MIXED MODE FRACTURE BEHAVIOR OF CELLULAR FOAM CORES USED IN SANDWICH STRUCTURES

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1 General Introduction

The utilization of polymeric composite based sandwich structures is of current interest to US and several European navies and finds increasing use in many composite material based structural applications. In our research, the composite sandwich material consisted of a thick closed cell polymeric foam layer, Divinycell Diab H100, having a density of 100 kg/m^3 that is placed between thin (approximately 2 mm) carbon fiber reinforced vinyl ester resin based polymeric composite facings prepared using VARTM process. The H100 foam used in this study has a high strength-to-weight ratio and a closed-cell structure that provides low hydraulic conductivity. Its lightweight lowers the center of gravity of the naval vessels, when incorporated in the super structure, and similarly increase the buoyancy of submersibles. Basic mechanical properties of individual foam and facing and their degradation to sea water have extensively been studied recently by the first two authors [1,7, 9].

One of the dominant failure modes observed in sandwich structures when subjected to blast or dynamic loading often involves the fracture of cellular foam core. Fracture mode mixity on PVC foam has been investigated analytically and experimentally in terms of fracture toughness K_{Ic} and K_{IIc} in the past [2,3]. Fracture toughnesses for mode I cracking of various PVC foam cores were comprehensively evaluated by Viana and Carlsson [4,5]. The fracture behavior of materials can also be evaluated using critical energy release rate, G_C, values for predicting crack propagation without the restrictive assumption associated with linear elastic fracture mechanics. In the past, the critical energy release rates for the interface of composite between foam and facing, commonly referred to as delamination, are presented experimentally by employing a custom made fixture and load application facilitated by using hinges glued to the facing using Double Cantilever Beam (DCB) set up [6]. If such methods used in the past to obtain delamination fracture toughness are applied to evaluate fracture behavior of pure foam only, then the experiment will not work in this type of configuration since it forces the natural crack from pre-crack to quickly propagate towards the interface of the composite facing boundary between carbon fiber/vinyl ester composite facing and PVC foam core. Typically the loading for an initially angled crack is a combination of Mode I and Mode II, but the crack tends to propagate normal to the applied load, resulting in Mode I loading. A propagating crack seeks the path of least resistance. Assuming the cellular solid material is isotropic and homogenous, the crack propagates in such a way as to maximize the energy release rate. In this study, the experimentally measured critical energy release rates for modified DCB specimens arranged at various angles to the reference horizontal axis were employed to simulate different levels of mode mixity. It is assumed that either crack propagation will occur at the crack tip where the energy release rate is maximum or when the energy release rate reaches some critical level. The crack propagation analysis in foam cored sandwich DCB specimen were provided in ref. 6 determining whether the crack would propagate self-similarly or kink upwards or downwards.

As mentioned above random crack kinking has been an important limitation to the currently available literature on describing pure and mixed mode fracture behavior of foam core materials for possible implementation in rigorous analytical formulation or in Finite Element Method [7]. To overcome the existing limitation, the foam fracture behavior is investigated in this study by employing a modified DCB specimen with notches on both sides to direct crack evolution and propagation within a channeled notch. From our experimental trials it was found that use of channeled specimen overcomes the cracks tendency to deflect towards the top or bottom boundary (facing). This study made an attempt to study mixed mode fracture behavior of foam core materials by the aforementioned procedure with a custom made fixture using modified DCB specimens tilted at various target values of inclination. Experimental data is collected by recording intermittent crack growth on pre-cracked and pre-notched samples for a given tilt angle.

2 Material and Preparation

In this investigation, PVC closed cell H100 foam material (100 kg/m^3) from DIAB [8] was studied. The foam panel was provided in the form of 25 mm thickness. A typical characteristic tensile stress-strain curve for this foam material is shown in Fig. 1. Typical mechanical and thermal properties of this cellular foam material both from axial (tension) and torsion (shear) are summarized in Table 1 from authors related research [9].

The H100 foam specimens were obtained from a large panel and machined to dimensions of 250 mm in length (L), 25 mm in width (H) and 25 mm in height (B). These specimens were integrated into load frame to perform fracture tests at target tilt angles (θ) from 0° to 40° as shown in Fig. 2. To maintain a straight crack front, all specimens were machined to have equal V-notches along both sides at the middle of their height dimension. An additional V-shaped sharp pre-crack (a) was cut 25 mm away from the loaded edge. Two side channels approximately 6 mm deep (d) were cut along the length of the modified DCB specimen at mid-height as shown in Fig. 3. In doing so, a crack was initiated and hence guided to extend along the channeled section either for pure mode-1 and for those experiments with desired tilt angle to yield a pre-determined mixed mode fracture. An example of the test specimen with side channels was shown in Fig. 4. Aluminum T-bars were adhesively bonded to the top and bottom of all foam samples using West System 105 epoxy resin mixed with West System fast harden and high density adhesive filler. A minimum of three specimens were evaluated at each tilt angle to determine average fracture properties that included mixed mode behavior. Given the inherent variation expected in cellular foam materials, repeating at least 3 times provided a measure of repeatability of fracture properties for these difficult and complex materials.

