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Determination of mode-I cohesive strength for interfaces

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Abstract. The cohesive strength is one of the governing parameters controlling crack deflection at interfaces, but measuring its magnitude is challenging. In this paper, we demonstrate a novel approach to determine the mode-I cohesive strength of an interface by using a 4-point single-edge-notch beam specimen. The test specimen is made of a glue cast onto a uni-directional, glass-fiber laminate. A crack is cut in the glue, orthogonal to the interface, which creates a high normal stress across the glue/laminate interface during loading. It is observed that a new crack can be initiated along the interface in response to this stress, before the main crack starts to grow. Observations using 2D digital-image correlation showed that an “apparent” strain across the interface initially increases linearly with the applied load, but becomes non-linear upon the initiation of the interface crack. The cohesive strength is determined, using a 2D, linear-elastic, finite-element model of the experiment, as the stress value where the experimental measured “apparent” strain value becomes non-linear across the interface.

1. Introduction
Crack deflection along interfaces is an important failure mechanism in adhesive bonded joints. Several studies on crack deflection have been presented previously, but with a primary focus on modeling. An early work was by Cook and Gordon [1], who used a stress-based approach to model an elliptical notch situated a short distance from a weak interface in a homogeneous substrate. The peak stresses normal to the interface and normal to the notch were compared to show that the interface fails before the substrate (causing crack deflection), if the interface strength is less than about one fifth of the substrate strength.

Later models of crack deflection used an energy-based approach by applying linear-elastic fracture mechanics (LEFM) [2, 3, 4]. These models indicated that, in the absence of a modulus mismatch, the interface toughness should be less than one fourth of the substrate toughness for the crack to deflect. Thus, modeling the deflection of a crack at an interface was, at first, either based on stress [1] or toughness [2]. These two distinct concepts, strength and toughness, are unified in a cohesive law [5]. It was shown that the cohesive strength of the interface is one of the governing parameters that controls crack deflection [5]. This cohesive strength can be measured experimentally using environmental scanning-electron microscopy (ESEM) [6] in conjunction with the J-integral [7, 8]. Unfortunately, this method requires advanced equipment and specialized loading devices.
Experimental studies of crack deflection at interfaces are very limited, and only a few have been found [9, 10]. Kendall [9] derived a deflection criterion for a Griffith crack, and used single-edge-notch-tension (SENT) specimens made from a brittle and transparent ethylene propylene rubber in which crack propagation could be monitored. Unfortunately, details and images of the crack deflection process were not presented in that paper. A subsequent experiment [10] used a wedge to load a single-edge-notch-beam (SENB) to show that an interface crack was initiated before the main crack reached the interface. This competition between growth of the main crack and initiation of an interface crack is similar to the model proposed by Cook and Gordon [1].

In this paper, crack deflection at an interface is studied using a 4-point SENB specimen. The test specimen is manufactured of a brittle vinylester glue cast onto a uni-directional glass-fiber-reinforced polyester laminate. 2D digital-image-correlation (DIC) is used to measure the full displacement field during loading of the specimen. It is found that a new crack initiates in the interface prior to the main crack reaching the interface. This is similar to the experimental observations of Lee and Clegg [10], but we use this failure mode to develop a new approach to measure the cohesive strength of the interface.

2. Approach
A new approach is proposed in this paper for measuring the cohesive strength of the interface, \( \hat{\sigma} \). This approach is summarized in figure 1. The strength is measured using 2D DIC (figure 1(a)), in combination with a linear-elastic finite-element (FE) model of the experiment (figure 1(b)). During the test, measurements of an "apparent" strain, \( \epsilon_{yy} \), acting normal to the interface allows the point at which the interface crack is initiated to be identified. \( \epsilon_{yy} \) is obtained from the displacement difference between two points on either side of the interface divided by gauge length, \( l_g \) as shown on Figure 2.

Figure 1. Approach to obtain cohesive strength of the interface.

