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Effect of Initial Debond Crack Location on the Face/core Debond Fracture Toughness

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Abstract. This paper studies the effect of initial crack location on the face/core debond fracture toughness under different mixed mode loading conditions. The mixed mode loading at the crack tip is defined in terms of the mode-mixity. In order to achieve the desired initial debond crack location, a pre-cracking technique is developed, where the mode-mixity, number of cycles, crack increment and load level are accurately controlled. Results show that the debond fracture resistance of foam-cored sandwich specimens depends on parameters such as loading condition (mode-mixity), core and face properties, as well as initial debond crack location. Lower fracture toughness values were measured for specimens with the initial crack location in the face laminate.

1 Introduction

The susceptibility to face/core debond propagation is a major concern for many sandwich structures. The critical energy release rate is a widely recognized parameter that properly accounts for the materials' fracture resistance [1-6]. It has been shown that the critical fracture energy, G_C, (fracture toughness) depends on the mode-mixity at the crack tip, which also influences in the resultant fracture crack path of debonded sandwich structures [1]. Since different fracture paths are likely, it is believed that different initial crack locations (in the core, in the face laminate and in the face/core interface) may lead to different fracture properties in sandwich structures. However, no in depth analysis regarding the effect of initial crack location on the debond fracture toughness is available, and thus there is a necessity for further evaluation and understanding concerning this phenomena. This is of crucial importance when performing damage assessments of sandwich structures (wind turbine blades, ships, etc) due to debonds.

Most sandwich specimens used in fracture experiments have the initial crack location just below the face/core interface in the core [7], while others at the face/core interface where the Teflon film was inserted during the manufacturing process [5]. The latter may cause unrealistic fracture property measurements due to the unrealistic crack front. This is caused by the shape of the crack tip at the end of the Teflon insert, which may serve as a resin accumulator during the resin infusion process, leading to an unrealistic crack shape, i.e. blunted crack. Due to the Teflon insert (blunted crack tip) an overestimation of the debond fracture toughness may be introduced, making pre-cracking necessary. Pre-cracking is suggested in order to achieve a more realistic and sharp crack front, thus more reliable fracture toughness measurements can be obtained [1]. It is important to point out that

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the pre-cracking procedure needs to be such that the initial crack location, i.e. in the core, in the face laminate and at the face/core interface can be controlled. However, a pre-cracking methodology for sandwich specimens is not available yet.

There are still many unknowns regarding the effect of the initial debond crack location on the debond fracture toughness and the resulting fracture crack path in sandwich structures. In order to achieve desired initial crack locations, it is important to develop a proper pre-cracking methodology, where the mode-mixity, number of cycles, crack increment and load level must be accurately controlled. As a part of this study, an initial attempt to develop a pre-cracking methodology for foam-cored debonded sandwich specimens is proposed.

In addition, the effect of initial crack location on the fracture behaviour of debonded sandwich structures is experimentally investigated. The fracture response of debonded sandwich specimens with different initial crack locations is evaluated and examined in term of fracture toughness. The fracture studies are performed using the Mixed Mode Bending (MMB) test method and the MMB sandwich specimen [1,2,8], as shown in Fig. 1.

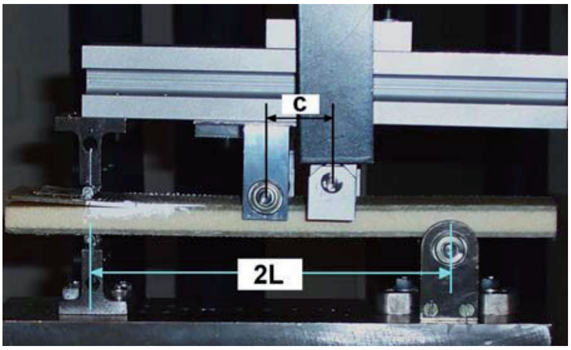


Fig. 1. Mixed Mode Bending test rig and MMB sandwich specimen.

2 Materials and specimens

Foam-cored sandwich specimens commonly found in wind turbine and marine applications are examined herein. MMB sandwich specimens consisting of polyester E-glass DBLT-850 multi-axial (0°/45°/90°/-45°) fibre face sheets bonded to a H100 PVC foam core material were manufactured using vacuum infusion technology. The H100 PVC foam core was bonded to the face sheets with polyester resin in a resin injection co-cure process at room temperature under vacuum. All manufactured specimens have an artificial face/core debond or interface crack achieved by inserting a folded 70μm thick Teflon film between the upper face and the core prior to resin injection during the manufacturing process of the sandwich specimens. The mechanical properties of the foam and face sheets are provided in Table 1.