3 Mixed Mode Fracture Experiments

To obtain mixed mode behavior and prevent the excessive bending of modified DCB specimens, aluminum T-bar were adhesively bonded to reinforce the top and bottom planes of the specimen. The experimental configuration is shown in Fig. 5. At each target inclination angle a piece of aluminum bar was welded to rotate an angle that corresponds to an increasing amount of Mode II. The angle θ used for this study included 0°, 10°, 15°, 20°, 25° and 30° (35° and 40° under investigation).

Mixed mode fracture tests were carried out using a 100 kN MTS tensile test system with a 3.5 kN external load cell. During the test, the top T-bars used to reinforce the specimen were attached to hinged connection where applied load was transferred. A magnifying optical window and DC beam back light were used to pinpoint the crack tip locations whenever intermittent crack growth came to a halt during a modified DCB fracture test. An example digital image of a crack front from back lighting for the setup is shown in Fig. 6. The crack tip location was recorded immediately using a digital camera and with channeled section painted white prior to crack initiation (load application) to clearly locate position of the crack tip after its propagation for a given load-displacement loop. Using digital image analysis software (ImagePro®), crack morphology was analyzed for use in determining critical energy release rates (G_c).

Load was applied to the pre-cracked specimen using displacement control at a constant rate of 1 mm/min. Load P_c and displacement δ data were recorded throughout the test. Axial tension was monotonically increased under displacement control until an abrupt drop in load amplitude was noted, at which stage crack extensions were observed, and at that point, the crosshead displacement was programmed to stop using well calibrated PID control algorithm at which point the tensile loading machine was allowed to unload to zero displacement. This procedure was repeated for few crack propagation cycles until the crack front approached the far edge of a specimen. The crack tip location were recorded on both front and back sides of the modified DCB specimens to obtain detailed information about the nature of the crack front and related estimates on critical energy release rate for a given crack advancement.

4 Results and Discussions

The critical energy release rate, which describes the fracture behavior of H100 foam, was obtained using the expression [10]:

$$G_c = \frac{1}{b}\frac{\Delta U}{\Delta a} \tag{1}$$

Where ΔU is the area under the load-displacement trace for a given crack advancement; Δa is the incremental crack length recorded during the test, and b is the width of specimen. The value calculated is the average critical energy consumed for the crack extension Δa.

Values of G_c were computed from almost linear load/unload-displacement data until fracture akin to those shown in Fig. 7 were obtained at various tilt angles. The results, tabulated in Table 2, suggest that G_c increases as the tilted angle increases. This can be explained due to the increase of Mode II portion of fracture toughness with increasing angle. As shown in Table 2, the average of G_c and standard deviation values are listed from over 30 cycles of data set for each inclination angle. The wide range of values listed in Table 2 reflects the cycle to cycle variability in the fracture behavior associated with random microstructure of cell walls associated with PVC foam core. Fig. 8 shows the resistance curves (R-curve) for the H100 foam. This is affirmed by previous investigators for delamination toughness [11] similar to the observed G_c increase with the increase of tilt angle, with the implicit assumption that tilt angle increase corresponds to increase in mode-II component. It can be seen that fracture toughness of PVC foam remains reasonably constant over the range of crack lengths, especially for low tilt angles of 0° to 15°. As an example, we show differences in measurements for critical energy release rate for various samples for the first cycle which corresponds to an identical length of pre-crack as shown in Fig. 9. It is observed that the average G_c due to artificially induced V-shaped sharp pre-crack corresponded to a measured average G_c value that is slightly lower than the average overall G_c as listed in Table 2 which includes varying crack lengths, many of which are naturally formed by the foam core material after first cycle. The measured data needs careful further analysis to extract the effects of artificially induced pre-crack, subsequent natural crack evolution, distance of pre-crack to loading point, and crack length. In this paper, we simply chose to present effects in an average sense considering fracture data for several loops (see Fig. 7 for an example).

