54 cm (1.0 in.) of one of the facesheets and all of the core were removed to grip the specimen. At the bottom of the specimen, 5.1 cm (2.0 in.) of one facesheet and core were removed for gripping into the drum. Also at the bottom of the specimen, a 7.62 cm (3 in.) long cut (precrack) was made between the facesheet to be peeled and the core. This was done to obtain a baseline load (P_1) for rolling up the facesheet without peeling. This prevented errors in where the load frame was "zeroed-out" since the difference between P_1 and the load to peel (P_2) are needed in the calculation of G_{IC}. A sketch of the specimen is shown in Figure 5.

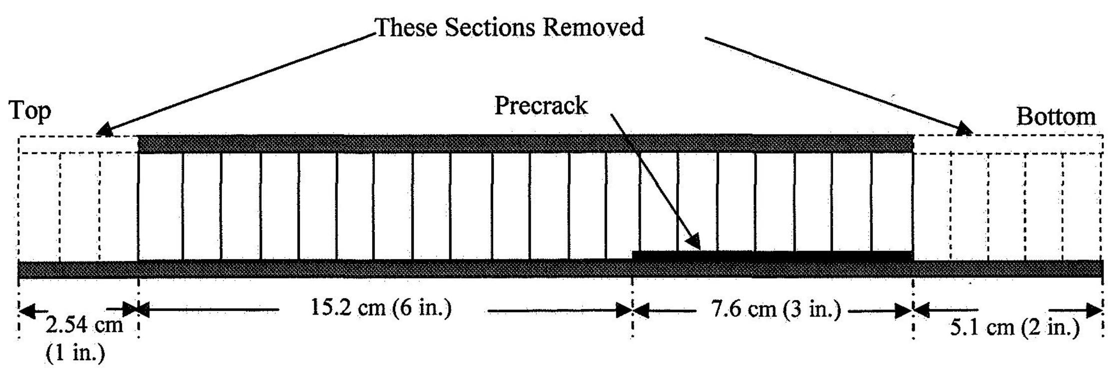

***Figure 5.** Schematic of the CDP test specimen.*

For the DCB tests, the cured panel was cut into 5.1 cm (2 in.) wide × 16.5 cm (6.5 in.) long test specimens. Each specimen had 2.54 cm (1in.) of core removed from one end to allow rods to load the facesheets from their inner surface thus precluding the need to bond hinges. A schematic of the DCB test specimen is shown in Figure 6. The bolts were placed at the end of the specimen to keep the loading rods from slipping out.

