On Fracture Testing of Sandwich Face/Core Interface using the DCB-UBM Methodology in Fatigue

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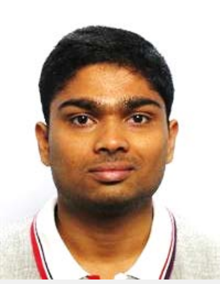

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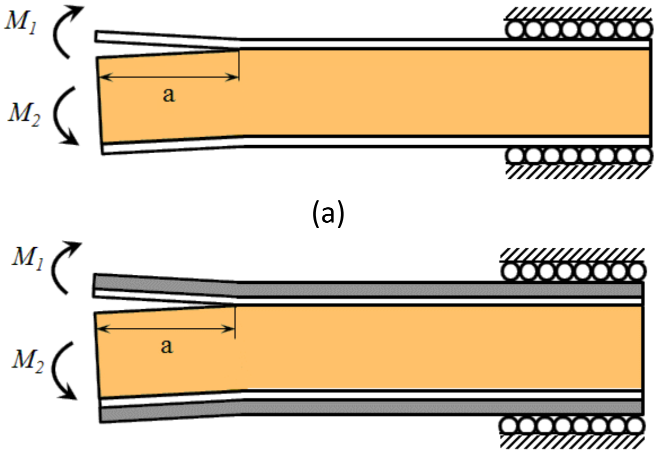
Abstract

The Double Cantilever Beam loaded with Un-even Bending Moments (DCB-UBM) test methodology is employed for fracture characterization in fatigue. A new test rig which applies moments using independent torsional actuators is used. The control algorithm in the new rig is modified to account for fatigue testing. A limited series of pilot study using honeycomb core sandwich composites is conducted to demonstrate fracture testing in fatigue using the novel DCB-UBM test rig. The new test rig is capable in handling fatigue testing and hence is a promising candidate for fracture testing in mixed-mode regime.

Introduction

Face/core interface failure is one of the critical damage modes in sandwich composites. The application of sandwich structures are increasing by several fold nowadays, hence the subject of damage tolerance is pertinent and need to be addressed. Face/core interface debonds or "disbonds" may be caused during the production phase due to insufficient wetting of face sheet mats, tool drop or impact events during in-service of the structure. It is vital to assess the residual lifetime and strength of a structure involving debonds from a damage tolerance perspective. Furthermore, cracks will typically propagate in mixed-mode condition due to the high elastic mismatch across the face and core in a typical sandwich interface. Therefore, the critical energy release rate needed to separate the face sheet from the core referred to as the interface fracture toughness, must be characterized in the mixed-mode regime. Mode-mixity can be briefly described as the ratio of sliding to the normal opening displacements close to the crack tip.

There exist several fracture methodologies to assess fracture toughness in sandwich composites. The Single Cantilever Beam (SCB) sandwich beam specimen introduced by Cantwell and Davis [1] is currently gaining wide attention owing to its simplicity for fracture characterization in predominant mode-I conditions. However, it is quite cumbersome to identify a suitable data reduction technique to deduce a fatigue law using the SCB test method. A G-control based fatigue methodology have been proven using the Mixed-Mode Bending (MMB) sandwich specimen [2]. However, the mixed-mode regime achievable in MMB sandwich specimen is limited. On the other hand, the Double Cantilever Beam loaded with Un-even Bending Moments (DCB-UBM) first introduced by Sørensen et al. [3] for laminates, and later extended to sandwich composites have been proven effective for fracture testing in a wide range of mixed-mode ratios for a range of different sandwich material systems [4]. In addition, closed form expressions for both energy-release rate and mode-mixity phase angle are available for both reinforced and un-reinforced sandwich DCB-UBM specimen [5], [6], see Figure 1.



(b)

Figure 1. Schematic illustration of sandwich DCB-UBM specimen (a) un-reinforced and (b) reinforced with stiff layers.

The original DCB-UBM test rig by Sørensen et al. [3] contains long wires which make it cumbersome to perform fatigue testing, as the long wires may hamper the test due to resonance. Recently, a stand-alone fatigue rated rig employing the DCB-UBM test method was constructed which is capable of applying moments with the aid of two independent torsional actuators (Berggreen et al., under preparation). Static fracture testing using the novel test rig was conducted on both honeycomb core and foam core specimens [7], [8] under mixed-mode conditions.

