Modelling of Crack Deflection at Core Junctions in Sandwich Structures

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Abstract. The paper treats the problem of crack propagation in sandwich panels with interior core junctions. When a face-core interface crack approaches a trimaterial wedge, as it may occur at a sandwich core junction, two options exist for further crack advance; one is for the interface crack to penetrate the wedge along the face-core interface, and the second is deflection along the core junction interface. Crack deflection is highly relevant and a requirement for the functionality of a newly developed peel stopper for sandwich structures. The physical model presented in this paper enables the quantitative prediction of the ratio of the toughnesses of the two wedge interfaces required to control the crack propagation, and the derived results can be applied directly in future designs of sandwich structures. The solution strategy is based on finite element analysis (FEA), and a realistic engineering practice example of a tri-material composition corresponding to face and core materials is presented.

1. Introduction

A sandwich material is a layered assembly made from two thin, strong, and stiff face sheets bonded to a lightweight compliant core material. This creates a stiff, strong and lightweight structural element. The sandwich concept has been vastly utilized by the aerospace industry for decades due to the requirements for high stiffness and strength and at the same time low weight. However the marine, transport, and wind turbine industries have developed a significant interest in adopting the sandwich concept during the last 20-30 years due to increased mechanical performance requirements in these sectors, the possibility of tailored design as well as cost effectiveness [4, 5]. Failure in sandwich structures has been and still is an important design issue due to their sensitivity towards the application of strongly localised loads and poor damage tolerance [1-3, 5].

Delamination/debonding failure and damage tolerance of sandwich structures have been considered previously by the authors of this paper [1-3], and a new concept to stop face-core debonding has been developed. This concept has been referred to as a peel stopper [1-3], see Fig. 1, which appears as a “wedge” like core constituent made from a specially chosen material. The principal idea behind the proposed peel stopper concept is to ensure that when a core-face interface crack is approaching the wedge of the peel stopper it will deflected away from face-core interface by the wedge. This particular mechanism has proven to be a very effective way of confining propagating debonding cracks [1-3].
This paper is associated with the further development of the proposed peel stopper in general, and with the development of an in-depth physical understanding of the crack deflection process in particular. The paper presents a physical model, based on Linear Elastic Fracture Mechanics (LEFM) that is able to predict crack deflection or wedge penetration. The developed model may in the future be used to improve the peel stopper wedge design.

![Complete delamination](image1) ![Crack deflection](image2)

Figure 1. Photos taken from a three point bending test with the debonding area in focus. Left: Shear crack initiated in the green polymer foam core (left); the crack kinked into a face-core interface crack underneath the yellow foam core followed by a complete core-face delamination/separation. Right: Peel stopper was embedded between the two foam cores. The wedge of the peel stopper deflected the interface crack into the core, where the crack was finally arrested [3].

The characterisation of failure phenomena in sandwich structures, whether they are considered from a failure initiation point of view or from a damage tolerance point of view, has been addressed by many researchers. Debonding failures due to the layered composition of sandwich structures have been studied intensely by a number of researchers. This includes experimental investigations of sandwich debonding and crack propagation [4-10], fatigue failure of sandwich structures [11,12] and local effects induced at core junctions, inserts and load introductions [13-17].

Cracks at bi-material interfaces between isotropic materials (i.e. like face-core interface cracks) were studied in [18-26]. Among the crack configurations relevant for the present study are edge cracks on bi-material interfaces [21-24], where [24] also considered crack kinking out of an interface. [25] considered a crack in a homogenous isotropic media approaching an interface with the aim of predicting whether the crack would penetrate the interface or be deflected by it. Finally [26] treats the stress singularities at a tri-material wedge for both fully bonded but also unbonded interfaces.

Several approaches have been proposed to characterise the tendency of a crack to propagate. The classical approach is to estimate the stress intensity factors of a given crack. Another method is to consider the energy release rate. The energy release rate may for linear elastic material behaviour be expressed in terms of the stress intensity factors. In this work the energy release rate is determined by evaluating the path independent J-integral around the crack tip [27]. The full details of the work presented herein may be found in [29] which again expands on the work in [2,3,28].

2. Modelling
A physical model has been proposed inspired by [21,22,25]. The model describes weather an approaching interface crack will be deflected by a tri-material wedge or if it will penetrate it. The model is based on LEFM, which limits the model to linear elastic material behaviour and small crack process zones. Moreover, the model presented is for homogenous isotropic materials only. However, the model can be expanded to orthotropic materials [29].

The aim is to establish interface toughness requirements for a broad band of mode mixities of an approaching interface crack. Furthermore a larger range of wedge angles will be considered. The work has been limited to only one interface composition, which is an isotropic approximation for a glass
fibre (GFRP) face laminate bonded to Divinycell H60 and a H200 cross linked PVC foam core materials. This forms a generic trimaterial wedge type of problem as seen in many foam cored sandwich structures. The problem has been approached by studying the stress intensity factors a short distance \((a)\) before and after the tri-material wedge (see Figure 2). This approach (or model) is here referred to as the “physical model”. The physical model consists of three sub-models, which are named “Crack Approach”, Crack Deflection”, and “Crack Penetration”, respectively, see Figure 2.