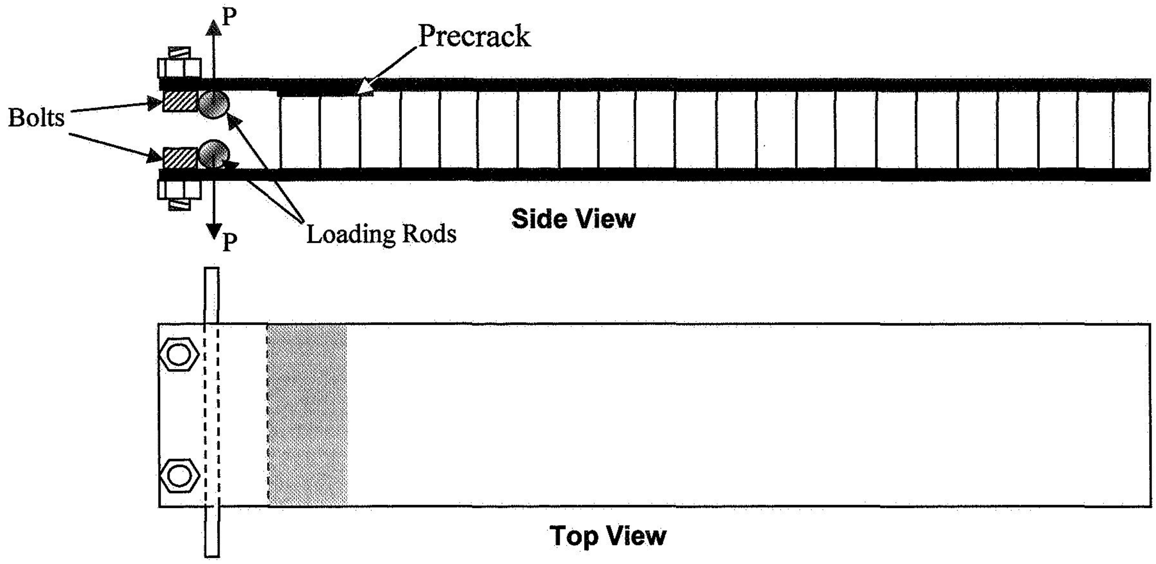

Figure 6. Sketch of a DCB specimen.

Mechanical Testing

The climbing drum peel apparatus was based on ASTM Standard D1781. Originally a fixture exactly like the one proposed in the Standard was used, however modifications were made to the drum attachment that provided for the testing of thicker facesheets. The original drum forced the facesheet to fold over a 90 angle before rolling smoothly up the drum causing facesheets thicker than 2 plies to snap along this severe bend as shown in Figure 7. A modification was made where the specimen was clamped tangentially to the drum as shown in Figure 7 to eliminate the folding of the facesheet. This modification allowed thicker specimens to be tested.

The (3 in.) long precrack was used to obtain the load needed to roll up the facesheet which was subtracted from the average load to peel the facesheet. A schematic of typical data is shown in Figure 8.

To find the value of P_1, an average of all of the load data from the first "knee" in the curve to the second "knee" was taken. To find the value to use for P_2, an average of all of the data from the start of the peel to the end of the test was used. The G_{IC} was found from equation (7) with the following drum dimensions:

r_1 = 5.08 cm (2.0 in) + $t_f/2$, where t_f is the thickness of the facesheet being peeled.
r_2 = 6.40 cm (2.52 in.)

