PRELIMINARY EVALUATION OF THE PERFORMANCE OF NOVEL FIBRE REINFORCED PEEL STOPPER CONCEPT IN SANDWICH STRUCTURES

G. Martakos[1]*, J.H. Andreasen[1], O.T. Thomsen[2,1]
[1] Mechanical and Manufacturing Engineering, Aalborg University, Aalborg, Denmark,
[2] Faculty of Engineering and Environment, University of Southampton, Highfield Campus Southampton, SO17 ABJ, UK
* Corresponding author (gm@m-tech.aau.dk)

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1 Introduction

Sandwich structures exhibit high stiffness and strength to weight ratios [1], and they are used extensively for multiple applications for this reason. However they are very sensitive to localized stress concentrations occurring at load introductions and discontinuities between the face sheet and core, which may lead to the development of interface debonds and cracks.

Particularly, interface cracks have been extensively studied due to their unique behavior and characteristics. Often the toughness of the face-core interface is lower than the toughness of the bonded materials causing the crack to propagate parallel to the interface. That way the crack path is imposed by the interface geometry. Thus interface cracks tend to propagate under mixed mode conditions, while both opening and sliding of the crack faces is observed. In addition, the difference in stiffness between the facesheet and core material creates a characteristic oscillatory singularity at the crack tip, which has been extensively studied together with its effect on propagation [2-3]. Jakobsen et al. [4] also derived explicit equations for stress intensity factors for an interface crack closing a tri-material wedge while studying crack deflection by core junctions.

Deriving crack propagation properties for a wide range of bi-material interfaces has been feverously followed. D.Zenkert and M Burman [5-6] performed a series of quasistatic and fatigue tests to identify fracture toughness properties and power law coefficients for propagation in fatigue for different facesheet-core interfaces. Quispitupa and Manca [7-8] studied interface crack propagation between a wide range of PVC foams and glass reinforced resin polymer and derived power law curves for different phase angles of mode mixity.

Together with the characteristics of crack propagation, the impact of cracks in sandwich structures has been investigated. D.Zenkert [9] used experimental tests and numerical tools to investigate the reduction in strength of sandwich beams with an initial face/core debond. Moreover, damage tolerance in sandwich structures has been researched by Zenkert and Hayman [10-11] for a wide range of applications in the industry. The importance of investigating the effect and severity of debonds in sandwich structures is underlined as well as the investigation of damage tolerance and ways to improve it.

For that reason, several crack stopping devices have been proposed [12-13] to limit the severity of debond propagation in sandwich structures. A new concept for a peel stopper was proposed recently by Jakobsen et al. [14], using Polyurethane (PU) for the manufacturing of a special core insert. The new peel stopper approach was tested in quasistatic and fatigue loading conditions [15], and it was proven capable of achieving crack deflection away from the face-core interface. Furthermore it was able to arrest the crack and prevent it from kinking back into the face-core interface and continue propagating.

The purpose of the current investigation is to test the performance of a new concept of fiber reinforced PU peel stopper under both quasistatic and fatigue loading conditions. The new peel stopper concept is fabricated in the shape of thin sheets to reduce the weight penalty associated with introduction the peel stopper device into a sandwich structure. Glass fibers were included in the PU material to increase the fracture toughness of the material and prevent crack kinking during fatigue loading conditions. In the present work, the investigation focuses on testing of beam specimens with embedded peel stoppers and as such serves as an evaluation step before fracture modeling, concept optimization and implementation of the new concept to sandwich panels. Evaluation criteria should rely on the ability of the peel stopper to deflect a propagating crack to the center of the core material, its resistance to kinking and crack penetration. Furthermore an extended life behavior in fatigue should be observed before a re-initiation and crack propagation.

2 Method and Materials

2.1 Test Specimens

Twelve sandwich beams, each containing the new fiber reinforced peel stopper were fabricated. Six of the beams were loaded quasistaticaly and the six remaining were loaded in fatigue.