The specimen has an initial pre-crack introduced at the center. In order to propagate a crack, the applied load is resolved into two components, Mode I opening P_I and Mode II shear P_{II} component as shown in Fig. 10. Therefore, the mixed mode fracture is calculated by inserting P_I and P_{II} to determine the area under load-displacement corresponding to G_I and G_{II}, respectively.

$$P_I = P_c \cos\theta \tag{2}$$

$$P_{II} = P_c \sin\theta \tag{3}$$

The measured critical energy release rate G_c can now be related to the component levels of opening mode (G_I) and shearing mode (G_{II}) of fracture energy,

$$G_c = F(G_I, G_{II}) \tag{4}$$

However, to evaluate such data from measured results reported in this paper requires additional analytical and numerical work based on fracture mechanics solutions with some restrictive assumptions. Currently analytical and experimental solutions for the data reported in this paper are ongoing.

Li and Carlsson [11,12] studied mixed mode fracture of Tilted Sandwich Debond (TSD) specimen using Finite Element Method and showed that if one does not prevent face sheet bending component, then mode mixity is very minimal even for large variations in tilt angle from -15° to 20°. However, numerical analysis from a recent paper by Berggreen and Calsson [13] also shows that if one uses reinforcement on the upper side of the tilted sandwich sample by reinforcing the upper face with a steel plate, similar to what was implemented in this study by authors using a channel section, it was found to significantly increase the contributions of mode mixity (I versus II) on face/core interface of cellular solids by altering tilt angle.

Property	Foam	Dimension
Coefficient of thermal expansion, α	70	$\mu\varepsilon/^{\circ}C$
Moisture expansional strain at saturation, ε_H	2200	$\mu\varepsilon$ at saturation
Longitudinal modulus, E	60	MPa
Shear modulus, G	25	MPa
Poisson's ratio, v	0.13	

Table 1: Mechanical properties of H100 PVC foam

Tilt angle θ	Average G_c (J/m^2)	Average STD of G_c
0°	836	261
10°	940	168
15°	1014	235
20°	1107	286
25°	1365	340
30°	1557	378
35°-40°	In progress	

Table 2. Results from Mixed mode test of H100 PVC foam at various angles.

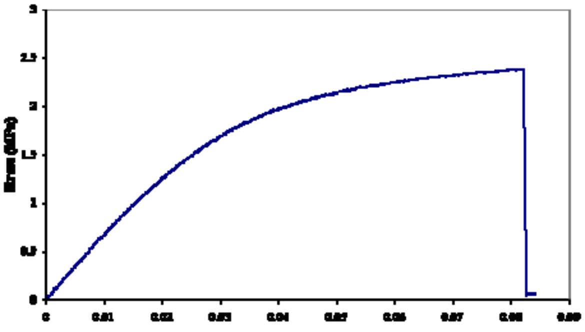

Fig. 1. Tensile stress-strain relation of H100 foam.

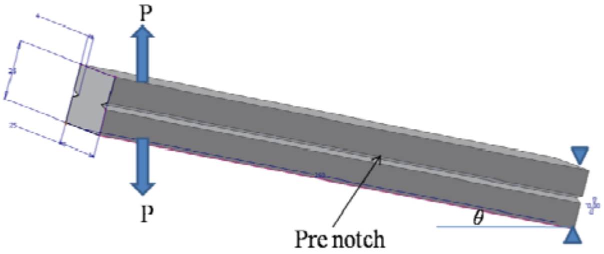

Fig. 2. Schematic of H100 foam sample configuration with applied load.

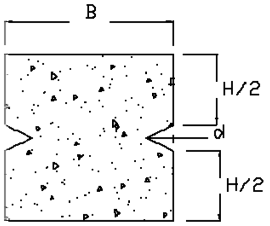

Fig. 3. Schematic of H100 foam cross-section.

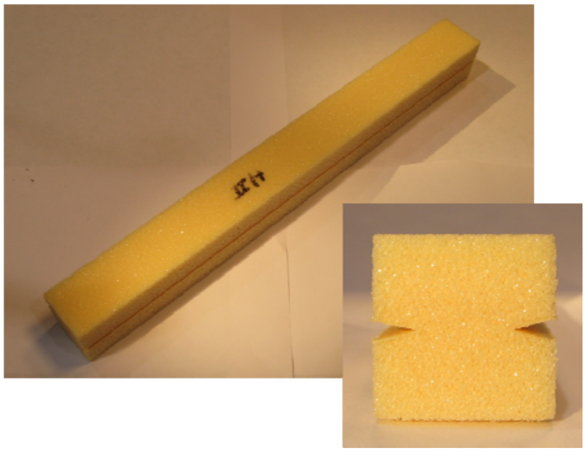

Fig. 4. An example of polymeric H100 foam specimen and cross section with notches.

Fig. 5. Experimental set up.

