AN EXPERIMENTAL STUDY OF CRACK PROPAGATION IN STIFFENED OVER-HEIGHT COMPACT TENSION (SOCT) SPECIMENS

Xiaoyang, Sun[a], Xiaodong, Xu[a,b], Shimizu, Takayuki[c], Michael R. Wisnom[a]

a: Bristol Composites Institute, Queen's Building, University Walk, Bristol BS8 1TR, UK – xiaoyang.sun@bristol.ac.uk
b: University of the West of England, Coldharbour Lane, Bristol BS16 1QY, UK
c: Research & Innovation Centre, Mitsubishi Heavy Industries, LTD. 10, Oye-cho, Minato-ku, Nagoya, 455-8515, Japan

Abstract: *In this paper, three Stiffened Over-height Compact Tension (SOCT) specimens were tested to investigate the damage mechanism when a crack encounters a stringer in Quasi-Isotropic (QI) laminates, where the stringer is simulated by a strip representative of a stringer foot. SOCT specimens consist of a 4 mm thick skin sandwiched by a 2 mm stringer on each side of the skin at the rear of the specimen, the stringers were co-cured to the skin. It was found that severe skin-stringer debonding occurred while no stringer breakage was observed. It is believed that as the crack propagates in the skin and causes skin-stringer debonding, load is transferred to the stringers. Skin fracture did not induce crack propagation in the stringer, but rather large areas of skin-stringer debonding.*

Keywords: Fracture; Debonding; Stiffener; Stringer; Delamination.

1. Introduction

With the desire for more efficient design of composite structures, detailed knowledge for the onset and subsequent propagation of damage is very important. Designing large composite structures is a complex task of balancing many design drivers - with notched strength being one of the critical ones. Large load-carrying notched composite structures used in aerospace applications often consist of a skin and stringers which may act as crack stoppers. Hence an accurate understanding of the interaction between trans-laminar fracture propagating in the skin and stringers and stringer debonding is of vital importance. Previously, we reported the damage evolution [1] and initial R-curves [2] for translaminar fracture of laminates using three different sized in-plane Over-height Compact Tension (OCT) specimens. In this study, two stringer feet are co-cured to the rear end of the OCT specimen on either side to form a new Stiffened OCT (SOCT) specimen. The aim is to investigate the interaction between trans-laminar fracture and stringer debonding.

2. Test method

The SOCT specimen geometry is shown in Figure 1. SOCT specimens were manufactured with Hexcel's HexPly® IM7/8552 carbon/epoxy unidirectional prepreg with a 0.125 mm nominal cured ply thickness. The stacking sequence was $[45/90/-45/0]_{4s}$ for the skin and $[45/90/-45/0]_4$ and $[0/-45/90/45]_4$ respectively for the 2 mm stringers on either side of the specimen, creating a symmetric layup. The location of the stringers is highlighted in Figure 1. The stringers were laid-up on the skin prior to curing, with 2 mm spacers also made from IM7/8552 pre-preg placed adjacent to the stringers to ensure the whole laminate panel stays flat during curing. The laminate panel, including the skin, stringers and spacers were all cured in one session according to the manufacture's specifications. Individual SOCT specimens were cut from the large laminate using a diamond coated saw cutter. The SOCT specimens were tested in a hydraulic-driven Instron 100kN test machine under displacement control at a rate of 1 mm/min. No anti-buckling guides were necessary as no overall buckling of the specimen was observed. Figure 2 shows the test set-up, with the loads being applied via loading arms and pins. The loads were measured at the test machine, and the displacements were measured at the pins which were connected to the crossheads. It was found that the crosshead displacement is very close to the video extensometer measured displacement at the loading pins, so crosshead displacements are used throughout this paper for the Pin Opening Displacement (POD).

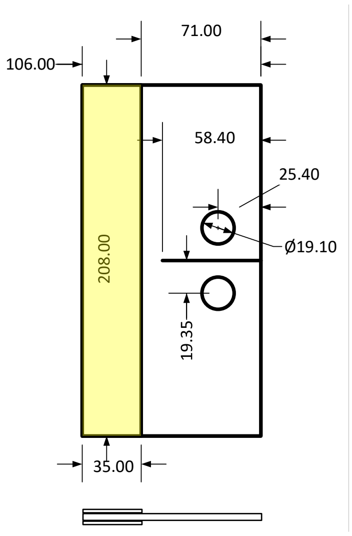


Figure 1. SOCT specimen dimensions, all dimensions in mm.

Figure 2. A photo showing the test set-up.