The main features of the geometry and the constituent materials of the test specimens can be seen in Fig. 1. The core structure consists of Divinicell H100 foam in its main part while H200 was used to reinforce the edges and the loading point.

The peel stopper was fabricated using a two component PU resin that was impregnated into a layer of UD glass fibre rowings. A specially manufactured mold was used to obtain the desired geometry of the peel stopper. The glass fibres were aligned in the direction along the height of the peel stopper (Fig. 2) to increase the fracture toughness of the material.

The face sheet laminates of the sandwich beams consist of 4-plies of $0^o/90^o$ glass-epoxy laminae and were both infused at the same time using vacuum assisted resin transfer moulding (VARTM).

The mechanical parameters for the constituents of the beam specimens are given in Table 1.

2.2 Experimental procedure

The experimental investigation utilizes beam specimens loaded in 3-point bending, Fig. 1. The objective of the investigation is to assess the ability of the new peel stopper concept to deflect and arrest a propagating face-core interface debond under both quasistatic and fatigue loading conditions.

For the quasistatic loading experiments, six beams were tested. The tests were conducted in displacement control at a rate of 5 mm/min. The maximum load at crack initiation was recorded and used as a reference for the fatigue loading tests. The load though, as it will be shown later, was over estimated by the quasistatic test. The reason is an increased initial resistance effect introduced by the resin, resting around a strip of TEFLON film at the crack tip. In order to overcome the limitation, a sharp crack tip is necessary to induce.

The remaining six specimens were tested under fatigue loading conditions. Before, loading the specimens in fatigue the correct maximum quasistatic load had to be identified. A methodology for achieving that goal was developed and at the same time, it was used as a way to initiate a sharp crack tip at the crack fronts.

The methodology uses the displacement at failure from the quasistatic tests as the maximum displacement. A displacement controlled fatigue test is initiated starting at 40% of the maximum displacement for as many as 500 cycles. After all the loading cycles are completed, the displacement is increased by 5% and the specimen is loaded for another 500 cycles. The procedure continues until a sharp crack is created and until a considerable reduction in load is observed with each cycle. The method assumes that when loading for a small number of cycles, the crack should propagate considerably only when the fatigue load is close to the quasistatic limit. Displacement controlled loading is chosen as a means to avoid unstable crack growth after initiation and extensive propagation of the crack front. The force taken at the start of the 500 cycle round in which the crack tip initiated is considered close to the quasistatic maximum.

After crack initiation, the fatigue test was run in displacement control to avoid unstable crack growth. The initial maximum fatigue displacement was chosen at the 80% of the maximum displacement, derived from the initiation method described above. The frequency of the loading was set to $f=3Hz$ and the stress ratio at $R=0.1$ to avoid heating and crack closure respectively. As the crack propagated, the applied load decreased and the cracks decelerated. When a specified certain amount of cycles was over, the displacement was increased and the specimen was loaded again. The test was terminated when failure outside of the crack stopper limits occurred.

3 Results

3.1 Quasistatic test

The quasistatic tests were mainly conducted to identify the maximum load in static for crack initiation and growth. As mentioned above the initial resistance to crack growth due to resin around the crack tip leads to over predicting of the maximum static load for initiating crack propagation. The maximum load and displacements for the quasistatic tests were recorded and are given in Table 2 for all the six beams. After the first failure, the right front of the crack had propagated unstably, towards the lower interface and then got deflected by the crack stopper. At the same time a new crack appeared on the other side of the crack stopper and propagated towards the outer support of the 3-point bending test set-up. It is clear that the instability due to extensive initial quasistatic loading affected the response. The crack propagated instantly to reach the state of fig. 3 which doesn't provide any information on the effect of the crack stopper in the structure. Only the right crack front propagated during the quasistatic test. The crack kinked directly to the core material and propagated towards the lower interface. The crack afterwards, continued to propagate parallel to the face/core interface until it got deflected by the peel stopper. The peel stopper deflected the crack away from the interface and into the core material. Instantly, after the crack reached the peel stopper limits another crack initiated on the other side of the peel stopper material in the foam. The left crack tip, in all cases, kinked upwards in to the facesheet as it was loaded under a negative phase angle with mode II dominance. The behavior observed, explains the increased fracture resistance of the left crack front and the much slower propagation rate in comparison to the right. In all cases the peel stopper was able to deflect the crack and also resist crack propagation into its material. A new crack always started on the foam behind the stopper.