Table 1. Mechanical properties of H100 core and face laminate.

Properties	**H100**
Average cell size (mm)	0.45
Compressive Strength (MPa)	2
Compressive Modulus (MPa)	135
Poisson ratio	0.325
Shear Strength (MPa)	1.6
Shear Modulus (MPa)	35
Shear Strain (%)	40

Fracture Toughness G_{IC}(J/m^2)	310
Face DBLT-850 (0/45/90/-45)	
Young's modulus (E), GPa	16.4
Shear modulus (G), GPa	5.8
Poisson's ratio (ν)	0.306

2.1 MMB sandwich specimen

The MMB sandwich specimen and the MMB test method have been applied as a reliable test method for face/core debond fracture characterisation [1]. The mixed mode loading at the crack tip, i.e. mode-mixity, is changed by changing the loading application point on the MMB test fixture, denoted as *c*, see Fig. 1.

Close form solutions for determining MMB compliance and critical energy release rate have been presented in [8]. The analytical solution for energy release rate is used to determine the critical fracture energy, i.e. the debond fracture toughness at different loading conditions which are controlled by *c*. The fracture toughness or critical energy release rate for crack propagation is determined using the experimentally measured critical load for crack propagation, as described in Section 4. Further information about the analytical solution for the MMB compliance and energy release rate are provided in [8] and face/core debond fracture characterisation in [1].

The specimen dimensions are length L=80mm, width b=35mm, face sheet thickness h_f=2mm and core thicknesses of h_c=10 and 20mm. Specimens with h_c=10mm were mainly used to promote mode II dominated loading, whereas specimens with h_c=20mm for mode I dominated loading.

3 Initial crack locations

The face/core debonds in the sandwich specimens were created artificially by implanting a thin Teflon insert between the face and the core during the manufacturing process, denoted as an artificial debond in Fig. 2a. The different initial face/core debond locations (after pre-cracking) are schematically presented in Figs. 2b-2d. In Fig. 2, the face/core interface is a thin layer created by open foam cells filled with resin during the resin injection process, and it is often stronger than the core itself. The thickness of this layer is generally of the order of the foam cell size, i.e. approximately 0.45mm for H100 PVC foam core, see Table 1.

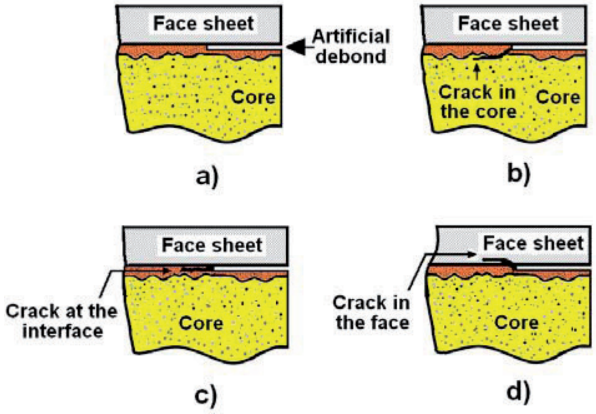
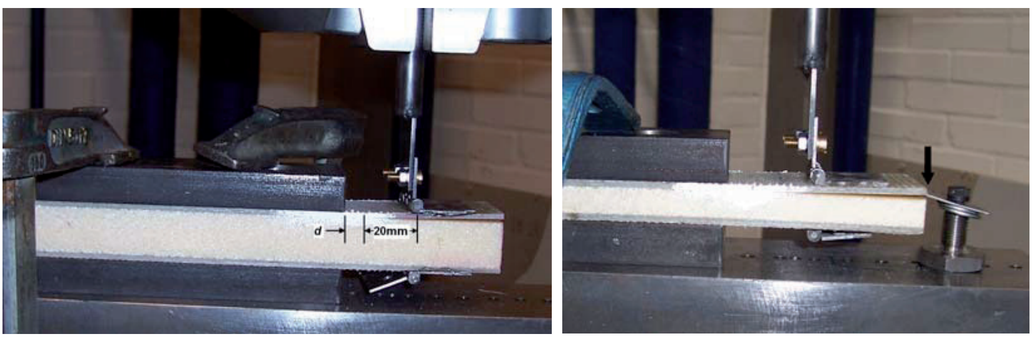


Fig. 2. Schematic initial crack locations a) artificial debond, b) debond crack in the core just below the face/core interface, c) debond crack directly in the face/core interface, and d) debond crack in the face laminate.