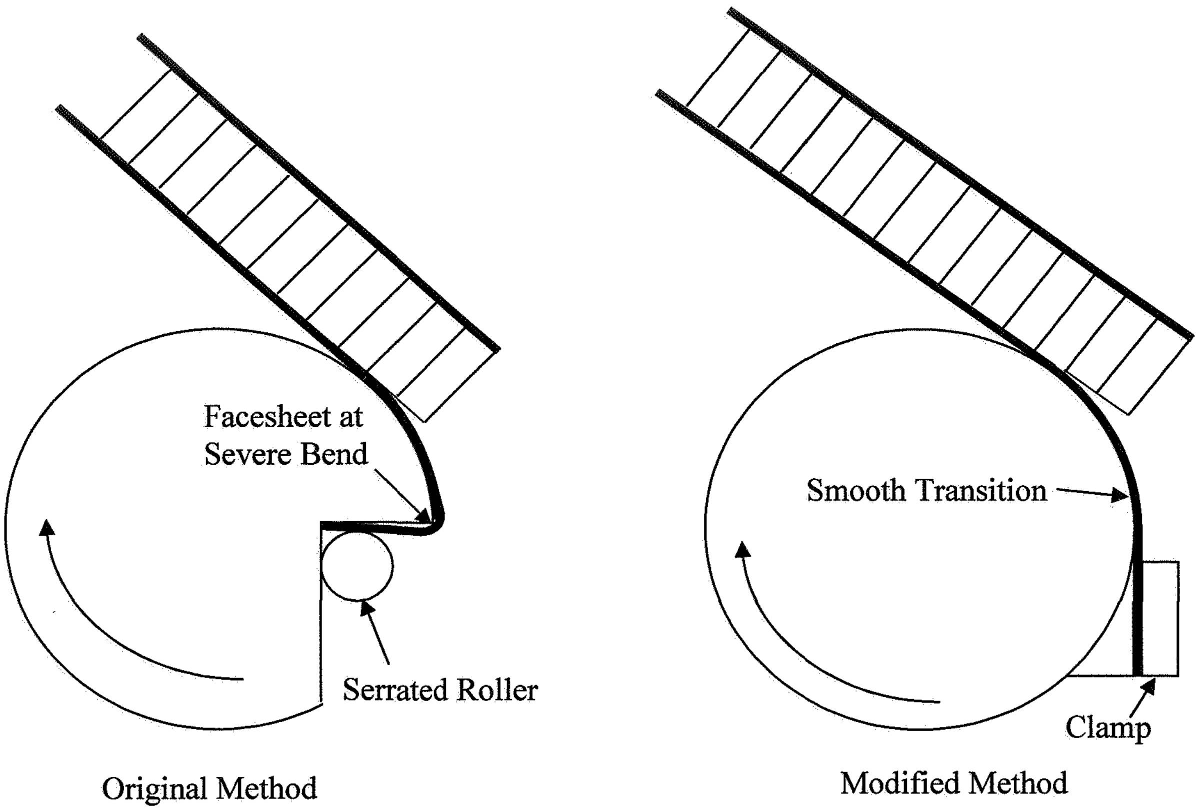

Figure 7. *Schematic of original and modified methods to grip the specimen to the drum.*

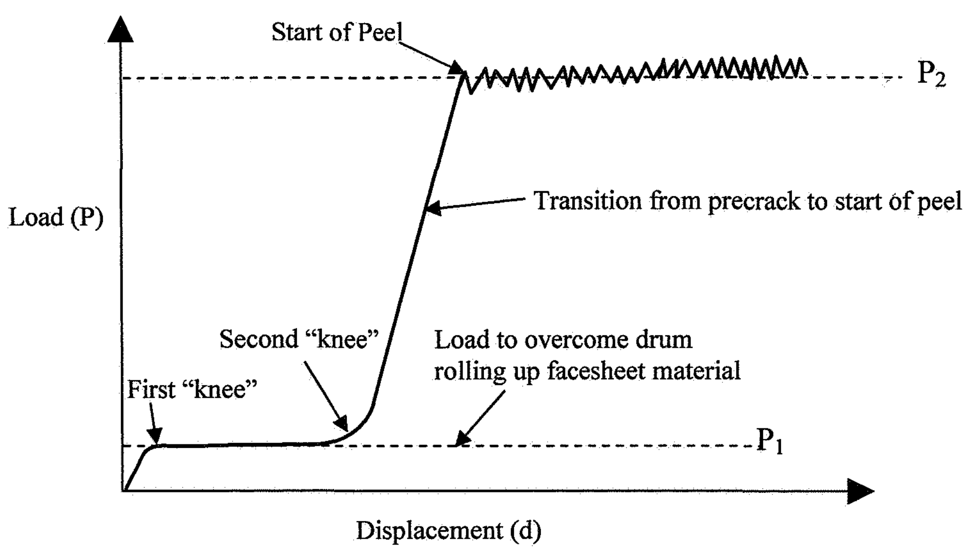

Figure 8. *Example load-displacement data from a CDP test.*

The DCB test methodology was based on ASTM Standard D5528 with some modifications. These included:

- Loading the specimen from the inside of the facesheets rather than using hinges or blocks.
- Marking the crack front and recording data after a discreet growth occurrence due to the "stick-slip" behavior of the specimen.
- Filling the exposed honeycomb edge with spackling compound to provide a smooth surface which facilitated taking crack growth measurements.
- Using the "areas" method of data reduction as mentioned in the Analysis section.

RESULTS

Results from the CDP tests are summarized in Table 1. Tests were conducted with the core oriented with the "L" (ribbon) and "W" (width) direction parallel to the peeling. These indicate the "pull direction" in Table 1. The number of plies of woven carbon/epoxy prepreg used to make the facings is also indicated in the table. A cursory examination of Table 1 shows that the critical strain energy release rate is independent of core density, facesheet thickness, and core orientation. Specimen CD7-26-05B was an outlier for which the measured G_{IC} was abnormally low. No known factors could be attributed to this low value. For specimens that had facesheet thickness of 6 plies, the facesheets would break in flexure and thus 5 plies was the upper limit of thickness that could be tested with the materials used in this study. A larger diameter drum may help alleviate this problem should thicker laminates need to be tested.