The strain field at the interface increases linearly with load until the point at which the interface crack initiates. The applied bending moment, \( M^d \) and the crack length, \( a \) at the point when DIC indicates that the "apparent" strain is no longer linear are identified. Linear-elastic materials and a zero-thickness interface are assumed hence the non-linearity in measured "apparent" strain is due to interface separation. Separation of interface is the first step in the crack initiation process and this is the beginning of delamination. These conditions are then used in a linear-elastic finite-element model of the experiment, assuming an orthotropic substrate and an isotropic glue, to calculate the normal stress at the interface. The maximum stress calculated from this numerical analysis is taken to be the cohesive strength of the interface.

3. Methods
The 4-point SENB specimen is illustrated in figure 3, and the dimensions are given in table 1. In this figure and table \( a_0 \) is pre-crack length, \( a \) is the actual crack length, \( b \) is thickness of the glue, \( c \) is thickness of the laminate, \( w \) is width, and \( L \) is the length of the specimen.
3.1. Design of experiment by finite element modeling

The purpose of the main crack is to create a high normal stress across the interface. Furthermore, this geometry containing a crack is selected because it can be modeled precisely using FE, allowing the interface stress to be determined accurately. The interface stress is extracted in the symmetry line ($x = 0$, $y = -c$) where the shear stress is zero hence the crack initiation is mode-I. For the approach to work, the interface crack must initiate before the main crack reaches the interface, and, if the main crack starts to grow, it should do so in a stable manner.

The energy-release rate of the main crack, $G$, shown on figure 3, can be determined for a homogeneous specimen using the results of Tada et al. [11]. However, the energy-release rate for the present case of an orthotropic substrate and an isotropic glue depends on the following parameters:

$$a/b, \quad c/b, \quad E_{xx,s}/E_g, \quad E_{yy,s}/E_g, \quad \mu_{xy,s}/E_g, \quad \nu_{xy}, \quad \nu_g$$

where $E$ is in-plane stiffness, $\mu$ is shear modulus, $\nu$ is Poisson’s ratio, and the subscripts $s$ and $g$ represent the substrate and glue, respectively.

It is important that the main crack grows stably to avoid dynamic effects i.e. rapid, unstable crack growth, in the experiment. A 2D plane-strain linear-elastic finite-element model is used.
to determine a suitable initial length for the main crack to ensure stable crack growth. The normalized energy-release rate of the main crack is determined as a function of the relative crack length, \( a/b \), from the FE calculations and shown in figure 4.

Stable growth of the main crack is achieved if \( \partial G/\partial a < 0 \). If the pre-crack is very long then the main crack will grow stably, but it will be very close to the interface. Therefore, from figure 4, a normalized pre-crack length of \( a_0/b = 0.6 \) is selected as the best compromise between length and stability.

### 3.2. Test specimen and speckle pattern

The test specimen is manufactured from polyester reinforced with fabrics of uni-directional glass fiber, using vacuum-assisted resin-transfer moulding (VARTM). A brittle vinylester glue is subsequently cast onto the glass-fiber laminate creating a zero-thickness interface. The exact material data are confidential, and the results are, therefore, normalized when presented. The pre-crack is cut in the glue using first a thin hack saw, then a standard razor blade, and finally an ultra-thin razor blade of thickness 74 microns. See figure 5 and figure 6 for images of the pre-crack.

![Figure 5. Image taken in optical microscope, of the front of the test specimen showing the pre-crack and speckle pattern.](image1)

![Figure 6. Zoom of the dashed square on figure 5 showing the speckle pattern close to the pre-crack tip.](image2)

A speckle pattern is applied to the front surface using an Iwata CM-B airbrush. First, a white baseline paint is applied to cover the front surface of the specimen. Afterwards, a carbon black paint is applied with increased pressure to minimize the speckle sizes. 3-5 pixels across each speckle diameter, and 10 speckles per subset are desired to track displacements accurately, and to maximize the spatial resolution in DIC [12].

