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ON THE APPLICATION OF FRACTURE MECHANICS TO A FULL-SCALE STIFFENED COMPOSITE PANEL TEST

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Key words: Fracture mechanics, Notch, VCCT.

Summary: *This paper investigates the initial fracture propagation within a full-size stiffened panel. The data scheme used includes scaled-down coupon testing and VCCT. The current approach has some important implications for engineering applications.*

1 INTRODUCTION

The 21st century has witnessed the wide application of large composite structures. In the aerospace industry, full-scale composite fuselage panels have been tested. These were followed by the construction of large composite structures for commercial aircraft. However, a crucial question still remains: how can we relate the large panel tests to small coupon tests? Implications from previous studies of size effects [1, 2] can help answer the above question. Specifically, fracture mechanics is discussed as a good approach for failure predictions of large notched composite laminates. Trans-laminar fracture toughness is the key, and in this paper the relevant concept of damage zone is also discussed.

The Virtual Crack Closure Technique (VCCT) is often used to determine the Strain Energy Release Rate (G) for composite laminates [3-5] and compared with a critical value (G_C). One of the limitations of this approach is that it ignores the effect of a damage zone. In contrast, this paper considers the effect of a fully developed damage zone on G when using VCCT.

A stiffened composite panel test [6] was carried out at JAXA. The aim of the test was to investigate the fracture propagation within the stiffened panel under the scenario that a burst fan disk penetrates the composite structure. According to the current study, the centre-notched tensile strength of the large panel could potentially be predicted by a combination of small coupon tests and Finite Element Analysis (FEA). Specifically, the failure loads taken from the large panel and small coupon tests, are related to the critical strain energy release rates (trans-laminar fracture toughness) calculated through VCCT.

2 EXPERIMENT SETUP

The stiffened panel is 900 mm × 750 mm with three hat-shaped stringers as shown in Figure 1. The panel was manufacturing though Vacuum assisted Resin Transfer Moulding VaRTM, one of the low-cost composite integral moulding methods. The material used was biaxial non-crimp carbon fabric (made from STS-24k fibres, SAERTEX Co. KG) and epoxy resin (XNR6809/XNH6809, Nagase Chemtex Co.). The layup of the skin and stringer was $[(45/-45)/(0/90)]_{2s}$. All the plate thicknesses were 2 mm except for the end of the stringer foot which was tapered. The 200 mm central notch was introduced to the panel by using a saw.

