NEW CRACK STOPPER CONCEPT FOR SANDWICH STRUCTURES

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Abstract

This paper presents a new crack stopper concept for sandwich structures. The proposed concept relates to a specially shaped core insert, which has the ability to confine face sheet peeling by re-routing the delamination front away from the face/core interface into a bulk of the sandwich core and by constraining the core damage to a limited prescribed area. The concept was implemented in the form of a specifically shaped insert embedded into the core of a sandwich beam, which was tested experimentally in three-point bending with controlled crack initiation and propagation. Two other conventional sandwich beam designs were tested under similar conditions in order to access the ability of the peel stoppers to stop face/core delamination. In all test cases the face sheets of the sandwich beams consisted of CFRP and the cores were Rohacell 51WF and 200WF foams. The studied peel stoppers were manufactured from solid Polyurethane. High speed video recordings were performed to monitor crack initiation and crack progression.

A finite element model describing the crack propagation along the face-core interface based on the energy release rate criterion was developed, and the influence of the model parameters on the crack propagation was studied. A satisfactory consistence between the numerical and the experimental observations was generally achieved.

1 Introduction

A sandwich material is a layered assembly made from two thin and strong face sheets bonded to a light weight compliant core material. This creates a stiff, strong and also a very light-weight structural element [1]. The sandwich concept has been vastly utilized by the aerospace industries 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 gained a significant interest in adopting the sandwich concept during the last years due to competitive prices, tailored design and high mechanical performance requirements.

Sandwich structures often display brittle behaviour when/if they fail, and since this is highly undesirable a significant amount of the research into sandwich structures technology concerns the investigation of failure behaviour [2]. Classical failure propagation in sandwich beams loaded in three-point bending was studied by Zenkert and Burman [3,4], who have uncovered that the principal failure mechanism of such structures is by shear. They found that shear failure initiated in the centre of the specimen, and then kinked toward the face sheets and continued as face/core delamination. Local effects arising in the vicinity of core junctions were studied by Bozhevolnaya et al. [5-8]. It was found that the shape of a core junction and in general the shape of any insert in the core of a sandwich exerts a significant influence on the fatigue life of the sandwich assembly. Moreover, face/core delamination was observed to be the dominating failure mode in their experiments.

Sandwich elements have great advantages when building light and stiff structures. However, the sandwich concept is highly vulnerable to face/core delamination also called face sheet peeling. As known for structures made from ductile metals like steel or aluminium, the ability of a material to display plastic yielding may extend or slow down the collapse process of a failing structure. Of almost equal importance is the fact that substantial deformations of ductile metallic structures prior to collapse/failure very often are visible, which provides a forewarning of progressing loss of structural integrity. However, material yielding and visible deformations of composite/sandwich structures are insignificant, which in most cases might lead to a rapid failure progression without any possibility to prevent a fatal collapse of the structure. This rapid progression of failure is due to the layered constitution of sandwich structures, which facilitates the propagation of cracks along the material interfaces. Delamination of the sandwich constituents is one of the common failure modes, and the prevention (or delay) of face sheet peeling is very important from a practical applications point of view.

Several solutions/suggestions to overcome this problem are known today. One method is to use stitching techniques, which in principal is to stitch/connect the upper and lower face sheets together by means of fibres stitched through the thickness of the sandwich. This method increases the debonding strength between the core and face sheet by several magnitudes [9-12]. However production wise it may cause some difficulties and local repairing of stitched components may not be possible without replacement of larger parts of the structure.

Another method for preventing face/core delamination is by adopting a so-called “peel stopper” invented by J. Grenestedt [13, 14]. The idea here is to manufacture sandwich panels in such a way that smaller areas of the faces may be peeled off, but that the debonding is effectively stopped at certain locations, and in this way prevent that larger parts of the face delaminates and the structure collapses. Tests have verified that the invention worked as expected: the delaminated face sheet was discarded from the structure when the delamination front reached the “peel stopper”, and no further debonding/delamination occurred after this. However, the invented “peel stopper” is rather difficult and expensive to produce. Moreover, when one face sheet discarded from the structure a major decline in bending and in-plane tensile stiffness has occurred.