3.2 Fatigue test

The crack initiation methodology/routine was applied to each beam before fatigue testing. From Table 2 the average maximum displacement before failure from the quasistatic test is found to be $W_{avg}=14,39mm$. Starting at 40% of the maximum displacement with a step of 5% for 500 cycles per step the specimens were loaded until crack initiation. In Fig. 4. the change in load during the last 500 cycles of the routine is plotted. The load reflects the load that initiated a sharp crack in each specimen for the 500 cycles. In all cases when lower displacement was applied no visual confirmation of a sharp crack tip was possible. A reduction though in the applied load was observed in all cases but of less magnitude than for the initiation loads. For beam 9 the routine ended after 250 cycles as a relatively large crack had already propagated, to about 4 mm.

The load and displacement for crack initiation as derived from the crack initiation methodology is given in Table 3. The displacements and loads reflect to 60-65% of their quasistatic tests equivalents. The results show that the static load for failure could be overestimated as much as 35% in such cases if relied only on the quasistatic tests values.

The test procedure was stopped when a new crack face, 3-5 mm, had initiated and when a certain loss of stiffness was observed, Fig.4. The loss of stiffness is attributed mainly to the creation of new cracks but also to some plastic deformation of the beams.

Furthermore, the initial crack tip had initiated only in the right crack side, as a kink of the crack inside the foam material. The left crack tip loaded, as mentioned before, under mode II dominant conditions, initiated later, during the actual fatigue tests. After a sharp crack was created the fatigue displacement for the rest of the fatigue test was chosen at the 80% of the average maximum displacement of the initiation routine.

In Fig. 5., the compliance of the specimens is plotted against the number of loading cycles. The Compliance is chosen here instead of the load signal because the fatigue tests under displacement control were executed within steps where the displacement was increased and thus only the load-displacement relation of the beams represents crack growth. In the plots three stages of the life of the beam during crack propagation are emphasized. In Figure 6. the three stages are shown in the beam and reflect the starting position of the crack tip from where the number of loading cycles starts to count. The maximum crack deflection point represents the arrest point, where the crack stops propagating. Finally, the third point represents the position and time when the new crack face is initiated on the other side of the peel stopper where the fatigue test stops and propagation accelerates. Although from the arrest point up to the re-initiation point there is no crack growth, the compliance of the beams increases in all cases. The increase is attributed to crack growth and damage development on the left part of the crack during the arrest period.

4. Discussion

The results from the quasistatic experiments showed the difficulties in deriving the static limit for damage propagation when initial damage is included in the structure. Alternatively, a fatigue procedure was developed to identify the static limit and at the same time initiate the crack propagation. The maximum load for crack propagation in quasistatic was found as low as 60% lower than the loads derived from the quasistatic experiments. Such difference may lead to an over estimation of the maximum strength of the structure when an initial debond is present.

The purpose of the investigation was to evaluate the performance of the new peel stopper made of glass fibre reinforced PU and shaped in thin sheets. The effectiveness of the peel stopper is evaluated based on its ability to deflect and arrest propagating face-core interface cracks/debonds for the duration of the experiment. In case of fatigue loading, the performance is evaluated additionally by the number of cycles the peel stopper was able to contain the crack.

In all cases the embedded peel stopper managed to successfully deflect the propagated crack into the inner area of the core. In quasistatic tests the energy released upon initiation of the crack propagated it unstably and also created a new crack in the foam material, on the other side of the peel stopper.