3. Test results

Three uninterrupted tests have been carried out with the SOCT specimens. Loads increased linearly at the beginning. A high degree of resemblance can be found in these three cases during the initial linear portion of the test, followed by a number of small load-drops – caused by crack propagation in the skin. Load increases overall during these small load drops, reaching a maximum load of approximately 18kN. All three cases suffered from compressive failure at the rear of the specimen underneath the stringers at the final stage of the tests. None of the cases showed stringer fracture. Figure 3 shows the load-displacement curves from the three tests.

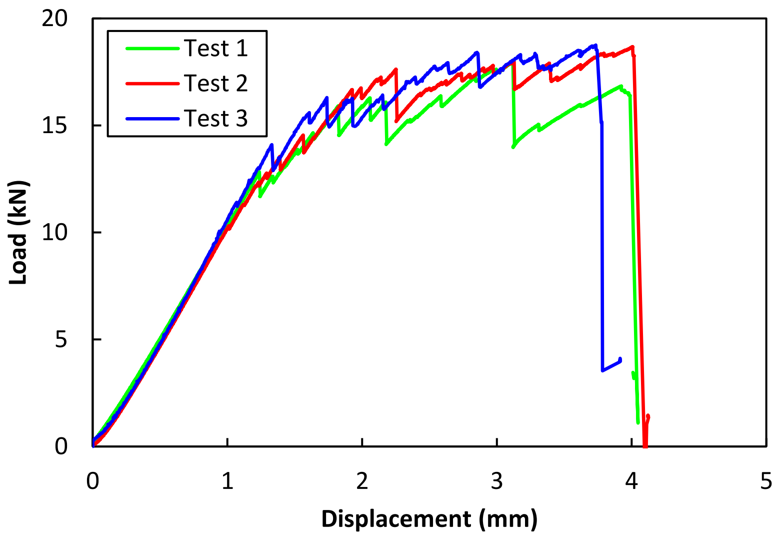


Figure 3. Load-displacement curves of the three SOCT specimens.

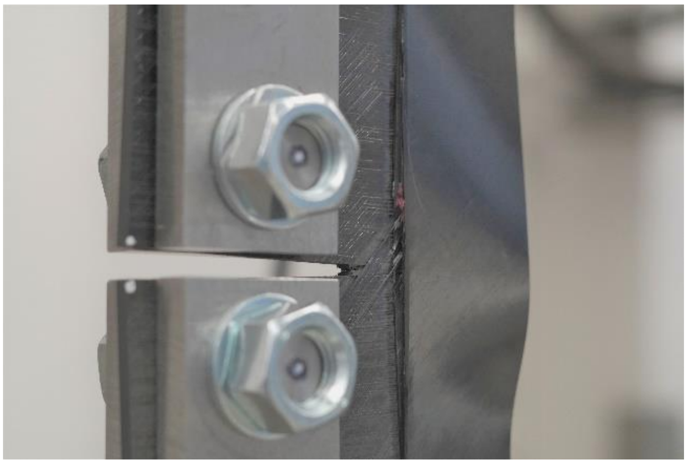
The peak load is approximately the same for all three specimens tested, with test 1 and test 2 having the same displacement at ultimate failure. The ultimate failure of the specimen for all three cases was induced by the compressive failure of the skin at the rear end. Special care has been taken during the testing phase to observe any potential buckling occurring of the specimen, and none was found.

4. Results Analysis

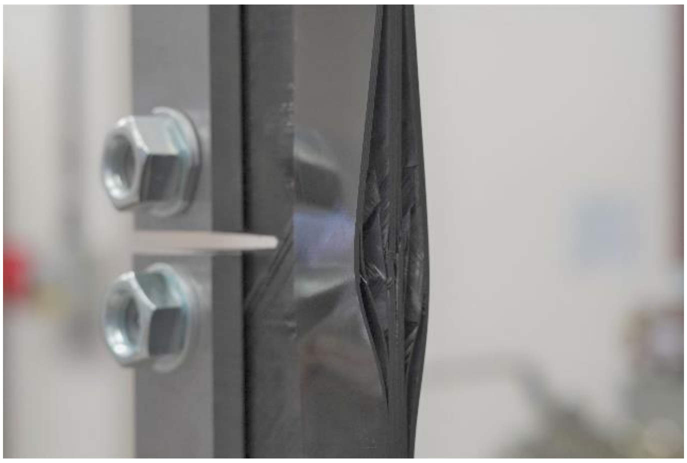
By observing the specimens both during testing and the failed specimens after testing has finished, shown in Figure 4 to Figure 6, a few observations can be made –

1. All three specimens exhibited severe skin-stringer debonding, the debonding is especially apparent within the area at the rear of specimen.
2. No stringer fracture or breakage has been observed and given all specimens have been tested to ultimate failure, it can be concluded that stringer fracture does not occur for this specimen geometry and material combination.
3. When fracture in the skin propagates towards the stringer it does not promote fracture in the stringers, rather, the skin fracture continues in the skin and causes skin-stringer debonding.
4. Compressive failure at the rear of the specimen occurs only in the skin, while the stringers avoid the compressive failure issue as they debond from the skin and locally buckle out.