This paper presents a new method to prevent progression of face-core delamination (peeling) in sandwich structures. The principle behind this invention is that a specially shaped core insert is embedded into the core of the sandwich structures. When the delamination front reaches the insert, the crack tip is rerouted to follow the internal boundary of the insert instead of continuing along the face/core interface or bond line. Thus, the delamination crack is confined and prevented from further propagation. In this paper the core insert is referred to as a “peel stopper”, i.e. the same notation adopted by Grenestedt [13, 14]. However, the new “peel stopper” is fundamentally different from Grenestedt´s. A patent application concerning the new “peel stopper” has been filed [15]. The present paper illustrates some experimental results, which have validated the principle behind the “peel stopper”. In addition, finite element analysis results are presented, which elaborate on and explain the conditions that have to be fulfilled in order to force the crack to propagate along the internal boundary of the peel stopper (and thus to stop delamination) rather than to propagate along the core-face interface.

2 Experimental Setup

The concept of the peel stopper is validated experimentally by comparing the performance of three different sandwich beam configurations loaded in three-point bending. The three configurations named (a), (b), and (c).are shown in Fig. 1.

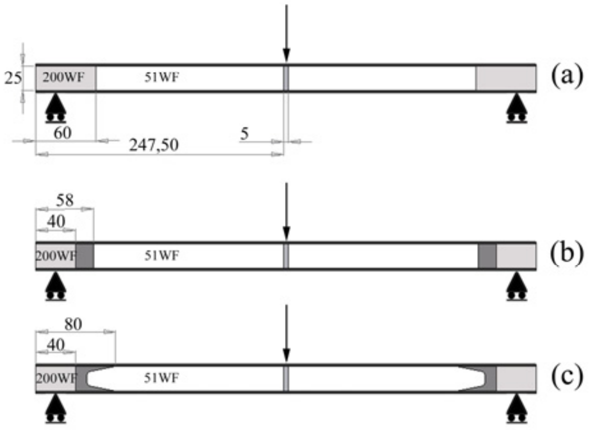

Fig. 1 The three configurations of sandwich beams tested experimentally. Configuration (c) has the presented peel stopper embedded.

All three beam configurations are made with carbon fibre prepreg face sheets with a stacking sequence of (0,90,0), where the zero-direction is in the beam length direction. The core consists of 200WF Rohacell PMI foam as edge stiffeners and an Araldite diaphragm in the centre of the beam to redistribute the external load and to prevent crushing of the core at the load point. Furthermore, the core of the sandwich beams consists of a compliant mid-section, which is made from 51WF PMI foam. The three configurations differ from each other by the shape of the core insert, which has been embedded between the 51WF and 200WF core. Configuration (a) is a conventional beam with an edge inserts, i.e. no core insert is used. Configurations (b) and (c) are made with Polyurethane inserts of an identical weight but of different shapes. The insert of configuration (b) is made as a rectangular block, whereas in configuration (c) the insert is shaped with an internal curved boundary, which purpose is to re-route a delamination crack to follow the internal boundary of the insert.

The experimental test setup is shown in Fig. 2. All tests were performed on a 100kN servo hydraulic Schenk Hydroplus®. In order to obtain the best possible accuracy the lower load range (12.5kN) of the machine was used. This gave a discrepancy between input and output signal of less than 2%

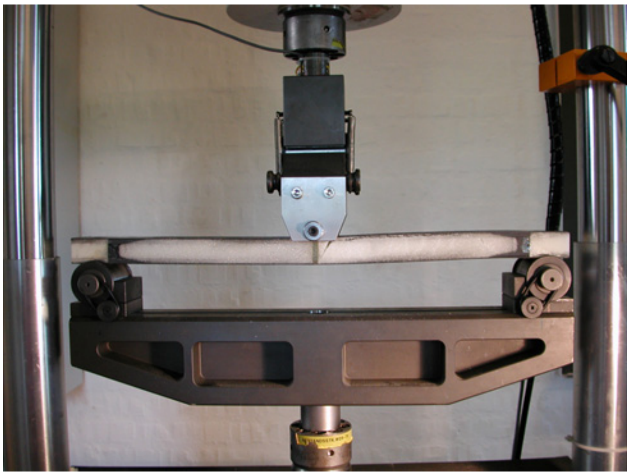

Fig. 2. The test specimens were loaded in three-point bending up to failure.