Table 1. Results of the CDP tests.

Specimen ID	Facing Thickness (Plies)	Core Density (kg/m^3)	Pull Direction	G_{IC} (J/m^2)
CD7-15-05A	2	64.2	"L"	1278
CD7-16-05A	3	64.2	"L"	1384
CD7-16-05B	3	64.2	"L"	1366
CD7-16-05C	3	64.2	"L"	1201
CD7-18-05NVA	2	64.2	"L"	1348
CD7-18-05NVB	2	64.2	"L"	1313
CD7-18-05NVC	2	64.2	"L"	1366
CD7-18-05VA	2	64.2	"L"	1348
CD7-18-05VB	2	64.2	"L"	1313
CD7-18-05VC	2	64.2	"L"	1366
CD7-20-05A	5	64.2	"L"	1243
CD7-20-05B	5	64.2	"L"	1366
CD7-26-05A	2	128.4	"L"	1261
CD7-26-05B	2	128.4	"L"	963
CD7-26-05C	2	128.4	"L"	1278
CD7-27-05A	3	128.4	"L"	1243
CD7-27-05B	3	128.4	"L"	1383
CD7-27-05C	3	128.4	"L"	1296
CD7-28-05A	4	128.4	"L"	1401
CD7-28-05B	4	128.4	"L"	1121
CD7-28-05C	4	128.4	"L"	1243
CD7-28-05-1A	2	128.4	"W"	1418
CD7-28-05-1B	2	128.4	"W"	1383
CD7-28-05C-1C	2	128.4	"W"	1453

CD7-29-05-1A	3	128.4	"W"	1331
CD7-29-05-1B	3	128.4	"W"	1261
CD7-29-05-1C	3	128.4	"W"	1313
CD7-29-05-2A	4	128.4	"W"	1173
CD7-29-05-2B	4	128.4	"W"	1348
CD7-29-05-2C	4	128.4	"W"	1243
CD11-11-05A	2	128.4	"L"	1138
CD11-11-05B	2	128.4	"L"	1156
CD11-09-05A	3	128.4	"L"	1243
CD11-09-05B	3	128.4	"L"	1278
CD11-21-05A	4	128.4	"L"	1138
CD11-21-05B	4	128.4	"L"	1156
CD1-08-05A	5	128.4	"L"	1121
CD1-08-05B	5	128.4	"L"	1138
CD2-17-06A	4	128.4	"L"	1278
CD2-17-05B	4	128.4	"L"	1296

A plot of G_{IC} versus the number of plies in the facesheet is shown in Figure 9. For similar specimens each point represents an average value. Specimen CD7-26-05B has been removed due to its abnormally low value. The data have been separated out by pull direction and core density.