3.1 Pre-cracking

The precracking setup employed in this paper is a variant of the double cantilever beam configuration and is presented in Fig. 3. A pulling force is applied at the upper debonded face sheet using a sinusoidal cyclic loading with a load ratio of R=0.1 and frequency of 3-5Hz. As shown in Fig. 3a, the specimen is clamped between two steel blocks at an approximately 2-12mm distance from the crack tip. The steel block is used to limit the crack extension during pre-cracking and to ensure a straight crack front. The initial maximum load applied during pre-cracking was 10% of the estimated static failure load (or its equivalent in displacements), for approximately 3.000-5.000 cycles. If no crack propagation at the desired crack location is observed, the load must be increased by 5% of the estimated static failure load. If needed, further load increments of 5% may be applied, and the process repeated until crack propagation is observed. A maximum of 50% of the estimated static failure load can be applied to the specimen under precracking in order to avoid undesired large crack increments. For the specimen under evaluation, i.e. sandwich specimen with H100 core, a total of 15.000-50.000 loading cycles were required to achieve a crack increment of 0.5-2mm.



(a) (b)

Fig. 3. Precracking of debonded sandwich specimens.

The current pre-cracking procedure outlined above promoted an initial debond location at the face laminate just above the face/core interface and in the core just below the face/core interface. Large number of cycles was needed in order to locate the crack in the core using pre-cracking configuration presented in Fig. 3a, thus, in order to speed up the pre-cracking process and to locate the crack in the core; an alternative pre-cracking arrangement is presented in Fig. 3b. A downward force (black arrow, Fig. 3b) is applied to the lower sub-beam (core+face) of the cracked region of the MMB specimen. This downward force is relatively small and forced the crack to be located in the core, but relatively high loads may cause failure of the core by bending, i.e. an undesired crack perpendicular to the artificial debond. Since the magnitude of the load was not measured, no mode-mixities were determined for this configuration, but it is believed that this configuration promoted positive mode mixities at the crack tip helping the crack to go the core. A pre-crack directly in the face/core interface was not possible to achieve. This may be due to the stronger and tougher face/core interface (the resin-rich region of the core is often stronger/tougher than the pure core and face sheet, and especially in the present study where polyester resin was used). This may also be due to the limited variation in mode-mixity using the current pre-cracking configuration.

The mode-mixity is an important parameter in determining the resultant fracture crack path in sandwich structures, since the mode-mixity is a measure of the loading conditions at the crack tip, i.e. ratio between mode II/mode I at the crack tip. The mode-mixity formulation employed in this paper is the reduced formulation which is expressed as $\psi_R = \tan^{-1}(K_{II}/K_I)$ [9]. The mode-mixity can also be seen as a measure of the relative amount of shearing and opening stresses acting at the crack tip and is generally determined using finite element analysis [4,8]. For the current pre-cracking configuration, the mode-mixities as function of different distances from the crack tip to the steel-block (denoted as *d* in Fig. 3a) are provided in Table 2.

Table 2. Mode-mixity, ψ_R, as function of core thickness and different distances *d*.

d (mm)	h_c = 10mm	h_c = 20mm
2mm	-1.28°	2.82°
4mm	2.46°	5.12°
8mm	1.75°	6.47°
12mm	1.05°	6.03°

As can be seen in Table 2, a mode I dominated loading at the crack tip exists for all loading configurations. However, using a short distance *d*=2mm, h_c = 10mm, negative mode-mixities are achieved which promotes crack locations just above the face/core interface in the face laminate, whereas when using thicker specimens (h_c = 20mm), cracks in the core were mainly promoted for mode I dominated positive mode-mixities.

It is important to point out that large crack increments (>2mm) at the face laminate should be avoided, since this may cause the development of fibre bridging at the crack front. The current study is performed within the linear elastic fracture mechanics framework. In order to include the effect of fibre bridging, non-linear cohesive zone fracture models may be deployed [10,11], however, this is out of the scope of this paper.

4 MMB fracture testing

The load was introduced quasi-statically through a steel loading joke and saddle, and transferred to the sandwich specimen via rollers and steel hinges. The ratio between mode II/mode I is controlled by varying the distance of the lever arm position, *c*, see Fig. 1. Furthermore, Fig. 4 shows a MMB specimen during testing and it can be observed that the crack is propagating in the core just below the face/core interface, as shown earlier in Fig. 2b.

Fig. 4. Observed crack propagation path in a MMB specimen during testing, with crack growth in the core.