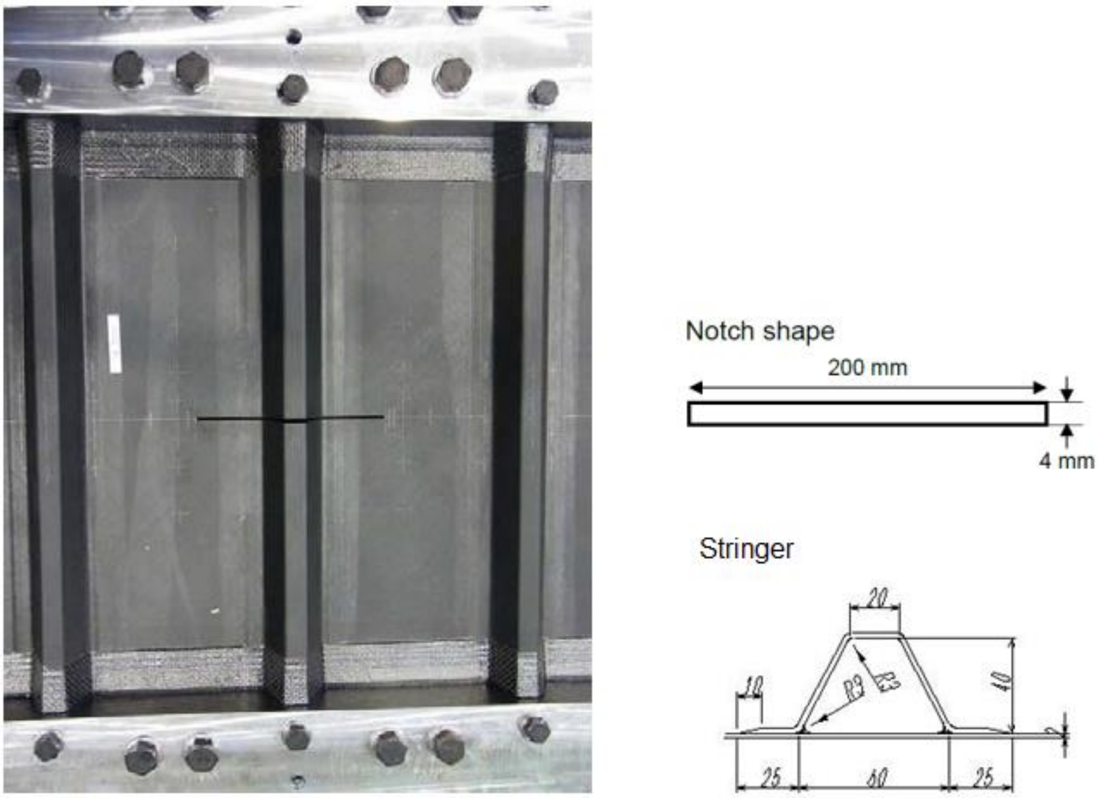
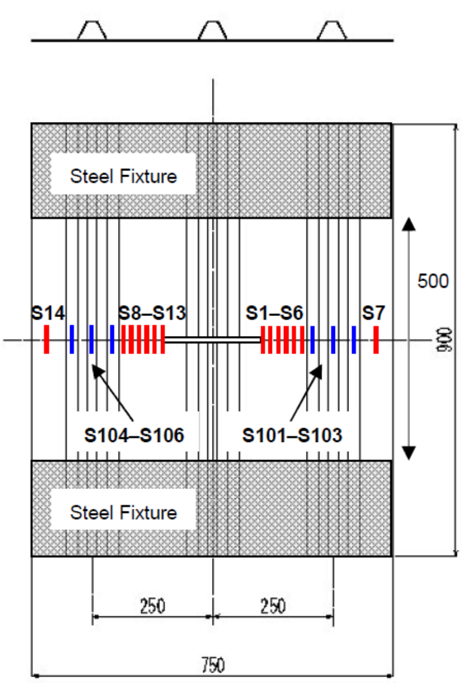


Figure 1: Stiffened panel test at JAXA [6].

The tensile load was applied by an Instron 2500 kN hydraulic-driven test machine under displacement control at 0.5 mm/min. The load sequence was monotonic tension till the final failure of the panel. Steel fixtures were fitted to both ends of the panel. A total of 60 electrical strain gauges and 6 Acoustic emission sensors were attached on the surface of the stringer side. Figure 2 illustrates a summary of the gauge locations along the expected crack path. When damage grows in the panel, the strains should change rapidly owing to the change in load path.



Gage No.	Location
S1(S8)	1.5 mm from notch tip
S2(S9)	5 mm from notch tip
S3(S10)	10 mm from notch tip
S4(S11)	20 mm from notch tip
S5(S12)	50 mm from notch tip
S6(S13)	80 mm from notch tip
S7(S14)	35mm from skin edge
S101 (S104)	On foot near to notch
S102(S105)	On top of stringer
S103(S106)	On foot far to notch

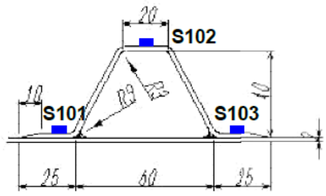


Figure 2: Location of strain gauges in the large panel.

The small coupons were fabricated in the same way as the stiffened panel through VaRTM. The mechanical properties and thickness of the coupon therefore are also the same as those of the stiffened panel. The coupons are 300 mm × 210 mm with a stringer foot attached to each long edge as shown in Figure 3. 2 mm-wide central notches with 1 mm radius at the tips were introduced to the coupons by machining. The lengths of the two central notches are summarised in Table 1. The tensile load was applied by an Instron 2500 kN hydraulic-driven test machine under displacement control at 0.5 mm/min. Thick GFRP tabs were attached to both ends of the coupon so as to fit into the grips. A total of 6 electrical strain gauges were attached on the surface of the foot side as shown in Figure 4.