Two specimens of each configuration were manufactured. This is insufficient to establish a significant statistical trend, but it is enough to provide a tentative confirmation of the new “peel stopper” concept. All specimens are manufactured as one single panel and then cut into the proper dimensions afterwards. The panels were cured at 100ºC for 6 hours and then post cured for another 48 hours at room temperature, before they were cut into specimens.

3 Experimental Results

The tested sandwich beams were loaded up to failure. The load vs. centre displacement responses of all three configurations were sampled and compared (see Fig. 3). A similar flexural response from the three configurations was observed. This was also expected, since the geometry of the three configurations is similar, and since the design of the beam edges exerts little influence on the overall structural responses of the tested beams.

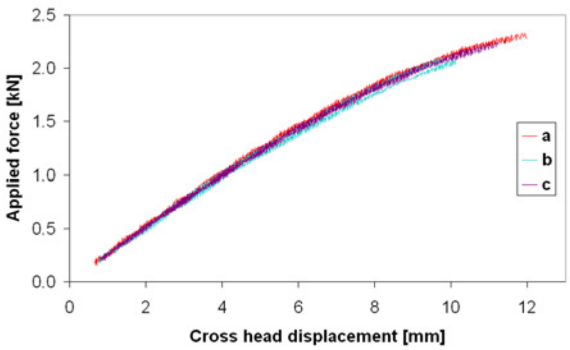

Fig. 3. Load vs. central displacement.

The failure loads and centre displacements at failure were recorded and are given in Table 1. The recorded values for each configuration are very similar and differ only by a few percents. The highest failure load was measured for configuration (a) followed by (c) and (b), but again the recorded failure load for all six specimens are similar. The centre displacement at failure followed the same trend as for the failure load.

Table 1. Failure loads and central displacement at failure

Specimen/ Configuration	Failure load [kN]	Cent displ. At failure [mm]
a1	2307	11.58
a2	2332	11.97
b1	2094	10.11
b2	2106	9.80
c1	2185	10.43
c2	2246	11.22

The loading sequence and crack propagation until failure was recorded with a high speed camera for all specimens. A frame rate of 6000 frames pr. second was used, and this enabled the capture of initiation and further propagation of the cracks. For all six specimens the failure process initiated as shear cracking in the compliant core, followed by kinking of the crack towards the upper and lower sandwich faces and then propagation of delamination cracks between the faces and the core as the last stage of the failure process (see Fig. 4 to Fig. 6).

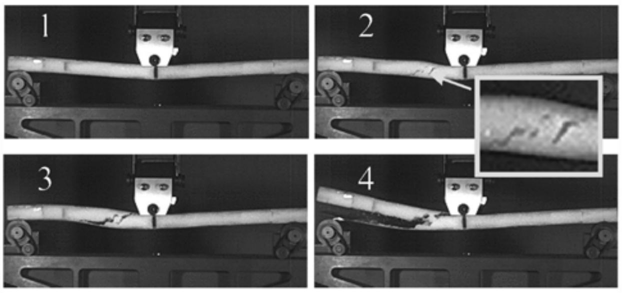

Fig. 4. High speed images of crack propagation in a specimen of configuration (a).

Only one image sequence is shown for each configuration because they are very similar.