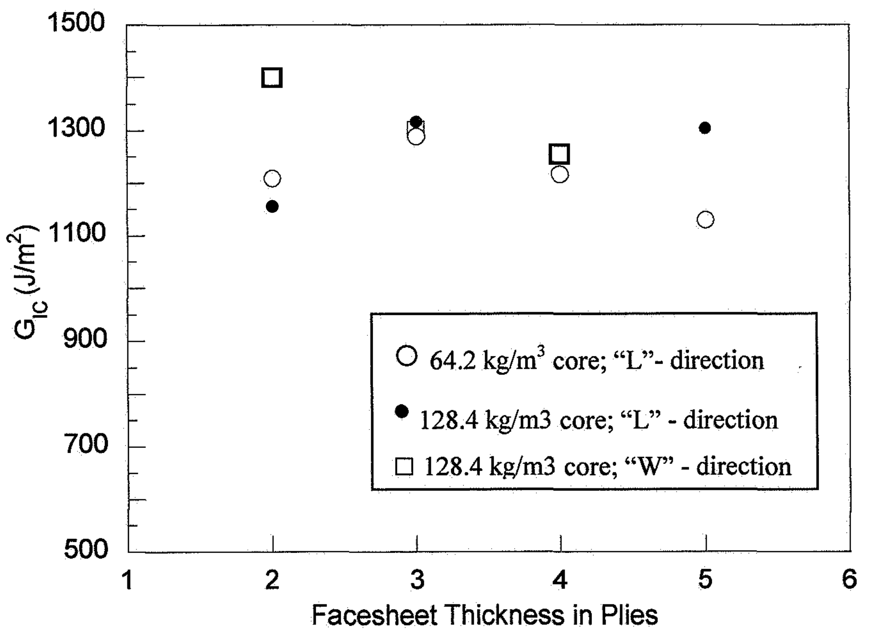

Figure 9. *G_{IC} versus facesheet thickness for CDP data.*

The data are essentially uniform and an average of all of the data taken as one group gives a G_{IC} value of 1258 J/m^2 (7.2 in-lb/in^2). In this study this value will be compared to G_{IC} values obtained via a modified DCB method as noted earlier.

Actual data for an "L"-direction and "W"-direction peel are shown in Figure 10. From these data it can be seen that the "saw tooth" pattern is not much more pronounced in the "L"-direction as expected and outlined in reference [3]. While "stick-slip" behavior was observed in the form of the drum and specimen "jerking" at discreet intervals, the data does not clearly show a saw tooth pattern but more of a random one during the peeling of the facesheet from the core.

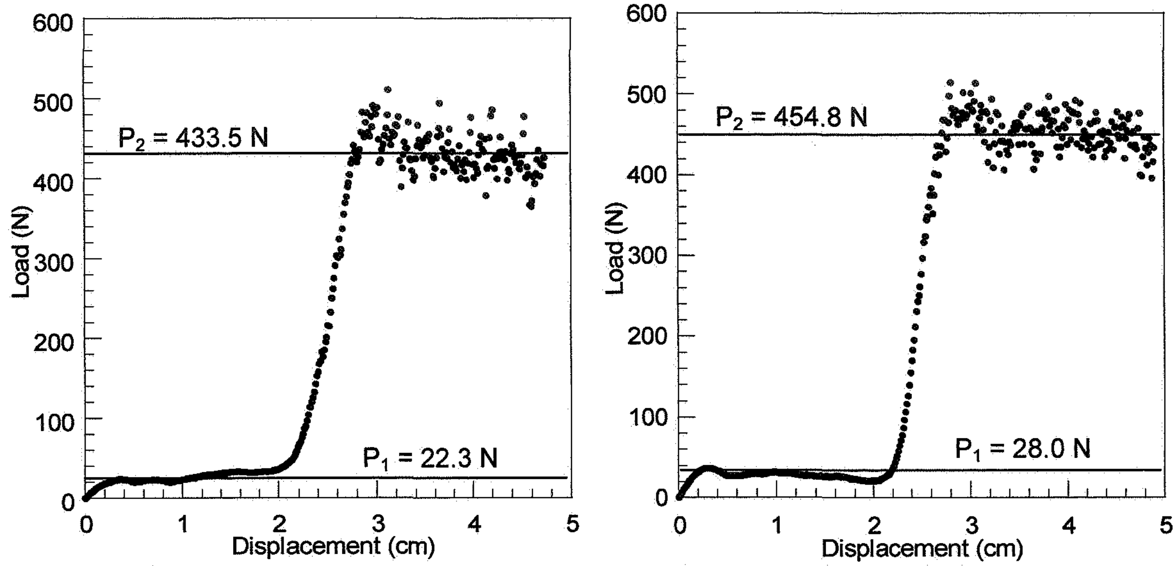

Figure 10. *CDP load-displacement data for "L" (left) and "W" (right) direction peels.*

Figure 10 also shows the average loads used as P_1 and P_2 for equation (7).