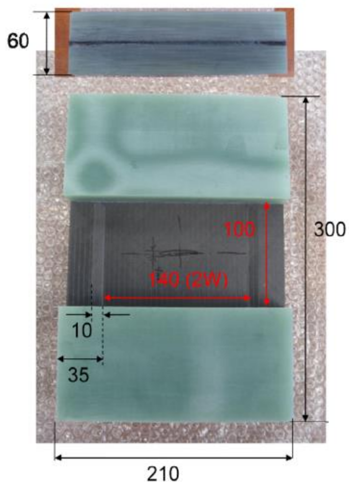


Figure 3: Scaled down coupons (with the same stringer foot as the large panel).

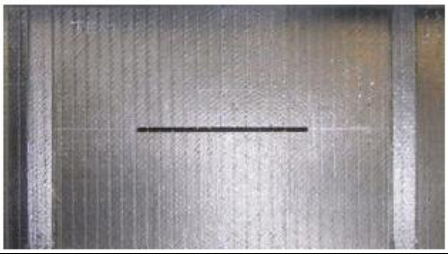
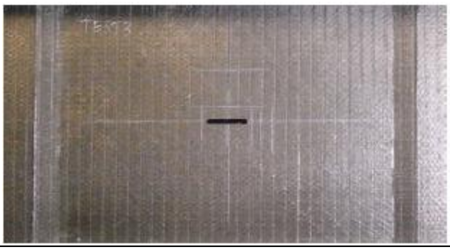
Tip radius (*r*)	**Length (2*a*)**	
	Long-notch 70 mm (*W/a* = 2)	Short-notch 17.5 mm (*W/a* = 8)
1 mm		

Table 1. Summary of the central notches.