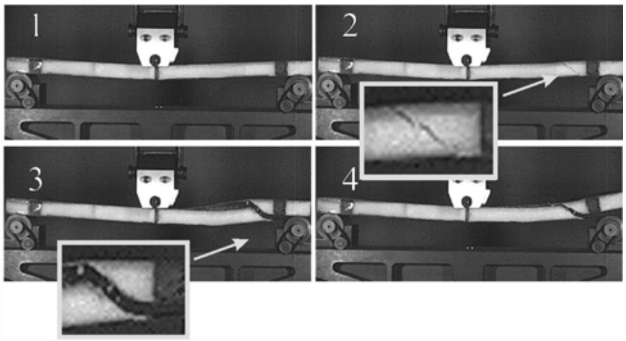

Fig. 5. High speed camera images of crack propagation in a specimen of configuration (b).

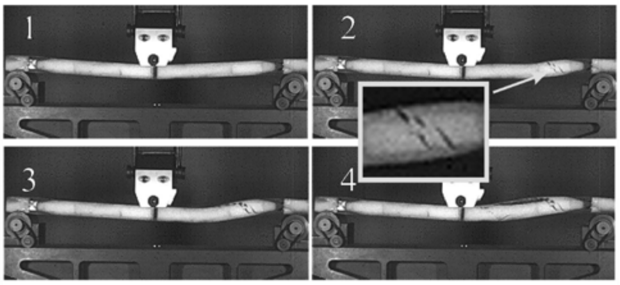

Fig. 6. High speed camera images of crack propagation in a specimen of configuration (c).

From Figs. 4-6 it appear that the crack initiates in the area closer to the Polyurethane insert for configuration (b) and (c). This may be explained by the presence of the local effects (causing stress concentrations) introduced by the mismatch in stiffness between the compliant core (51WF) and the Polyurethane insert. However, it seems not to influence the load bearing capability and flexibility of the sandwich beam structure in a significant way (cf. Table 1).

It should be noted that the experiments document that configuration (c) is the only one of the tested configurations that was able to confine the crack growth inside the sandwich core, and to prevent complete delamination of the specimens, as observed from the undamaged edges of the specimens of type (c). For configuration (a) and (b) the delamination continued along the face/core interface until it reached the free edge of the specimens, whereas for configuration (c) the delamination front was re-routed and confined by the internal boundary of the "peel stopper". Furthermore, it is observed for the type (c) specimens that the core beyond the "peel stopper" boundary was left intact and undamaged.

Post mortem inspection of the specimens of configuration (c) (see Fig. 7) revealed that the edge part of the specimens furnished with the peel stoppers were intact.

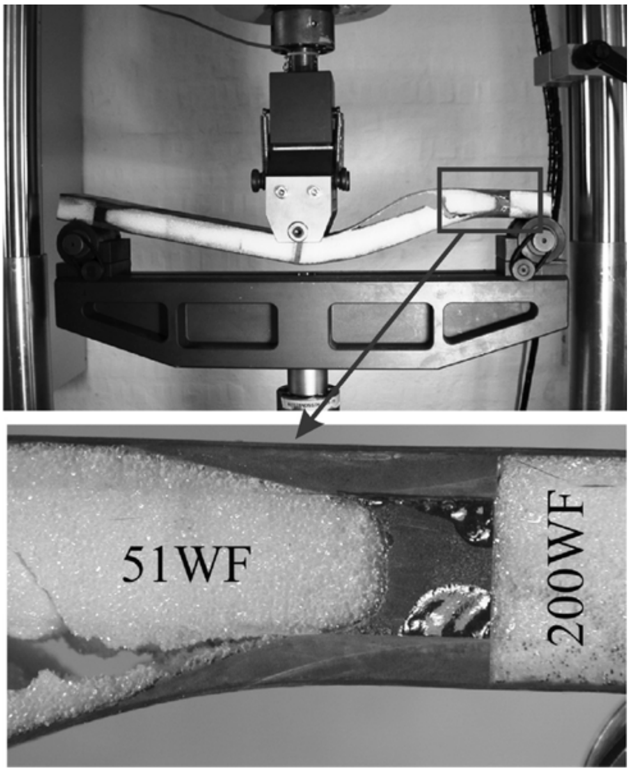

Fig. 7. Post mortem inspection of a configuration (c) specimen shows that the crack had been successfully re-routed by the internal boundary of the peel stopper.