Results from the DCB tests are summarized in Table 2. Tests were conducted with 128.4 kg/m^3 (8.0 ln/ft^3) core, (except for the two tests noted), oriented with the "L" (ribbon) direction parallel to the peeling. The number of plies of woven carbon/epoxy prepreg used to make the facings is also indicated in the table. An ANOVA analysis suggests that the number of plies does not affect the G_{IC} value.

Table 2. Results of the DCB tests

Specimen ID	Facing Thickness (Plies)	G_{IC} (J/m^2)
DCB11-09-05A	3	1226
DCB11-09-05B	3	1208
DCB11-09-05C	3	1383
DCB11-09-05E	3	1331
DCB11-21-05A	4	1348
DCB11-21-05B	4	1191
DCB11-21-05C	4	1243
DCB1-17-06A	4*	1191
DCB1-08-06B	4*	1086
DCB1-08-06A	5	1243
DCB1-08-06B	5	1348
DCB1-08-06C	5	1303
DCB1-08-06E	5	1366
DCB1-08-06F	5	1366
DCB1-20-06A	8	1366
DCB1-20-06B	8	1611
DCB1-20-06C	8	1471
DCB1-20-06D	8	1278
DCB1-20-06E	8	1278

*Core was 64.2 kg/m^3 (4.0 lb/ft^3)

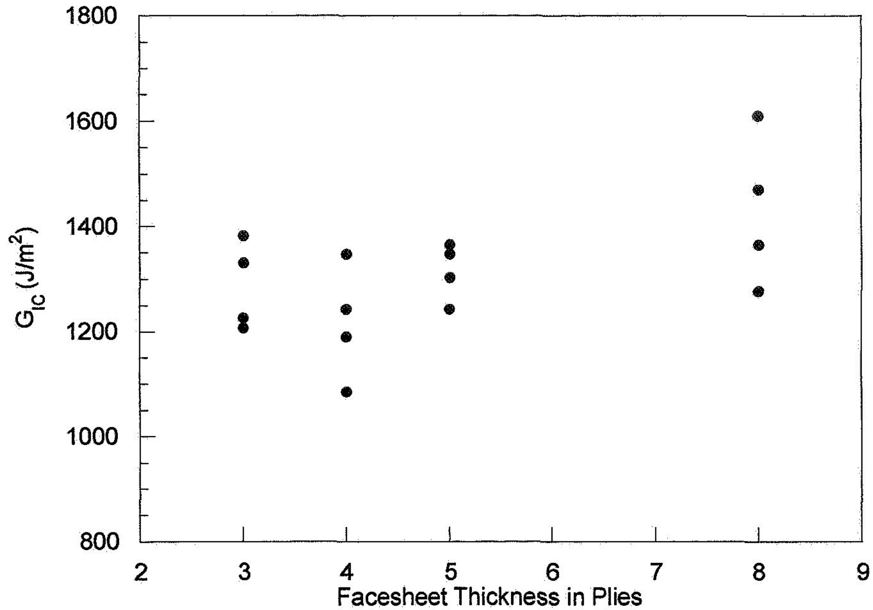

Figure 11. *G_{IC} versus facesheet thickness for DCB data.*

Figure 11 is a plot of the DCB data as a function of number of plies in the facesheet. The data are fairly uniform with no distinct trend. Averaging all of the data gives a G_{IC} of 1313 J/m^2 (7.5 in-lb/in^2) which compares similarly to the G_{IC} value of 1258 J/m^2 (7.2 in-lb/in^2) as given by the CDP test.

Additional CDP and DCB testing with a tougher film adhesive used to bond the facesheet to the core demonstrated that the bondline can be tougher than the core and failure will take place within the core itself rather than the core pulling off of the facesheet. For these tests, upper G_{IC} values of between 1576 J/m^2 (9 in-lb/in^2) and 1751 J/m^2 (10 in-lb/in^2) were calculated for two tough film adhesives tested. For these particular tests, 64.2 kg/m^3 (4.0 lb/ft^3) Nomex core was used. In actual practice core failure is desirable as it indicates a high quality bond similar to having the core fail before the bondline in a flatwise tension (FWT) test. Pictures of the fracture surfaces are shown in Figure 12 (Honeycomb) and Figure 13 (Facing).