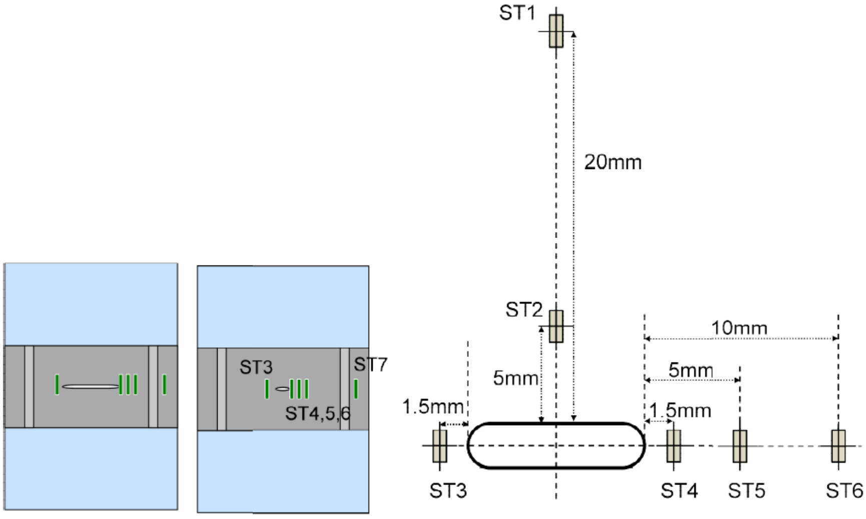


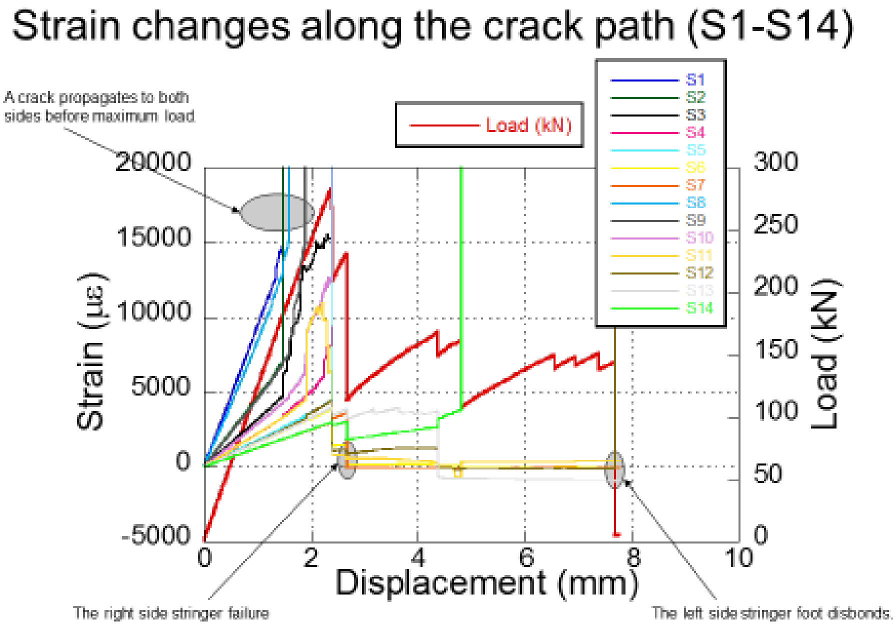
Figure 4: Location of the strain gauges in the small coupon specimens.

3 EXPERIMENTAL RESULTS

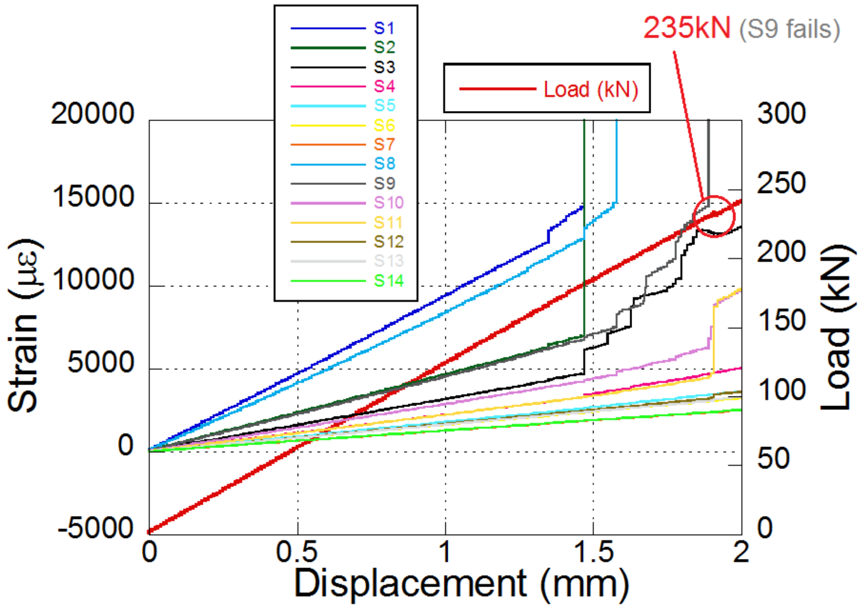
3.1 Test results of large stiffened panel

It is crucial to determine the experimental load for initial fracture propagation in the large stiffened panel test, which can be indicated by the failure of the strain gauges close to the boundary of the full damage zone in the present test. In previous tests of Hexcel HexPly® IM7/8552 carbon/epoxy quasi-isotropic laminates, the fully developed damage zone is larger than 2.3 mm [1]. It was therefore expected that the strain gauge at 1.5 mm in the present tests would not give an indication of fracture propagation since the size of the fully developed damage zone is likely to be larger than 1.5 mm. The strain gauge at 1.5 mm may only indicate the damage zone development. Thus the failure of the S2 and S9 gauges, which are 5 mm away from the notch tips, may be more representative of failure propagation, consistent with a damage zone size of 5 mm or slightly less.

As shown in Figure 5, at 235 kN S2 and S9 gauges at 5mm from the notch tips both fail. As a result, the experimental failure load for initial fracture propagation is taken to be 235 kN, when the damage zone is expected to be fully developed. Beyond this point, the panel sees a short period of stable fracture propagation before the maximum load. When G exceeds the fracture resistance G_C even under constant displacement, unstable fracture occurs, which is accompanied by a large load drop.