The objective of the current paper is to modify the control algorithm to equip the new test rig to perform fatigue fracture testing. A pilot study to demonstrate the efficacy of the control system is carried out using a honeycomb core sandwich specimen.

Test Procedure

The sandwich DCB-UBM is a steady-state fracture specimen, in which crack propagates inherently at a constant energy-release rate. By fixing the ratio of moments, $MR = M_1/M_2$, crack propagation can be performed at a constant mode-mixity phase angle (ψ). Selection of moment ratio, MR, which corresponds to a particular phase angle, ψ, must be performed prior to testing and can be done numerically or analytically. A finite element (FE) model in conjunction with the mode-mixity method, Crack Surface Displacement Extrapolation Method (CSDE) [9] d can be utilized. Closed form expression to estimate phase angle is based on the scalar parameter, ω, which needs to be determined once using an appropriate numerical mode separation method. The closed form expression for both G and ψ are provided by both Kardomateas et al. [5] and Saseendran et al. [6].

The DCB-UBM test rig along with the specimen installed is shown in Figure 2. It can be seen, by bonding steel layers, referred to as “doublers” on both sides of the specimen enable easy attachment of specimen insert and gripping of the specimen. Doublers play a vital role especially with specimens with thin compliance face sheets. Not only do they help in application of moments through the specimen inserts, but they reduce excessive rotation of the face sheet. In order to keep the fracture testing in the Linear Elastic Fracture Mechanics (LEFM) regime, the deformation of face sheet must be reduced and kept at minimal.

A dedicated two channel controller, MTS FlexTest ™ [10] is used for fracture testing along with the control software, MTS TestSuite™ Multipurpose Software [11]. The test is performed in rotation control, in which rotation command is supplied to arm-1. Arm-2 is controlled in such a fashion, that it follows arm-1 at fixed moment ratio, MR, input prior to the test. The control algorithm is presented in Figure 3.

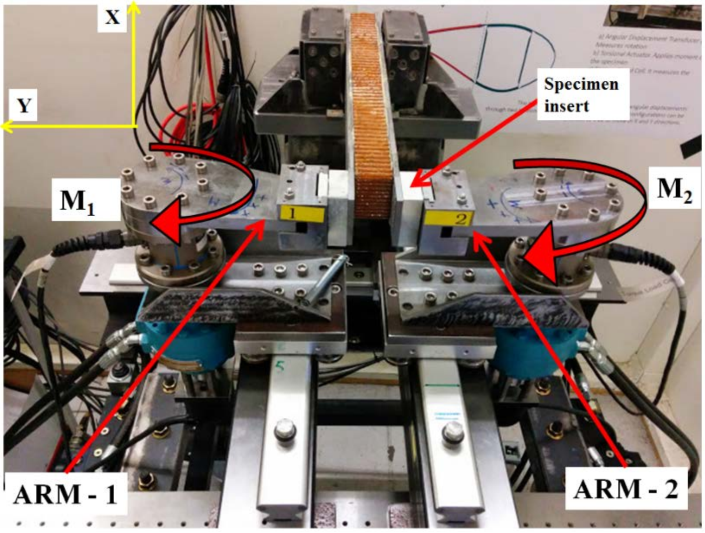


Figure 2. DCB-UBM test rig with honeycomb core specimen installed.