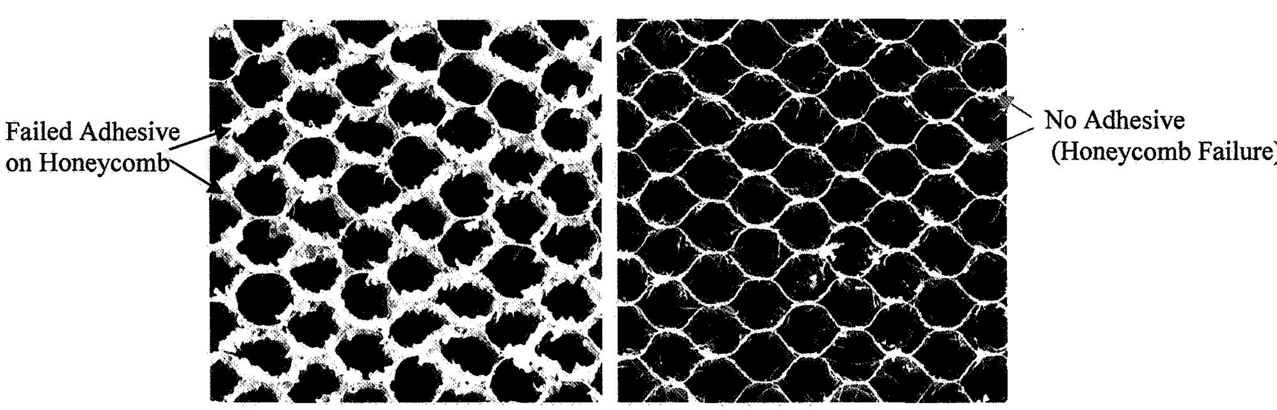

Figure 12. *Surfaces of honeycomb after CDP tests for a bondline failure (left) and core failure (right).*

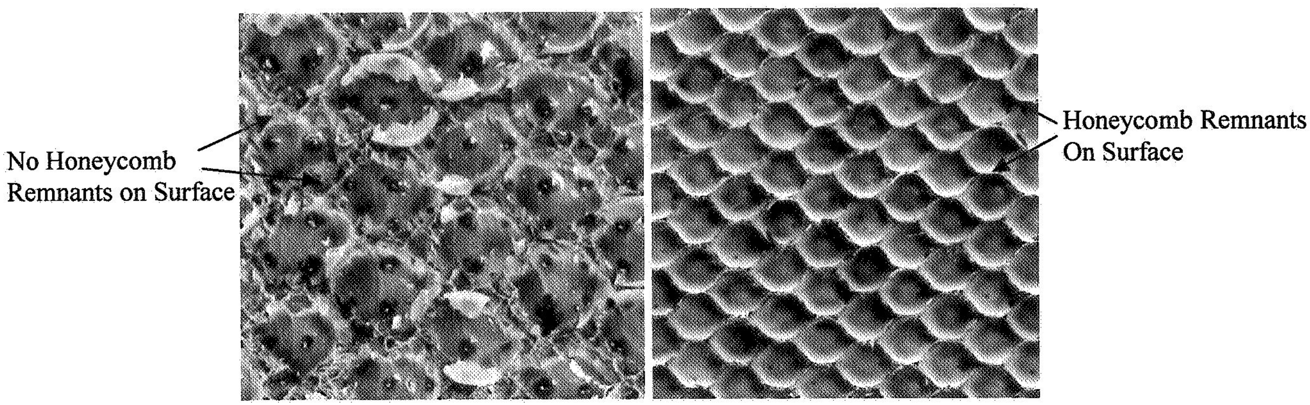

Figure 13. Surfaces of facesheet after CDP tests for a bondline failure (left) and core failure (right).