Similar experiments with Aluminium face sheet and Divinycell cores were carried out in order to test the "peel stopper" concept on different material compositions. The results of these extensive tests have shown that the new "peel stopper" is very effective in preventing core-face delamination for all the tested combinations of face and core materials.

4 Numerical Modelling

The modelled sandwich beam loaded in the three-point is shown in Fig. 8. The loading is applied as a prescribed vertical displacement of 11mm acting downward at the centre of the top face. The crack path is marked with a red line in this figure. Only the part of the sandwich beam, where the crack initiates due to shear, propagates towards the top and bottom face-core interface, kinks and propagates as face-core delamination and further develops around the peel stopper, is studied closely.

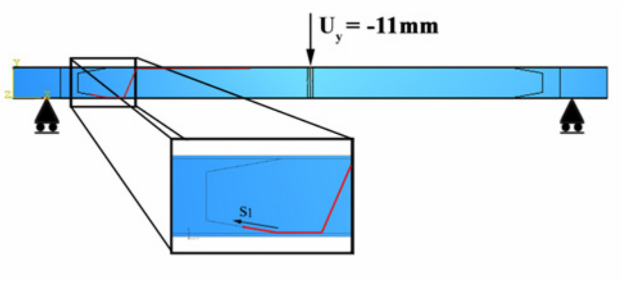

Fig. 8. The sandwich beam is loaded in three point bending. The numerical model covers an area in the close vicinity of the peel stopper. The initiation of the crack path is modelled according to experimental observations.

The constituent materials in the numerical model are modelled as homogenous and linear elastic. This clearly is an approximation of the reel material behaviour, but it is assumed to be satisfactory for this study. It should be noticed that especially the Polyurethane has a very non-linear material behaviour but its nature is simplified to be linear, which able us to use Linear Elastic Fracture Mechanics (LEFM) on this problem. Furthermore, the model is analysed under the assumption of plane strain conditions. The elastic properties of the constituents are given in Table 2.

Table 2. Elastic properties of the constituents in the numerical model.

Material	E-modulus [MPa]	Poisson's ratio
CFRP (UD)	129200	0.34
CFRP (0,90,0)	88800	0.34
Polyurethane	100	0.35
200WF	350	0.30
51WF	75	0.30

Previous numerical studies of the stress state in sandwich beams that were similarly loaded, as well as the experimental studies presented here have disclosed the crack path including the point of initiation [19]. A section of the modelled sandwich beam is shown in Fig. 9, where the red line indicates the possible crack path, which starts in the centre of the core, kinks towards the faces and propagates along the face-core interfaces. The crack propagating towards the "peel stopper", see Fig. 9, is the object of the numerical modelling described herein. The major objective of the model is to predict what happens when the crack reaches the three-material corner (face/core/"peel stopper"). This includes the questions about how the shape of the "peel stopper" influences the crack propagation, and if the crack will propagate along the "peel stopper"-core interface, or if it continues to progress along the face-"peel stopper" interface? These two possible scenarios are shown in Fig. 9.

The energy release rate is used as criterion to assess the most probable path for the crack growth. Accordingly, the conditions under which a crack will be re-routed by the internal boundary of the "peel stopper", or if it will continue its progression along the face/"peel stopper" interface, may be stated by the following two criteria in terms of the J-integral J and fracture toughness Γ

$$\begin{aligned} &\text{path } s_1: \quad J_{s1}(\psi(\theta)) > \Gamma_{1,2}(\psi) \\ &\text{path } s_2: \quad J_{s2}(\psi(\theta)) > \Gamma_{2,3}(\psi) \end{aligned} \tag{1}$$

In Eq. (1) ψ is the mode mixity, and indices 1,2 and 3 in the fracture toughness $\Gamma_{1,2}$ and $\Gamma_{2,3}$ refer to the core, peel and face materials, respectively, as indicated in Fig. 9. J_{s1} and J_{s2} have to be evaluated along the two possible crack paths s_1 and s_2 (see Fig. 9).