(a) Overall results



(b) Zoom-in view around initiation

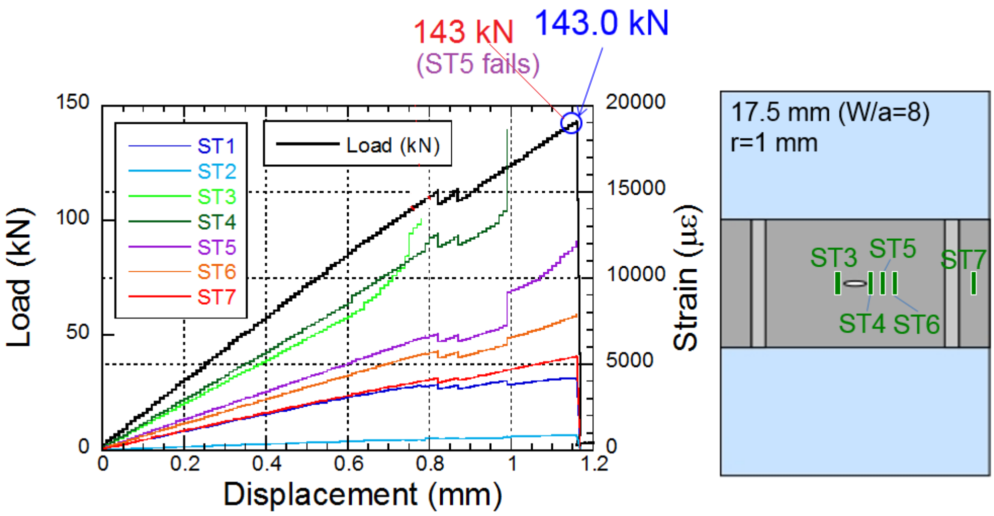
Figure 5: Experimental results of the large stiffened panel test.

3.2 Test results of stiffened coupons

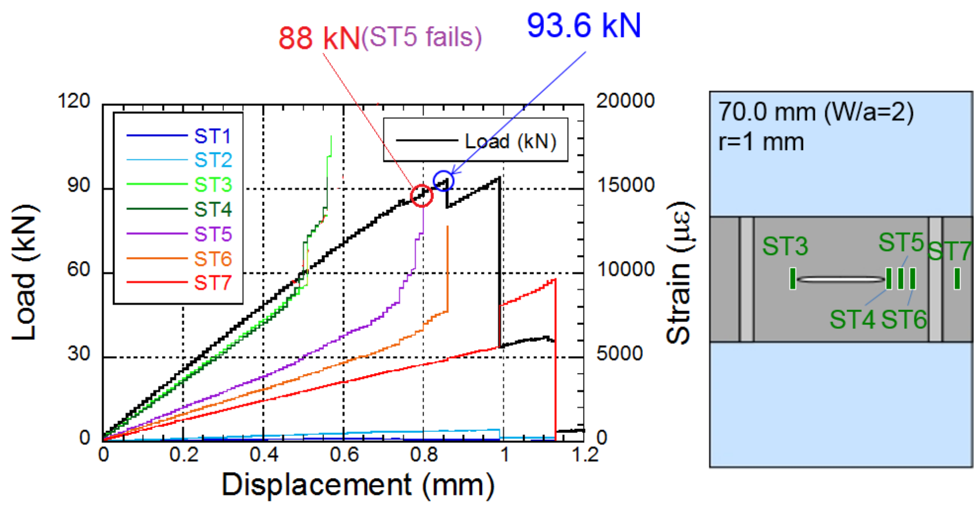
It is also crucial to determine the experimental loads for initial fracture propagation in the small coupon tests. It was again assumed that the full damage zone is larger than 1.5 mm but less than 10 mm, so the failure of the nearest strain gauge to the notch tip does not represent the formation of a fully developed damage zone. Instead, the failure of ST5 gauge which is 5 mm away from the notch tips may be more representative.

As shown in Figure 6 (a), at 143 kN ST5 gauge fails in the short-notch coupon. As a result, the experimental failure load for initial fracture propagation in the short-notch coupon is taken to be 143 kN, when the damage zone is also expected to be fully developed.

In Figure 6 (b), at 88 kN ST5 gauge fails in the long-notch coupon, which is taken as the experimental failure load for initial fracture propagation.



(a) Coupon with short notch



(b) Coupon with long notch

Figure 6: Experimental results of small stiffened coupon tests.