If a tough adhesive is used in conjunction with a relatively high density honeycomb, the problem of the specimen fracturing through the honeycomb is solved, but now the weak link may be the facesheet itself. For a woven carbon/epoxy 2 ply facesheet on 128.4 kg/m3 (8.0 lb/ft^3) core bonded with a tough adhesive, the debond would propagate into the facesheet and the test would actually become a test of the interlaminar fracture toughness of the facesheets. A photograph of this type of failure is given in Figure 14.

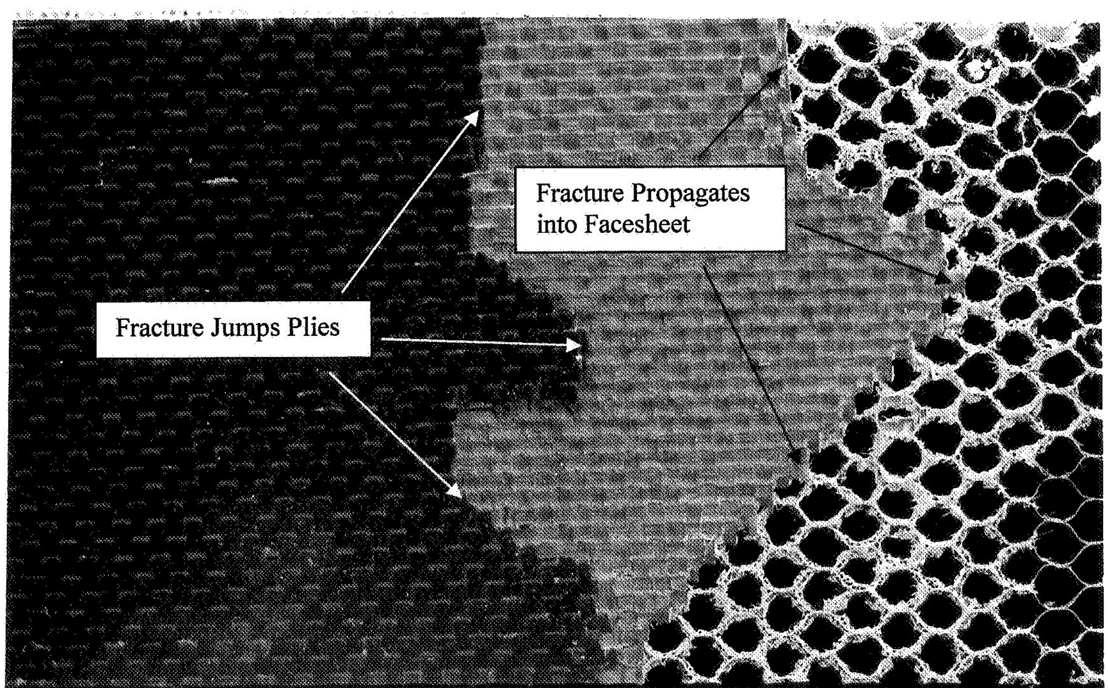

Figure 14. CDP specimen showing failure of the facesheet.

CONCLUSIONS

Climbing drum peel (CDP) tests were used to calculate a critical strain energy release rate (G_{IC}) for the peeling of a facesheet off of a honeycomb core. Using energy methods, the G_{IC}

value is simply the peel torque divided by the radius of the drum plus one half the facesheet thickness. Results showed that the value obtained using this method gave results similar to those obtained using a double cantilever beam (DCB) method. Restrictions on utilizing the CDP test are:

- The facing cannot be so thick (stiff) as to not bend around the drum
- The bondline must be the "weak link" in the sandwich structure. If not, the honeycomb core can fail (lower density core) or the facesheet can fail (higher density core)
- The facing must be strong enough not to fail in tension

It should be noted that in practical applications, it is actually desirable to have the honeycomb fail during a Mode I fracture test as this indicates that the facing is bonded to the core with sufficient quality as to not be the weak link. However this is not always possible, especially at high temperatures where the adhesive degrades and the CDP test can be effectively utilized to find a G_{IC} value for the core/facesheet bond.

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