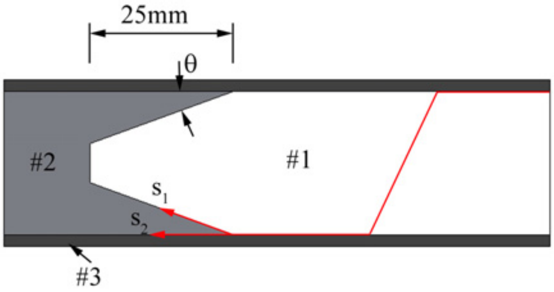

Fig. 9. Crack paths in the vicinity of the peel stopper. When a crack (red line) meets the peel stopper two options exist: one is to follow the path s_1, and the other is to follow the path s_2.

The fracture toughness depends on the interface composition and the mode mixity, and it has to be determined experimentally. At the time where this paper was prepared, the fracture toughness data for the modelled constituents were not available. In forthcoming studies the fracture toughness will be determined experimentally, and the numerical investigation outlined herein will be extended accordingly.

Three "peel stopper" re-routing angles which have been studied in this paper are θ = 10º, 20º and 25º (see Fig. 9), and the *J*-integral has been evaluated along s_1 for these three cases. The horizontal length of the re-routing path is kept constant at 25 mm for each of the three cases.

The standard software package ABAQUS® is used for the Finite Element Analysis (FEA) of the crack propagation in the sandwich beam. The simulation of the crack propagation consists of a series of linear static analyses starting with a crack path as illustrated in Fig. 8. The left crack tip is at the s_1 interface, which is as close to the tri-material corner as possible in order to be able to evaluate the *J*-integral. After the specific location of the crack tip has been analyzed, the geometry (i.e. crack path) is updated, and the crack tip is in turn analyzed in this new extended position. This procedure is repeated a number of times along the s_1 interface. Since the sandwich beam is subjected to a constant vertical displacement at mid-span, the value of the J-integral is expected to diminish along the s_1 interface. In reality the value of the *J*-integral should follow the value of the interface toughness. This, however, will require that the applied centre displacement should be updated/ adjusted at each crack advance, and this is not taken into account, because it is out of the scope of this study.

The model is meshed with an overall element edge length of 0.5mm, except for the area around the crack tip, which is refined to an element edge length around 0.036mm (see Fig. 10). All elements are second order elements (6 and 8 nodes). In order to obtain an improved element shape (element quality), the "peel stoppers" are meshed with triangular elements, and the rest of the model is meshed with rectangular elements. The mid side nodes of the elements surrounding the crack tip were moved to one quarter from the tip nodes. This creates a "√r" singularity, where r measures the radial distance from the crack tip. According to the elastic mismatch between the "peel stopper"/core interface, the oscillatory index ε has been calculated to ε = 0.0234 [16]. The "√r" singularity is not exact then, but is used as an approximation. However, the *J*-integral is evaluated with five contours surrounding the crack tip starting at a distance of 0.2mm (or 6 elements) away from the crack tip. This is done in order to obtain an indication of the convergence of the model.

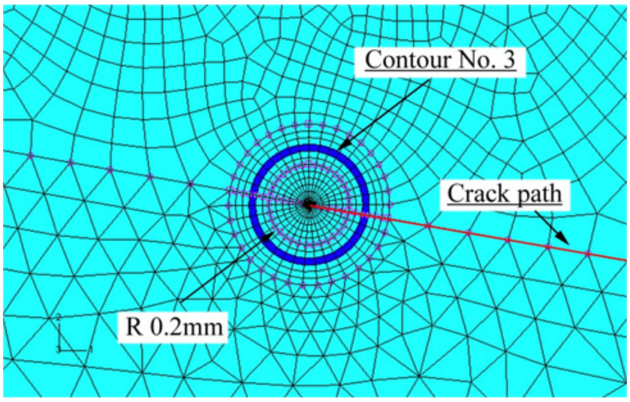

Fig. 10. The FEA mesh density is refined near the crack tip. The *J*-integral is evaluated in five contours around the crack tip starting at distance of 0.2mm.