4 FINITE ELEMENT ANALYSIS

VCCT is carried out in a linear elastic FEA. Quarter specimens were modelled with half of the specimen width and length. One 8-node solid element through the thickness of the specimen (2 mm) is used with homogenised isotropic material properties as shown in Table 2. The mesh is refined along the crack path. Symmetry boundary conditions are applied on the nodes at the boundaries. Multi-Point Constraint (MPC) equations link the nodes where the experimental failure loads for the half specimens are applied. In the small coupon models, the 29 mm-thick end tabs were also modelled with estimated properties, which are simplified as homogeneous isotropic, with the estimated out-of-plane shear modulus (1.5 GPa) taken from another resin. The results only slightly vary with the out-of-plane shear modulus taken as being equal to the estimated in-plane shear modulus of 5.6 GPa. All notches were represented by an infinitely sharp crack at the symmetry plane perpendicular to the loading direction.

E **[GPa]**	***G*** **[GPa]**	***υ***
37.9	14.7	0.29

Table 2. Material properties of solid elements for the skin.

4.1 Large stiffened model

4.1.1 FE mesh (quarter panel)

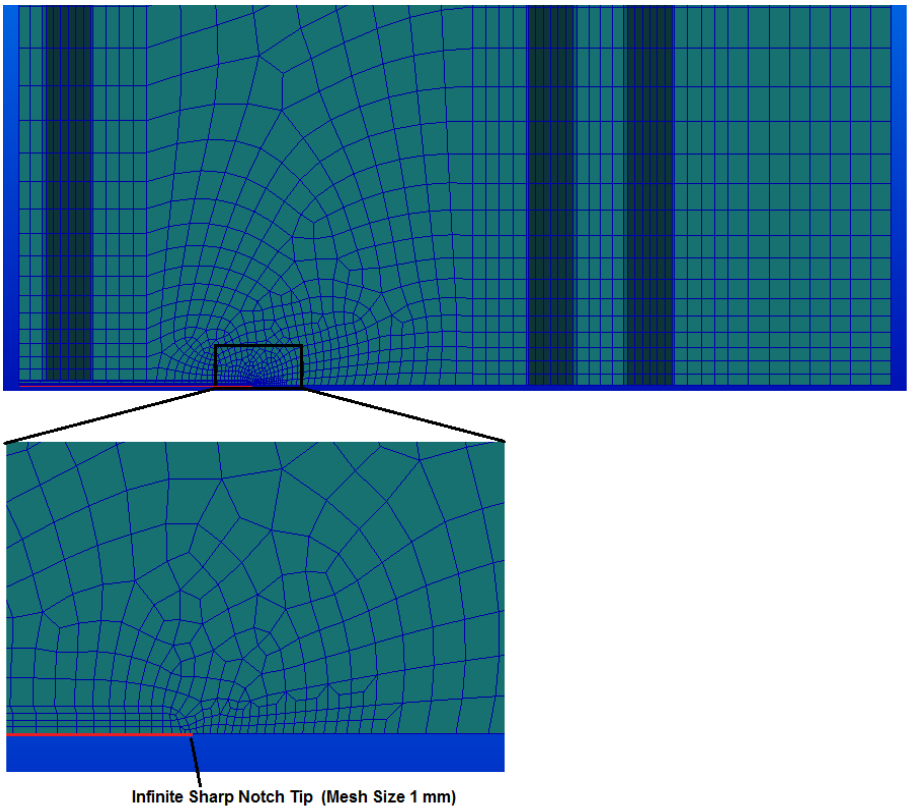


Figure 7: FE mesh for the large stiffened panel (minimum mesh size about 1 mm).