Figure 4 to figure 6 show the surface damage morphologies of the failed specimens. All three specimens are in very similar damage states – stringers showing no surface damage while skin-stringer debonding is apparent. Through these observations, the proposed damage mechanism of the SOCT specimens is as follows – as the load applied to the specimen increases, a crack starts to propagate from the machined notch towards the rear of the specimen. Such crack propagation in the skin is accompanied by growth of a damage process zone which includes local delamination and splitting of the 45° and 90° plies. As the crack and splitting reaches the stringer, skin-stringer debonding takes place. The debonded area increases as the displacement increases which allows the crack in the skin to open-up. The load-bearing capacity of the skin decreases as the crack propagates, resulting in the load being transferred to the stringers. Due to stringers being 2 mm thick on each side of the skin, their load bearing capacity is relatively high, hence compressive failure occurs at the rear of the skin prior to the stringers exhibiting tensile failure.



a) Test 1 after compressive failure showing large area of skin-stringer debonding without stringer failure.



b) Test 1 specimen showing compressive failure at the rear without stringer failure. Stringers at the rear of the specimen have bulged out due to compression, no stringer cracking observed.

Figure 4. Photos taken from SOCT Test 1.

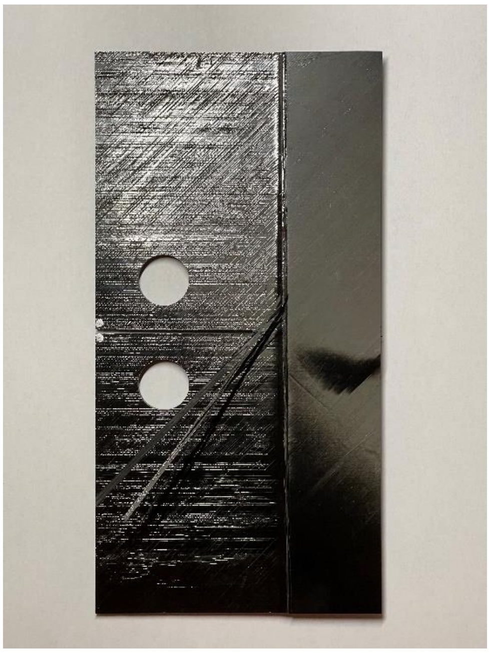
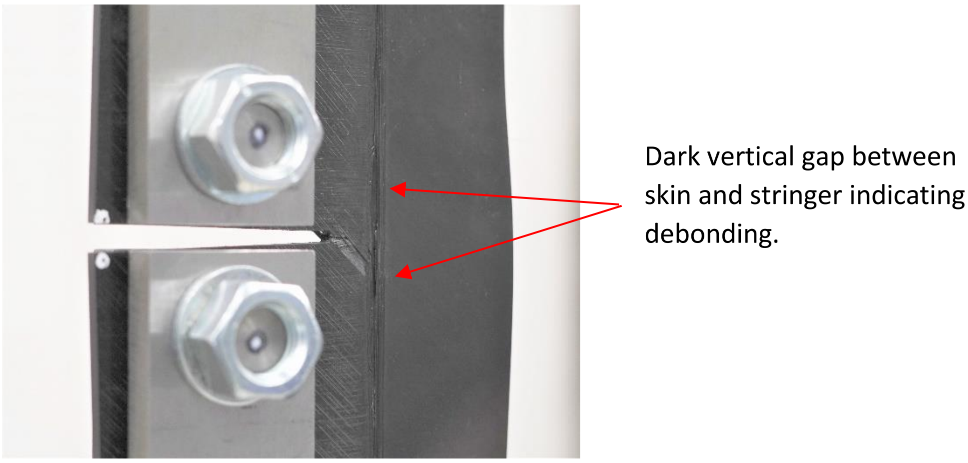
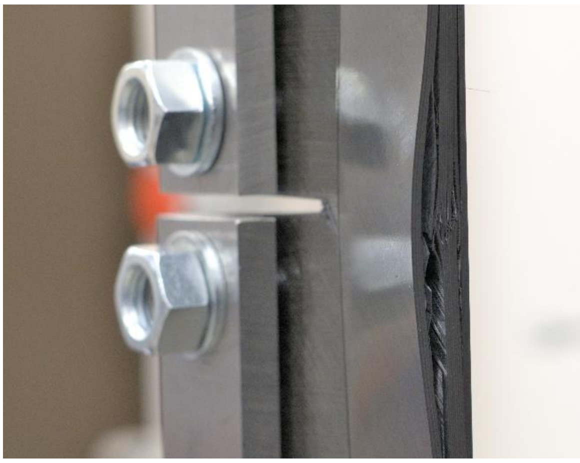


Figure 4. Test 2 specimen showing no stringer damage after compressive failure at the rear. Triangular black area on the stringer is the stringer bulging out as compressive failure in the skin underneath it has created a thicker damage zone in the skin.



a) Test 3 specimen showing skin surface splitting and skin-stringer debonding.



b) Test 3 specimen showing skin compressive failure at the rear and skin-stringer debonding.