5 Numerical Results

The *J*-integral is evaluated along the interface s_1 as illustrated in Fig. 8, which also corresponds to the lower boundary of the peel stopper/51WF core interface. The evaluation based on averaging the five contours around the crack tip increases the accuracy of the modelling. The discrepancy in the successive values of the *J*-integral at each of the five contours was around 0.2%, which indicates that convergence of the results has been satisfactorily reached.

The numerical representation of the *J*-integral together with extraction of the stress intensity factors (K_1 and K_2) are explained in details in [17]. The stress intensity factors are later used to evaluate the mode mixity along the crack path s_1.

The deformed solution to the considered problem is illustrated in Fig. 11, and due to the asymmetric failure of the beam structure a small rotation of the left part of the beam is induced. This was also observed during the post mortem inspections of the damaged peel stopper beams (see Fig. 7)

The *J*-integral is plotted against the lower "peel stopper" boundary coordinate s_1, and it may be observed from Fig. 12 that the lowest crack re-routing angle generates the highest level of energy release rate. This should be taken into account when designing a "peel stopper" similar to those investigated in this paper. The purpose of the "peel stopper" is to re-route the delamination away from the face/core interface, and the highest crack energy release rate (i.e. crack re-routing force) is obtained with the angle of 10º.

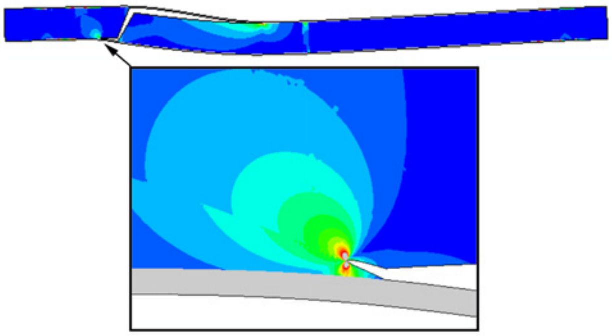

Fig. 11. The stress field is shown to illustrate the structural deformation of the analyzed crack problem and not to give specific values of stress levels at the crack tip.

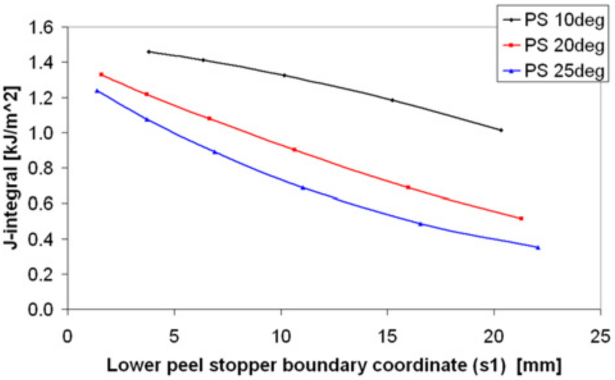

Fig 12. Three different crack re-routing angles were analyzed with respect to the *J*-integral. It is seen that the crack is able to release most energy per crack advance for low re-routing angles.

Additionally, the mode mixity along the same interface is studied for the three re-routing angles. The mode mixity may be defined in terms of the interface stress intensity factors K_1 and K_2 [18] as

$$\psi_K = \arctan \frac{\Im\left(Kl^{i\varepsilon}\right)}{\Re\left(Kl^{i\varepsilon}\right)} \tag{2}$$