The observation suggests that stresses in the area behind the peel stopper where new cracks are initiated are a major design variable for the peel stopper.

The same crack propagation scenario is observed in fatigue tests as well. In fatigue tests, although there is a significant time/loading cycles frame where the propagation of the crack is stopped completely before the new crack initiates. In figure 5, it is seen that in all beams the arrest period of the crack lasts longer than propagation, suggesting a substantial increase in fatigue life.

Also, it is important to point out that each beam required a different amount of loading cycles before the end of the experiment, Fig. 5. This unrepeatability of the results is mostly attributed to the behavior of the left crack front introduced by the TEFLON layer. The left crack front is loaded in a mode II dominant phase angle, which usually leads to an increased fracture resistance of the interface. In fatigue, where typically the energy release rate is lower than quasistatic testing, the effect was that the propagation and damage development scenario differed a lot between each beam. Three different propagation scenarios where identified: a) the crack didn’t propagate at all, b) the crack kinked into the facesheet where it propagated a few millimeters, c) the crack kinked in to the foam material where it propagated steadily. The three different cases encountered, affected the overall compliance of the beam differently. In displacement control the difference in compliance resulted in different load levels with a significant difference in the force applied while the investigated crack length was the same. When the loads were higher meaning that no damage has developed on the right crack front, the total load cycles were reduced. In all cases though, regardless of the total number of loading cycles, the initiation of a new crack required a significant amount of loading cycles compared to propagation.

Finally, from the results it is evident that the area investigated, pictured in Fig. 6., requires further attention. It was observed that the peel stopper was never penetrated by the propagating crack. Thus the re-initiation of the crack becomes a “fatigue life” problem for the foam rather than a propagation problem based on fracture mechanics. A numerical model of the beam is developed in order to capture stresses in the area at different stages of crack propagation. By extracting stress levels in the foam material, the number of loading cycles before re-initiation can be predicted. Finally, a shape optimization algorithm can be developed to lower the stresses in the critical area, and thereby increase the expected lifetime.

5. Conclusions

A three point bending test was utilized to assess the performance of a crack stoping element in sandwich beams. In total, twelve beams were tested in quasistatic and fatigue loading conditions.

The preliminary tests reported herein have shown that the proposed peel stopper concept is capable of achieving both deflection and arrest of propagating face-core delaminations/debonds in sandwich beams subjected to both quasistatic and fatigue loading conditions. The fatigue results showed a significant effect on the remaining life of the beam as load caring component. Observations suggest that the peel stopper element can potentially be used as a tool to improve damage tolerance in sandwich structures. Furthermore, one of the limiting factors of the new peel stopper design was identified in the foam area behind the peel stopper, where typically a new crack inititates . The next steps of the research will include detailed fracture mechanics modeling, peel stopper concept optimization (geometry and material composition) as well as implementation in representative sandwich plate and shell structures.

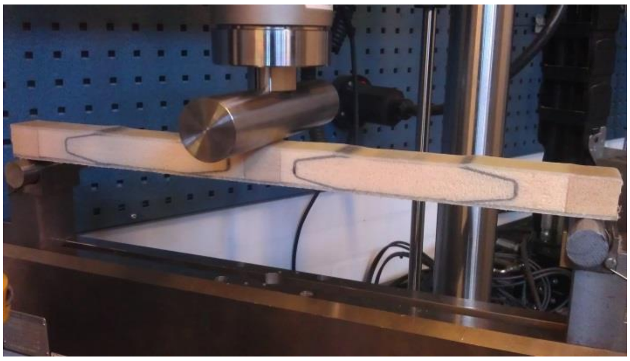

Fig. 1. Sandwich beam specimen in 3-point bending testing rig.