It is desirable to have a scaling factor between microns and pixels of about 3 microns/pixel or less to capture the crack initiation accurately. Thus, the speckles should be between 9 microns and 15 microns (3x3 and 5x3). Larger speckles would lower the spatial resolution, since a larger subset should be used to maintain the 10 speckles per subset. After application of the speckle pattern, the speckles are measured in an optical microscope to between 8 and 28 microns, see figure 6. The actual scaling factor is determined, based on a scale bar mounted on the images, to 2.8 microns/px leading to a field of view (FoV) of 6.8 x 5.7 mm (2448x2048 pixels). The pre-crack lengths are measured using a digital vernier caliper with an accuracy of \( a_0/b \pm 1\% \), while the crack length is measured during the test using the images, which can be measured with an accuracy of about \( \pm 4 \) pixels.
3.3. Experimental setup and procedure
A MTS 858 Mini Bionix II servo-hydraulic test machine is used in displacement control to load the specimen at a rate of 0.015 mm/min (0.00025 mm/s) for the cross-head displacement. The specimen is loaded slowly so many images can be captured during the test. The test is conducted at room temperature. Data (time, force, cross head displacement) are collected on a PC at 10 Hz.

Vic-2D DIC system (Vic Snap 8) is used to capture the images with an image frequency of 1 Hz. A CCD sensor of brand Grasshopper GRAS-50S5M and Fujinon CCTV Lens (1:1.8/50mm) are used with the DIC system. A fiber-optic illuminator from Cole-Palmer is used to illuminate the specimen surface. The camera is mounted on a tripod that can be moved in the y-direction and rotated around 3 axes. The lens aperture is set to a medium level of 8, where the minimum is 1.8 and the maximum is 22. This is found to be the best trade-off between capturing surface depth and the amount of light let through the lens.

3.4. Data analysis
Images are correlated with a subset size of 31 pixels and a step size of 3 pixels to obtain the full displacement field using the DIC software, DaVis from LaVision. The subset size is set hence approx. 10 speckles are found in each subset. The step size is set small enough to resolve the fine details of the interface.

The "apparent" strain is determined, by a script, using the displacement at two points across the interface divided by their separation to obtain an average "apparent" strain across the interface. Here a gauge length, \( l_g \) of \( l_g/b = 0.007 \) is used. This method is equivalent to using a virtual strain gauge across the interface in the DIC software. As a check, the normal strain at the interface is also calculated by the DIC software at different points across the interface. The precise location of interface is taken as the point with the largest strain value. The two methods resulted in the same strain value across the interface. The strains are not further post processed since the purpose of the strain measurement is to identify strain non-linearity.

4. Results
Figure 7 illustrates the relative crack length and the normalized moment as a function of time after the start of the experiment. According to figure 7, the moment increases non-linearly with time until about \( \sim 200 \) s. This is attributed the establishment of full contact of the rollers on the specimen. Thereafter, the moment increases linearly with time, until the main crack in the glue starts to propagate at \( t = 1100 \) s. Figure 7 also shows that when the interface crack is fully developed, the main crack grows and reaches the interface to form a doubly-deflected crack at the interface.

The role of the DIC measurements is to identify the "apparent" strain, \( \epsilon_{yy} \). These measurements indicate a transition from a linear relationship to a non-linear relationship between the "apparent" strain and the moment at \( t = 800 \) s (figure 8). The value of the "apparent" strain at which this occurs is designated by \( \epsilon_{yy}^d \). This is confirmed by observed changes in strain field by contour plots of the vertical strain, similar to those shown in figure 9.

A comparison between figures 9 and 8 shows that both the normal strain across the interface and the applied moment increase linearly with time until \( t = 800 \) s. In this regime, the "apparent" strain is proportional to the applied moment, as one would expect for a linear-elastic system.

After this point, the moment continues to increase linearly with time until the main crack in the glue grows at \( t = 1100 \) s, figure 7. However, even while there is still linear elasticity at the macroscopic scale (800 s < \( t < 1100 \) s) the strain across the interface increases significantly - this apparent localization of strain is taken to indicate the onset of interfacial delamination. If it is assumed that this is failure of the zero-thickness interface then the level of stress at which the onset of non-linearity occurs can be associated with the cohesive strength of the interface.
**Figure 7.** Left: Graph showing normalized moment and relative crack length as a function of elapsed time, $t$. The vertical blue dashed line indicates the time where the interface crack is fully developed. Right: DIC contour plot of the vertical $y$-displacement. The top contour plot is at time, $t = 1100$ s and the bottom contour plot is at time, $t = 1245$ s, just after the interface crack is fully developed. The red dashed line indicates the interface location.