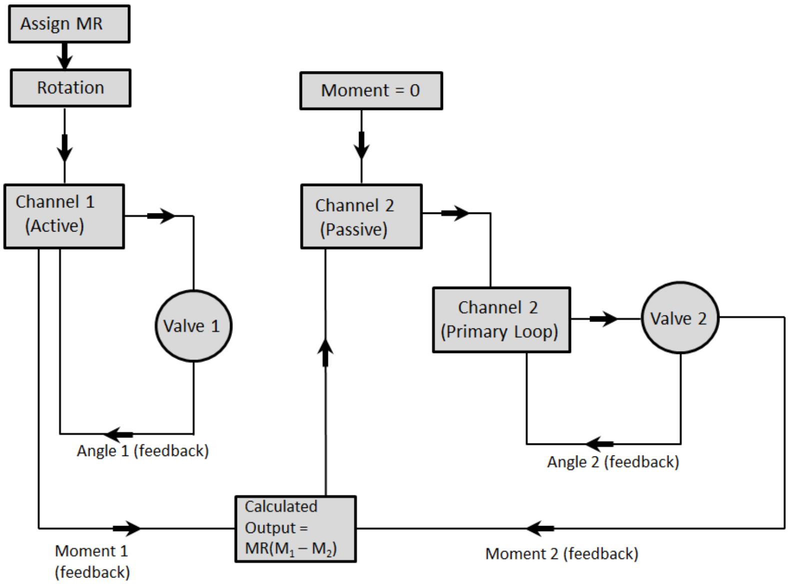


Figure 3. Control algorithm for DCB-UBM testing.

It can be noticed in Figure 3, that a dedicated output channel is configured which calculates the resultant output of the expression: $MR\cdot\ (M_1 - M_2)$. The output channel supplies the moment to arm-2 and ensures that the moment ratio, *MR*, is held constant. For static testing, the rotation control command is simply a ramp command along with the rate of rotation. Usually, an angular rotation rate of 10 °/min is used for static fracture testing. For soft foam core types, a smaller rate may be preferred such that the stick-slip phenomenon can be reduced at predominant mode II conditions.

The DCB-UBM test methodology, as mentioned previously, is *G*-controlled in nature. A framework for fatigue testing is built upon the existing control algorithm which ensures that the *MR*, in-turn the phase angle is kept constant throughout the test. The critical energy-release rate from a static DCB-UBM test can be identified from the critical moment, marked by sudden departure of the moment from the linear region, as shown in Figure 4 for a CFRP/Nomex honeycomb core specimen. The critical energy-release rate can then be obtained by substitution of critical moments into Equation (1).

$$G_c = \frac{1}{2b}\left[\frac{M_{1c}^2}{(EI)_1} + \frac{M_{2c}^2}{(EI)_2} + \frac{M_{3c}^2}{(EI)_3}\right] \tag{1}$$

where *EI* is the flexural rigidity of the beam. Subscripts 1, 2 and 3 refer to debonded, substrate and base beams. Debonded beam refers to the portion above the pre-crack length, *a*. Substrate beam refers to the portion of beam beneath the pre-crack length and base beam refers to the entire portion of the specimen in front of the crack length (refer to Figure 1).

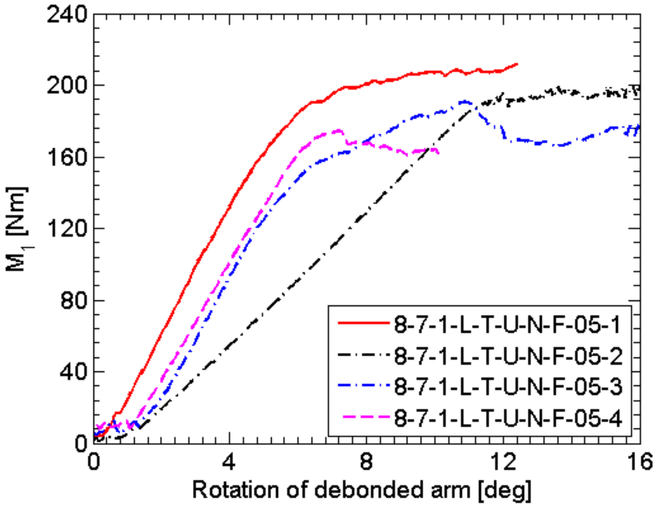


Figure 4. Moment (M_1) vs. rotation of debonded arm.

In order to perform fatigue fracture testing at say, 70% of the initiation fracture resistance value, the critical moment and the rotation of arm-1 associated with 70% energy-release rate can be picked from the plot in Figure 4. It should be noted that arm-1 is also referred to as the "disbonded arm" as the pre-crack lies between the face sheet and core in arm-1, see Figure 2. In the master command in which rotational ramp command is supplied to arm-1, the static command is replaced with a rotational cyclic command. A 2° amplitude is chosen in the cycle command initially with a frequency of 1 Hz as shown in Figure 5. Crack increment is monitored with the aid of a ruler which is glued on the edge of the specimen by pausing the test. Peak and valley of rotation and moment of both arms are recorded throughout the test. The moment ratio (*MR*) is kept constant at *MR* = -7.5, corresponding to a predominant mode I condition.