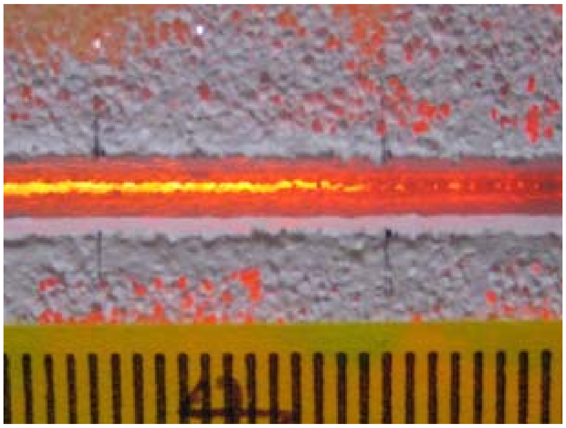

Fig. 6. An observed crack propagation.

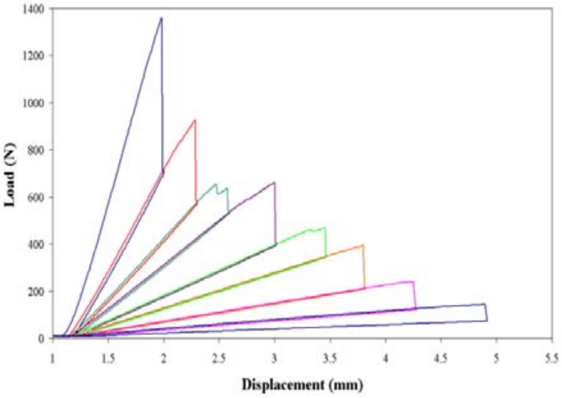

Fig. 7. Typical crack propagation results.

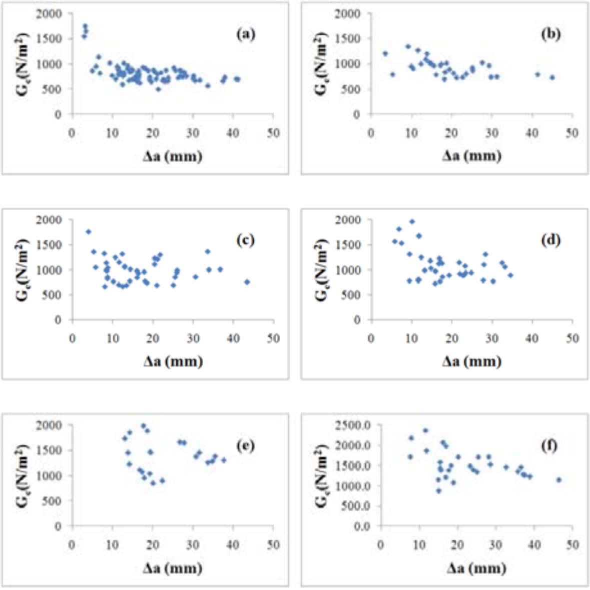

Fig. 8. Fracture resistance curve for PVC foams at different tilt angles: θ = (a) 0˚, (b) 10˚, (c) 15˚, (d) 20˚, (e) 25˚, (f) 30˚.

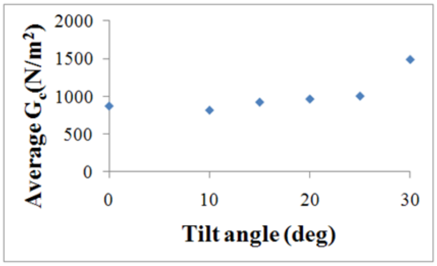

Fig. 9. The effect of V-shaped sharp pre-crack on G_c at various tilt angles.

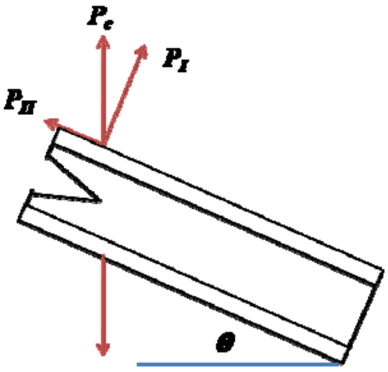

Fig. 10. Principle of a tilted specimen.

5 Concluding Remarks

The modified DCB specimen with a V-shaped edge notch along the length of the specimen provided a promising new approach to measure fracture behavior of pure foam core material of low density (H100 in this study) and allowed to the crack front to propagate within the notched section along the length in mixed mode fracture tests. With the simple experimental procedure developed in this study, critical energy release rate G_c was evaluated for cellular foam core using TSD configuration. Although pure Mode II fracture test is not easy to achieve in practice for these complex cellular solids, mixed mode fracture tests possibly provide G_c values which can be related to G_I and G_{II} as a function of tilt angle using conventional DCB specimens modified with 'channeled' geometry. With this technique reported results from repeated tests on same batch of foam samples provide an indication of inherent random nature of microstructure of cell walls influencing the measured fracture properties.

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