**Figure 8.** DIC: Normalized "apparent" strain, $\epsilon_{yy}/\epsilon^d_{yy}$, shown as a function of time. The "apparent" strain, $\epsilon_{yy}$ is normalized by the value of the "apparent" strain at the onset of non-linearity, $\epsilon^d_{yy}$. The interface is located at $y = -c$, according to figure 3.

**Figure 9.** DIC: Contour plot of the vertical strain, normalized by the "apparent" strain at the onset of non-linearity, $\epsilon^d_{yy}$, just before the main crack grows to the interface ($t = 1244$ s). The initiation of the interface crack is clearly identified. The interface is located at $y = -c$ according to figure 3.
The cohesive strength of the interface is determined by using an finite-element model (Section 3.1) to calculate the value of the normal stress across the interface at the conditions under which the onset of a non-linear strain were observed. It is estimated that the time of transition from linear to non-linear strain at the interface can be identified to an accuracy of $\pm 50$ s, the pre-crack length can be measured to an accuracy of $a_0/b \pm 1\%$, and other uncertainties are indicated by error bars in figure 7. As discussed earlier, the material properties that entered into this calculation are confidential information. However, the calculations result in a cohesive strength for the interface of:

$$\hat{\sigma} / \bar{\sigma}_g = 0.081 \pm 0.007$$  \hspace{1cm} (1)

Again, owing to the confidential nature of the system, the cohesive strength has been normalized with the macroscopic strength of the glue, $\bar{\sigma}_g$, which was obtained by a uni-directional tensile test of a dog bone specimen with a gauge length of 115 mm. It would be more appropriate to normalize with the cohesive strength of the glue, but this is not known.

5. Discussion

The cohesive strength can be determined with ESEM using a $J$-integral based approach [6]. This approach requires manufacturing tiny specimens and using specialized and expensive equipment, such as a special fracture mechanics loading stage for ESEM. A benchmark of the new approach with the ESEM and the $J$-integral based approach is proposed as a future study.

One of the advantages with the new approach presented in this paper is that there is no need to use advanced scanning-electron microscope equipment, since a standard 4 point bend rig with a DIC camera system can solve the task. During the last decade DIC has become a relatively easy, cheap, and efficient tool for measuring in-plane deformations, and it is available in most labs at universities [13]. The new approach is not limited to the 4-point SENB specimen, but it can be used with any other test specimen, provided that the interface crack initiation can be captured by DIC and the interface stress can be accurately determined using a model (e.g. FE or analytical).

The cohesive strength at the interface is extracted in the symmetry line ($x = 0$, $y = -c$) of the SENB specimen where the shear stress is zero and therefore the crack initiation is mode-I. If the interface crack initiates at other locations along the interface, e.g. due to a defect, the crack initiation will be mixed mode. This is also confirmed by the FE model.

It is beneficial that the interface crack initiates before the main crack starts to propagate so that the growth of the main crack does not change the strain field. For an interface cohesive law with a high $\hat{\sigma}$ it may not be possible to initiate the interface crack, but maybe the test specimen could be optimized further in the future to enable this. Another design of the test specimen to determine the cohesive strength could be a SENB geometry with an elliptical notch. The advantage of this geometry is that the stress concentration factor would be known, and it will be harder for the main crack to start growing. This might simplify the analysis. An analysis similar to that of Cook and Gordon [1] could then be used to determine the optimum distance from notch to interface.

6. Conclusion

It can be concluded that the mode-I cohesive strength can be determined using a 4-point SENB test specimen in combination with 2D DIC measurements and linear-elastic finite element modeling. For the material system tested, a normalized cohesive strength is determined to $\hat{\sigma} / \bar{\sigma}_g = 0.081 \pm 0.007$, meaning that the interface cohesive strength is about 0.08 of the macroscopic strength of the glue.
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