Figure 6. Photos taken from SOCT Test 3.

5. Discussion

Xu et al. [1] published tensile test results of unstiffened OCT specimens of three different sizes – scaled down, baseline, and scaled up. The baseline set is of value to the current study as the specimen geometry is identical to the SOCT specimen tested, except without the stringers. Figure 7 shows a comparison between the typical SOCT and baseline OCT load-displacement curves. SOCT results exhibit approx. 50% higher peak load values and a lack of the gradual load decreasing trend that is present in the baseline OCT specimens. The higher peak load shows that the SOCT specimen is much tougher than the OCT specimen. The lack of the load decreasing trend can be attributed to the load being transferred to the stringers as the crack propagates in the skin, a mechanism which does not exist in the baseline OCT specimens. Both the SOCT specimens and the baseline OCT specimens fail in compression at the rear at approx. 4 mm displacement.

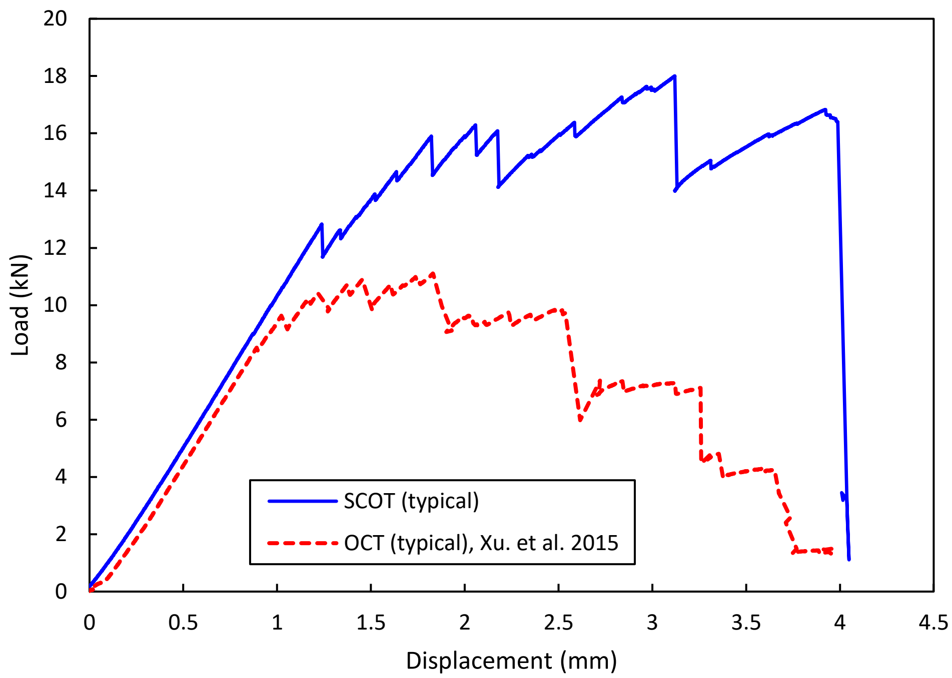


Figure 5. Comparison of typical load-displacement curves of SOCT specimens and OCT specimens of same in-plane dimensions, [1].

6. Conclusions

Compared to the same specimens without stringer feet, the SOCT specimens yielded substantially higher peak loads and were able to maintain the high load for much more of the displacement range. A closer inspection of the failed specimens showed a severe skin-stringer debonding – in all three cases, the stringer feet have debonded from the skin over a large part of the initially bonded area. No stringer foot failure was observed in any of the three specimens. Acting as a crack stopper, the stringer feet lead to a significantly delayed crack propagation even after skin-stringer debonding has initiated.

References

[1] Xu X, Wisnom MR, Mahadik Y & Hallett SR, Scaling of fracture response in over-height compact tension tests, Composites, Part A: Applied Science and Manufacturing, 2015;69: 40-48. https://doi.org/10.1016/j.compositesa.2014.11.002

[2] Xu X, Sun X & Wisnom MR. Initial R-curves for trans-laminar fracture of quasi-isotropic carbon/epoxy laminates from specimens with increasing size. Composites Science and Technology. 2021;216:109077. https://doi.org/10.1016/j.compscitech.2021.109077