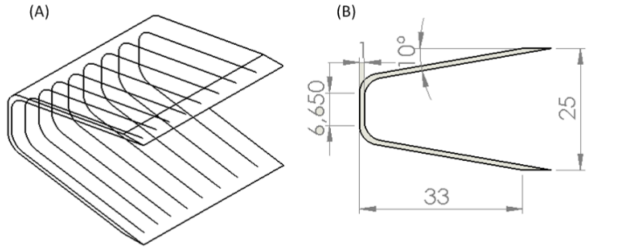

Fig. 2. (A) Fiber reinforced peel stopper design and fiber alignment. (B) Cross section of the peel stopper sheet.

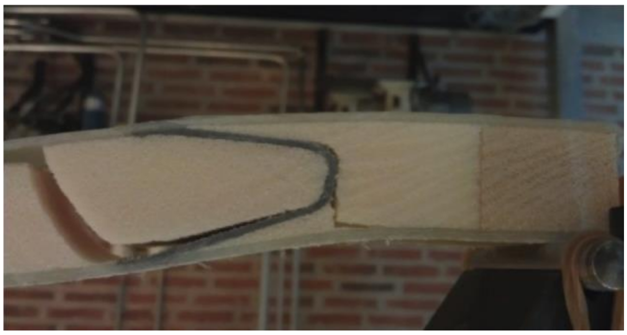

Fig.3. Crack path after initiation of damage in quasistatic test.

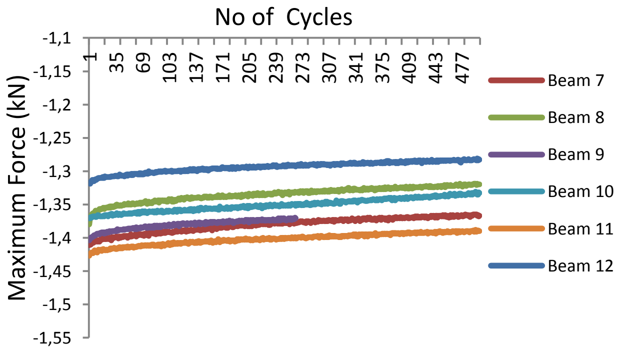

Fig. 4. Force at maximum displacement for the last 500 cycles of the crack initiation routine.