The thickness of the face sheet is modelled as finite and set to 2mm; whereas the other dimensions are modelled as “semi-infinite”. The distance \((a)\) indicated in the physical model (Figure 2) is considered as a characteristic distance of the problem, and it has been set to 1.26mm (see calculation of \(a\) in [28]). The choice of this value was based on the plastic yield zone size of the more compliant material, which for this tri-material composition is core-2 (H60). It should be mentioned that the sensitivity with respect to the face sheet thickness and characteristic distance values has not been analysed.

![Figure 2. Physical model with two stages: (1) “Crack Approaching” and (2) “Crack Deflection” or “Crack Penetration”. The wedge angle is \(\varphi\).](image)

![Figure 3. Illustration of method adopted for estimating the magnitude of the far field stresses. The stress level is determined at a distance \((a)\) from the tri-material wedge. No cracks appear in this sub-model, which is referred to as the “Far field stress” model or sub-model 4.](image)

The far field stresses may have a significant role in the interface toughness requirements (to provoke crack deflection), and they have been taken into account through a fourth sub-model (see
This sub-model is characterized by not having any crack included but it is being loaded in a similar way to the three other sub-models. The far field stresses are considered in three locations (A, D and P). These locations have been chosen to be identical to the crack tip positions for the “Approaching”, “Deflected”, and “Penetrated” crack stages, respectively.

In location A and P the transverse normal stresses ($\sigma_{22}$) and shear stresses ($\sigma_{12}$) will contribute to the singular stress field, whereas this is not the case for the normal stresses parallel to the interface ($\sigma_{11}$). For this particular reason only $\sigma_{22}$ and $\sigma_{12}$ are considered at locations A and P. Regarding location D the full 2D stress tensor is considered because all three stress component will contribute to the singular stress field at this location.

The physical model shown in Figure 2 and the far field stresses shown in Figure 3 have been formulated mathematically in terms of the stress intensity factors as shown in Eqs. (1) [29]:

$$K_{23} = cK_{12}a^{i(e_{12}-e_{23})} + \frac{d}{K_{12}}a^{i(e_{23}-e_{12})} + b_D\sigma_{11D}a^{\frac{1}{2}-i e_{23}} + g_D\sigma_{22D}a^{\frac{1}{2}-i e_{23}} + h_D\sigma_{12D}a^{\frac{1}{2}-i e_{23}} + h_A\sigma_{12A}a^{\frac{1}{2}-i e_{23}}$$

$$K_{13} = eK_{12}a^{i(e_{13}-e_{13})} + f K_{12}a^{i(e_{13}-e_{13})} + m_P\sigma_{22P}a^{\frac{1}{2}-i e_{13}} + m_A\sigma_{22A}a^{\frac{1}{2}-i e_{13}} + n_P\sigma_{12P}a^{\frac{1}{2}-i e_{13}} + n_A\sigma_{12A}a^{\frac{1}{2}-i e_{13}}$$

(1)

In Eq. (1) the stress intensity factors are named according to the interface combinations such that the stress intensity factor for the interface crack between material #1 and #2 is denoted $K_{12}$. Furthermore, the complex notation; $K_{12} = K_{1,12} + iK_{2,12}$, for mode-I and –II stress intensity factors has been utilized.

The stress components in Eqs. (1) refer to the far field stresses shown in Figure 3. The parameters $c$, $d$, $b_D$, $g_D$, $h_D$, $h_A$, $e$, $f$, $m_P$, $m_A$, $n_P$, $n_A$ are complex coefficients, which depend on the six elastic constants involved in a tri-material problem and also the wedge angle ($\Phi$). $e_i$ is the oscillatory index characterising each of the three interfaces, and ($a$) is the characteristic dimension of the problem (i.e. distance from the tri-material wedge). This distance has been given the same value along the three interfaces but it is possible to specify three independent distance values as well.

The results presented herein (see [29] for full details) have been solved in the absence of any far field stresses, but it should be mentioned that the influence from far field stresses may be significant. For that reason future work and development of this model should include determination of the complex functions associated with the far field stresses.

Similar to the crack kink problem summarized [28], the energy release rate for an interface crack can be determined from the stress intensity factors according to [30]. The energy release rates for the deflected and penetrated crack configurations are then formulated as shown in Eqs. (2):

$$G_{23} = \frac{\left(\frac{1-v_2}{\mu_2} + \frac{1-v_3}{\mu_3}\right)K_{23}K_{23}}{\cosh(\pi e_{23})}$$

$$G_{13} = \frac{\left(\frac{1-v_1}{\mu_1} + \frac{1-v_3}{\mu_3}\right)K_{13}K_{13}}{\cosh(\pi e_{13})}$$

(2)
Crack deflection may be predicted from the criterion stated in Eq (3), which was inspired by the work presented in [25]. Accordingly, crack deflection is predicted if the inequality condition in Eqs. (3) is fulfilled.