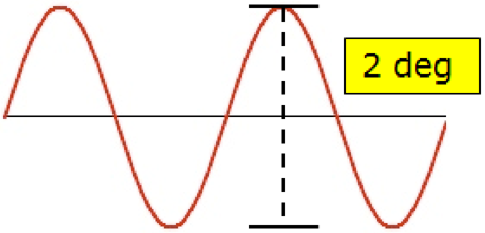


Figure 5. Rotation cyclic command applied on arm-1.

Results and Discussion

The moments recorded during the test is substituted into Equation (1) to obtain fluctuation in the energy-release rate (*ΔG*) which is plotted against the number of cycles in Figure 6. Interface crack propagation was observed under predominant mode I conditions. Crack increments were monitored at intervals of 500 cycles and the test was stopped when the crack length reached ~ 10 mm. It can be noted that the fluctuation in *ΔG* is from a maximum of 550 J/m^2 to 500 J/m^2. Least fluctuation of 10 J/m^2 is also observed (*ΔG* = 495 J/m^2). Table 1 provides the mean values of the energy-release rate along with the measured incremental crack lengths recorded for over 3000 cycles.

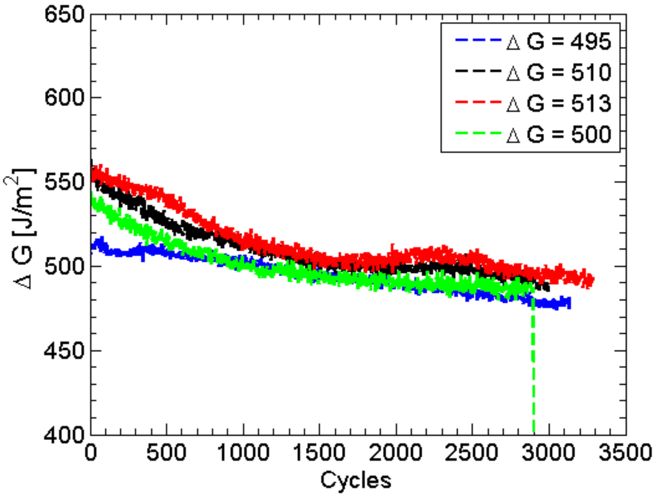


Figure 6. ΔG vs. no of cycles (CFRP/Nomex honeycomb).

The supplied command signal to arm-1 had an amplitude of 2°, which resulted in sliding of arms over the rails at an order of +/- 5 mm. However, as the crack length increases the magnitude of the sliding will increase. Low friction roller bearing support the sliding. The actuator along with the angular and torque measuring sensors are fixed on a plate which slide over the rails. For a higher frequency at large crack lengths, inertial effects may hamper the subsequent crack propagation. To overcome the effect of inertia and other frictional component on the energy-release rate, it is advised to devise a robust method in measuring fracture energy such that the spurious effects will be eliminated in the date reduction process.

Table 1. ΔG (mean) over incremental crack lengths (Δa).

ΔG (mean) (J/m^2)	**Δa (mm)**
495	10.10
510	12.10
513	15.60
500	10.60

Conclusions and Future Work

It was demonstrated that the control algorithm and the test rig are capable in handling cyclic commands at a desired moment ratio (*MR*). A small set of pilot runs were conducted using CFRP/Nomex honeycomb core specimen. Interface crack propagation was observed for all cases of crack increment, which was monitored by pausing the test at an interval of 500 cycles.

At present, there does not exist a robust data reduction method to deduce fracture energy in a sandwich DCB-UBM specimen. The novel test rig although is capable of conducting fatigue tests, frictional and inertial effects will affect the fracture measurement at higher frequencies as well as at increased crack lengths. Therefore, it is proposed to obtain the energy-release as a function of Crack Tip Opening Displacement (CTOD), which will help in encompassing all the spurious motions in the specimen. A kinematic relation connecting the energy-release rate is already under development and the initial phase in which the DCB-UBM specimen is treated as moment loaded SCB specimen is completed (Saseendran et al., manuscript under review).

Figure 7. Crack tip opening displacement (CTOD) measurement.

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