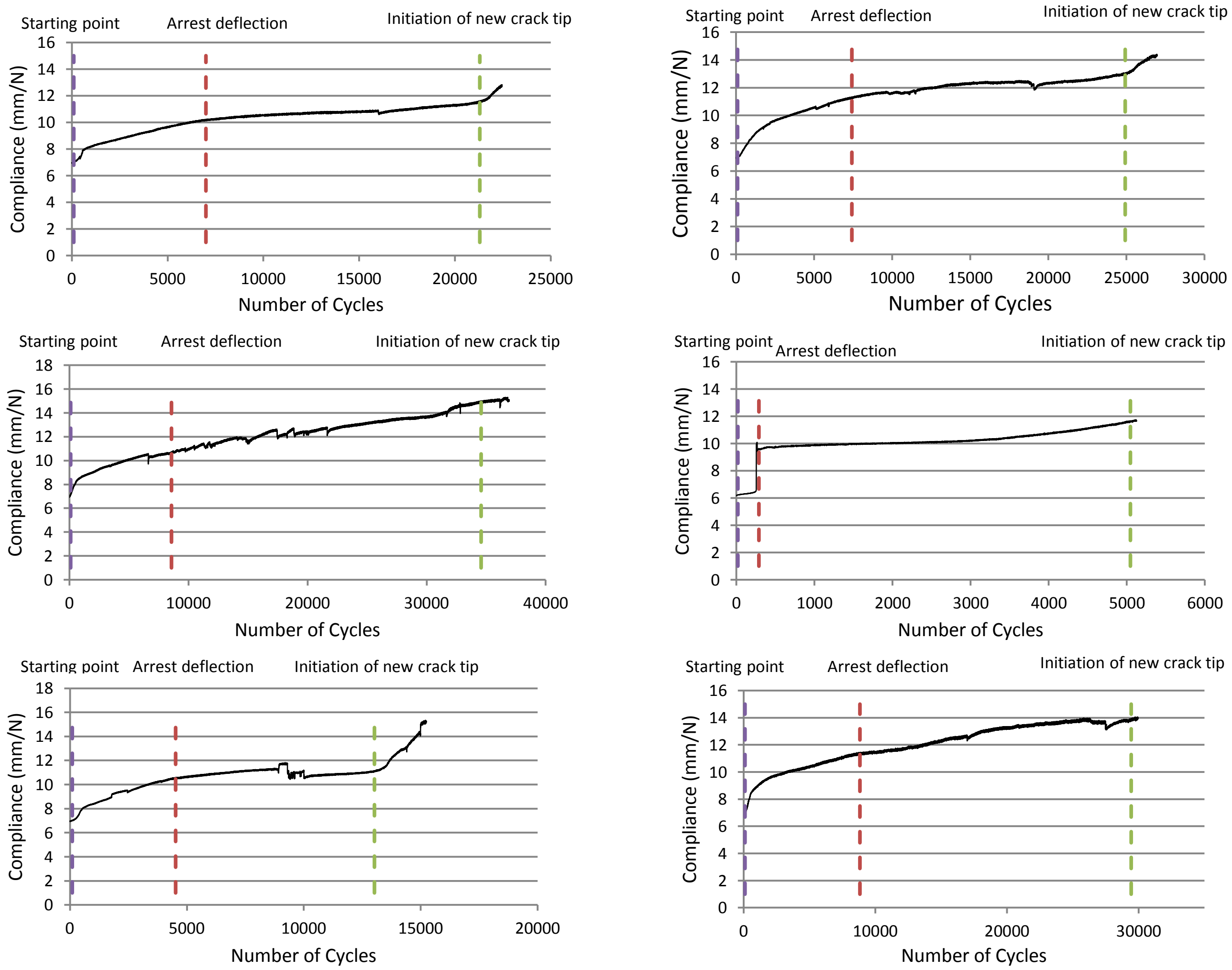

Fig. 5. Compliance – Number of cycles relation for the six beams loaded in fatigue. The borders reflect three different stages of life cycle of the beams. a) Starting point, initiation of the fatigue life cycle after crack has reached the lower interface, b) Arrest deflection, the maximum deflection length of the crack inside the peel stopper, c) Initiation of new crack tip, the time where a new crack face is created at the other side of the peel stopper

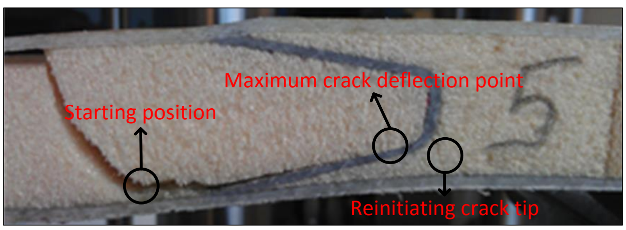

Fig. 6. The three stages of crack evolution in the sandwich beam

Material	Young's Modulus, MPa	Tensile strength, MPa
Face sheet GFRP	24050	467
Divinicell H-100	130	3.5
Divinicell H-200	250	7.1
PU	100	10
Fibre reinforced PU	-	-

Table 1. Estimated mechanical properties of the beam materials

Specimen		Maximum load (N)	Displacement (mm)
	1	1884,74	14,67
	2	1709,32	13,71
Beam	*3*	1829,54	14,21
	4	1807,89	15,69
	5	1831,92	14,38
	6	1756,38	13,73

Table 2. Maximum Load in static before crack initiation, as derived from the quasistatic test.

Specimen		Maximum load (N)	Displacement (mm)
	7	1400	6,5
	8	1370	6,5
Beam	*9*	1400	6,5
	10	1371	6,5
	11	1421	6,5
	12	1327	6,5

Table 3. Maximum Load in static before crack initiation as derived from the fatigue initiation procedure.

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