The fracture experiments were performed at several *c* values (i.e. different mode-mixities) in order to find the critical fracture load for debond propagation and from those measurements to determine the critical energy release rate, i.e. the debond fracture toughness. The critical load for debond propagation is defined as the load at which the MMB compliance has increased by 5%, or, the maximum load depending on which occurs first along the load – displacement curve. This is in agreement with the recommendation provided by ASTM [12] and supported by visual inspection during testing. The fracture toughness results as function of mode-mixity is presented and discussed in the following section.

5 Results and discussions

Fracture toughness results for MMB sandwich specimens with two initial crack locations, i.e. in the core and in the face laminate are presented in Fig. 5. For specimens with the crack located in the core, higher fracture toughness values were measured compared to specimen with the crack in the face laminate.

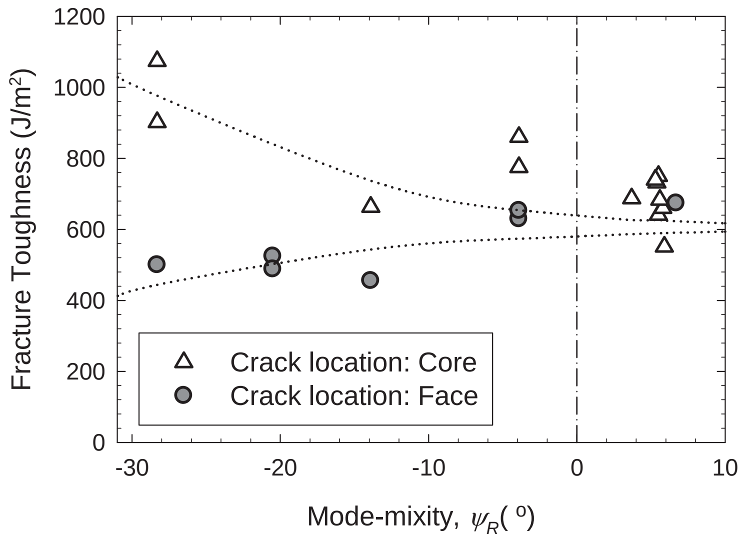


Fig. 5. Face/core fracture toughness for different initial crack locations.

Since the chosen MMB loading conditions promoted negative mode-mixities for most specimens, a tendency exists for the crack to propagate towards the face sheet just above the face/core interface. However, when the initial pre-crack is located in the core, then due to the tougher core + resin layer, the resultant fracture crack path remained in the core just below the face/core interface. Furthermore, higher fracture toughness values were measured for specimens with the crack in the core which may be due to the ability of the core to deform and absorb more energy, but also due to the tendency of the crack to seek towards the face sheet and thereby accumulating increasing amounts of strain energy for increasing negative mode-mixity in the tough resin rich region of the face/core interface. This observed crack path is in agreement with experiments performed in [13], furthermore in [13] the H100 core was typified as a ductile core. On the other hand, a crack located in the face laminate seems to propagate in a more brittle fashion than in the core, most likely attributed to the polyester resin type, and thus lower fracture toughness values were measured. In addition, the multi-axial (0/45/-45/90) mats where the 90° fibres are oriented perpendicular to the direction of crack propagation provide a low energy path. Thus, it should be pointed out that the orientation of the fibres in the face sheet plays an important role in the face/core interface toughness and observed crack propagation paths.

Earlier investigations showed that the fracture toughness in debonded sandwich structures increased for increasing magnitude in mode-mixity [1,3,4]. However, in the current study, for specimens with the initial crack in the face laminate, the fracture toughness decreased for increased magnitude of mode-mixity, i.e. increased shear loading at the crack tip.

6 Conclusions

The effect of initial crack location on the critical energy release rate (fracture toughness) for sandwich structures under quasi-static fracture testing were investigated using the MMB sandwich specimen. Higher fracture toughness values were measured for specimens with the crack located in the core just beneath the face/core interface, whereas lower fracture toughness values were measured for specimens with the crack located in the face laminate. The fibres orientation in the face laminate influenced the consequent crack propagation path and fracture resistance, emphasizing the importance of taking the initial crack location into account when performing damage tolerance estimation of debond damaged sandwich structures.

Further improvements in the pre-cracking methodology are suggested. Firstly, an improved control of the applied mode-mixity at the crack tip should be achieved in order to activate all desired initial crack locations. Secondly, expand the methodology to different foam-cored sandwich materials. These improvements are currently under development using the Tilted Sandwich Debond [3,6,14] test and specimen, which offers a wider variation in mode-mixities at the crack tip, from negative to positive values.

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