In Eq. (2) K is the complex stress intensity factor $K=K_1+ i\cdot K_2$, and l is a reference length, which depends on the particular problem. The reference length may be chosen arbitrarily, but it appears reasonable to base this choice on material characteristics such as plastic zone size and foam cell size. The influence from the characteristic length is neglected in this paper, since its value is close to one, if l is assumed to equal to the cell size, which for 51WF is 0.5mm (microscopic observations of this particular foam yield cell sizes from 0.2 to 0.8mm, which gives an average of 0.5mm):

$$\begin{aligned} l^{i\varepsilon} &= \cos(\varepsilon \ln(l)) + i\sin(\varepsilon \ln(l)) \\ &= 0.9999 + i0.01622 \approx 1.0 \\ when: &\quad \varepsilon = 0.0234 \quad , \quad l = 0.5 \end{aligned} \tag{3}$$

According to this simplification the mode mixity may be evaluated along s_1. This is illustrated in Fig 13. It should be noticed that the values of the mode mixities are negative, which indicates that the crack would kink downward out of the interface if is possible. According to the experimental observations the crack stays in the interface, which indicates that the fracture toughness of the Polyurethane material is high enough to avoid crack kinking.

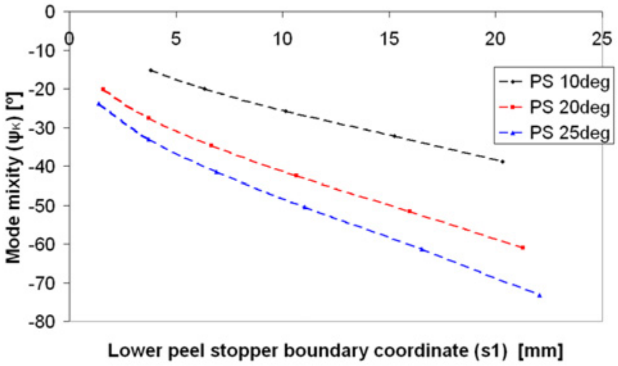

Fig. 13. The mode mixity has been plotted along the same interface as the *J*-integral. Due to the negative sign of the mode mixity the crack will tend to kink down.

Moreover, it is seen from the graphs in Fig. 13, that the mode mixities are increasing in value (becoming more negative) as the re-routing angle is increased, which is understandable since the higher angle will easily provoke kinking downwards from the interface s_1. The issue of increasing mode mixity along the interface s_1 may lead to an unfavourable situation, since the interface toughness is also expected to increase with increasing mode mixity. This could lead to a shift of the weakest interface from s_1 to s_2, and a crack may be initiated somewhere at the face/"peel stopper" interface. This has not been observed experimentally for the specific "peel stopper", due to its particular shape and the choice of materials.

6 Discussions/Conclusion

A new “peel stopper” for sandwich structures, in the form of a core insert, has been tested with respect to its ability to stop face-core delamination in sandwich structures. Three configurations of sandwich beams were tested in three-point bending, and it was shown that only the configuration with presented “peel stopper” embedded was able to confine and stop the unwanted delamination of the face-core interface.

In order to understand the functionality of the “peel stopper”, and the underlying physics of the delamination and crack propagation phenomena, a numerical model was developed, that takes into account the loading situation, the geometry/design and the material properties of the sandwich constituents. The energy release rate was chosen as the criterion for the delamination and crack propagation. A high energy release rate at an interface is favourable for crack propagation, and for this particular study it will be favourable for the crack re-routing. Three different peel stopper shapes, where the re-routing angle was varied, were analyzed with the respect to this criterion, and it was found that the energy release rate had the highest level for low re-routing angles.

In addition it was found from the numerical analyses that the mode mixity along the peel stopper/core interface is negative and increasing in magnitude (becoming more negative) with increased distance from the tri-material wedge. The negative sign of the mode mixity indicate that the crack would kink downward out of the interface if it had the possibility. Fortunately crack kinking does not occur and it may be explained with a very high fracture toughness of the Polyurethane material. Furthermore crack kinking studies is going to be performed in the near future and it will help to gain knowledge about which material candidates that may be suitable for the presented peel stopper.

The work and results presented herein will be continued with extensive tests aimed at determining the facture toughnesses of the materials involved, further crack/delaminations studies of sandwich panels with “peel stoppers” in different configurations as well as extensive numerical studies of crack/delamination growth.

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