\[
\frac{G_{23}}{G_{13}} \geq \frac{\Gamma_{23}(\psi_{23})}{\Gamma_{13}(\psi_{13})} \geq \frac{\left(1 - \nu_2 \frac{1 - \nu_3}{\mu_2} \right) K_{23} K_{23} \cosh(\pi \epsilon_{13})}{\left(1 - \nu_1 \frac{1 - \nu_3}{\mu_1} \right) K_{13} K_{13} \cosh(\pi \epsilon_{23})} \geq \Gamma_{23}(\psi_{23}) \geq \Gamma_{13}(\psi_{13})
\]

In Eqs. (3) G_j and Γ_j are the energy release rate and the interface toughness for the interface ij, respectively. In the absence of far field stresses the interface toughness ratio can be fully determined from the stress intensity factor of the “Crack Approaching” stage. The toughness ratio requirement may then be used as a design tool for a further development of the peel stopper proposed in [3].

3. Solution and generation of “prediction surface”

The solutions for the complex coefficients c, d, e and f can be obtained by analyzing and solving the four sub-models (See Figures 2 and 3) analytically, and using the output/results as input to the formulation of a set of algebraic equations which may subsequently be solved. See [29] for details.

However an approximate solution for the complex functions c, d, e and f was determined by solving a linear elastic fracture mechanics problem (LEFM) for the crack models sketched in Figures 2 and 3. Finite Element solutions for the LEFM problem and the different crack models were derived using ABAQUS v6.6®. Thus, FE-models corresponding to the three different crack configurations, See Figure 4 for the converged mesh distributions.

The models were analysed for a range of wedge angles (φ) starting from 10º and ending at 90º. This range was chosen because of its relevance to future peel stopper designs for sandwich structures [2,3]. Only solutions for positive mode mixities of the approaching crack have been performed. The reason for this is related to the materials commonly used in the experimental testing of the sandwich peel stopper [3]. These types of core materials will not allow an interface crack to propagate toward the wedge with negative mode mixities, because a negative mode mixity will make an approaching crack kink out of the interface before reaching the wedge. For full details see [29].

The solutions of the complex functions and the criterion in Eqs. (3) can be used to create a “prediction surface” as shown in Figure 5. Crack deflection is then predicted if the interface toughness ratio is below the red surface shown in Figure 5.

The prediction surface has not been drawn for the full range of mode mixities (ψ_{12}) because parts of the range yield negative values, with the physical implication that the crack faces overlap. This is (of course) not physically reasonable, and therefore the surface in Figure 5 has been cut off (“truncated”). For this particular tri-material composition only values (ψ_{12}, ϕ) within the green area represent a physically meaningful design space. By studying the prediction surface it is seen that for low core junction angles (ϕ) the physical model predicts the highest interface toughness ratio, which further leads to a lower manufacturing quality requirements (easier to fulfill the interface toughness ratio requirement). Moreover it may be seen that the physical model predicts physical results for the entire range of studied mode mixities (ψ_{12}). Based on these results, it is recommended that small wedge angles should be recommended for future development of the peel stopper, and this is in close agreement with the combined experimental findings and modeling results presented in [2,3,28].
Figure 4. Mesh distributions in the vicinity of the tri-material wedge and the crack tip for the three crack stages [29].

Figure 5. “Prediction surface” (shown in red) seen from two directions. Interface toughness ratios ($G_{23}/G_{13}$) below the surface will yield crack deflection, whereas crack penetration will occur for $G_{23}/G_{13}$ ratios above the surface. The surface is cut off (truncated) as it only is physically meaningful for $K_{1,23}>0$ [29].
4. Conclusions
A physical model, based on LEFM and the assumption of isotropic material constituents, that is able to predict crack deflection or penetration for tri-material wedge problems has been presented. In principle the model relates the stress intensity factors of an approaching interface crack to the stress intensity factor of a deflected or penetrated crack through the determination of transition functions. These functions are formulated in terms of complex coefficients that depend on the actual composition of the tri-material wedge and the wedge angle. A solution to the complex coefficients and a FE-based solution approach has been demonstrated for a specifically chosen tri-material wedge composition. The selected composition is a close approximation to a tri-material wedge consisting of a glass fibre composite laminate, and two polymer foam core materials of different densities (PVC, Divinycell H200 and H60) as discussed in [2,3,28]. The practical background for this particular choice of material combination and geometry is a newly proposed device for crack deflection and crack arrest in sandwich structures, a so-called peel stopper, where the chosen tri-material configuration represents a sandwich face sheet and two adjoining core materials.

The purpose of the FE based approach is to create input to the physical model in such a way that the complex coefficients can be determined. The results presented only cover solutions to the singular part of the model/problem.

The complex coefficients determined from the FE analyses were used to construct a “prediction surface” for the analysed composition of the tri-material wedge through the proposed physical model. The “prediction surface” may be used as a design tool for identifying and choosing proper wedge angles, which further may be used to improve future peel stopper geometries as discussed in [2,3]. It was found that small wedge angles allow the highest interface toughness ratio, which means lower fabrication demands if an effective “peel stopper” is to be designed and manufactured.

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