4.1.2. Boundary conditions

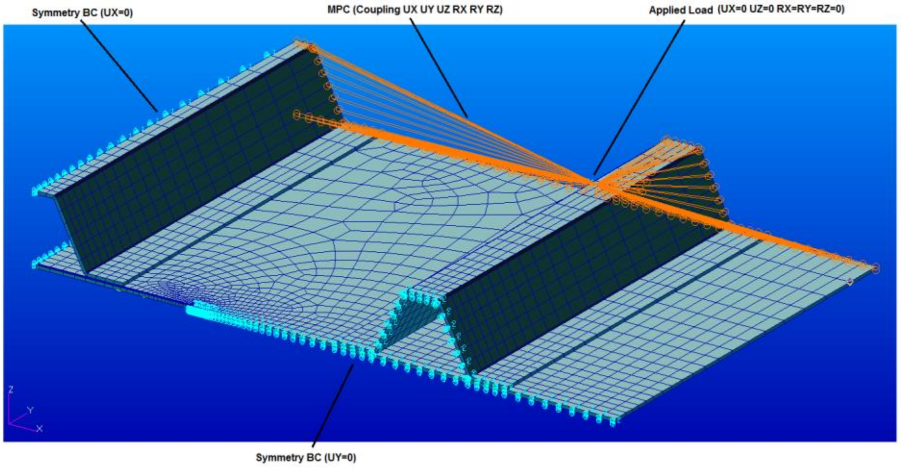


Figure 8: Boundary conditions for the large stiffened panel.

4.2 Stiffened CNT coupon model

4.2.1. FE mesh (quarter coupons)

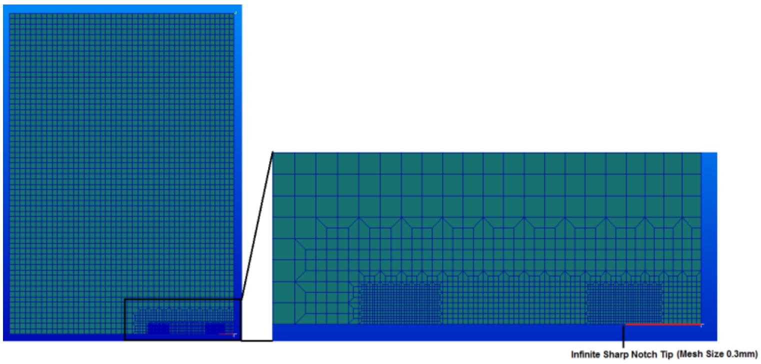


Figure 9: FE mesh for the small coupons (minimum mesh size about 0.3 mm).

4.2.2. Boundary conditions

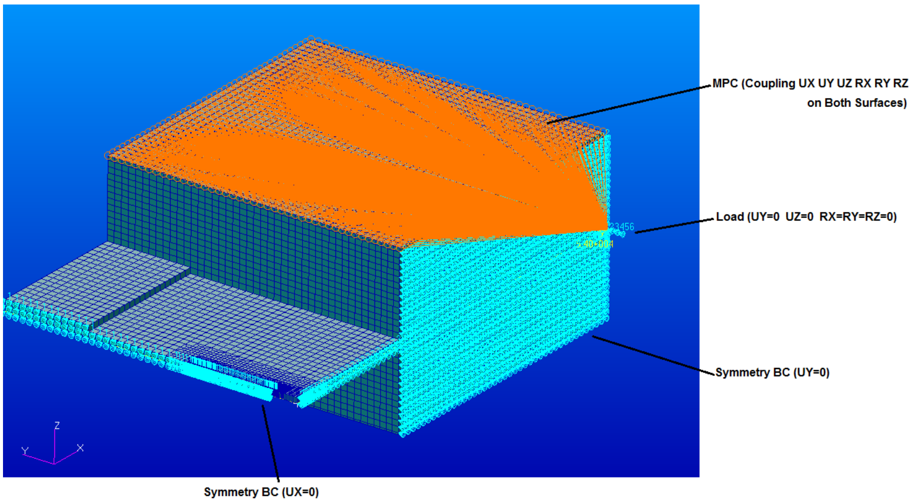


Figure 10: Boundary conditions for the small coupons.

5 DATA REDUCTION

G is calculated according to Equation 1 and Figure 11 in a two-step VCCT. The stress Intensity Factor (SIF) calculation under a given load follows in Equation 2,

$$G = \frac{1}{2\Delta a}[X_{1l}\Delta u_{2l} + Z_{1l}\Delta w_{2l}]. \tag{1}$$

$$\text{SIF} = \sqrt{EG} \tag{2}$$

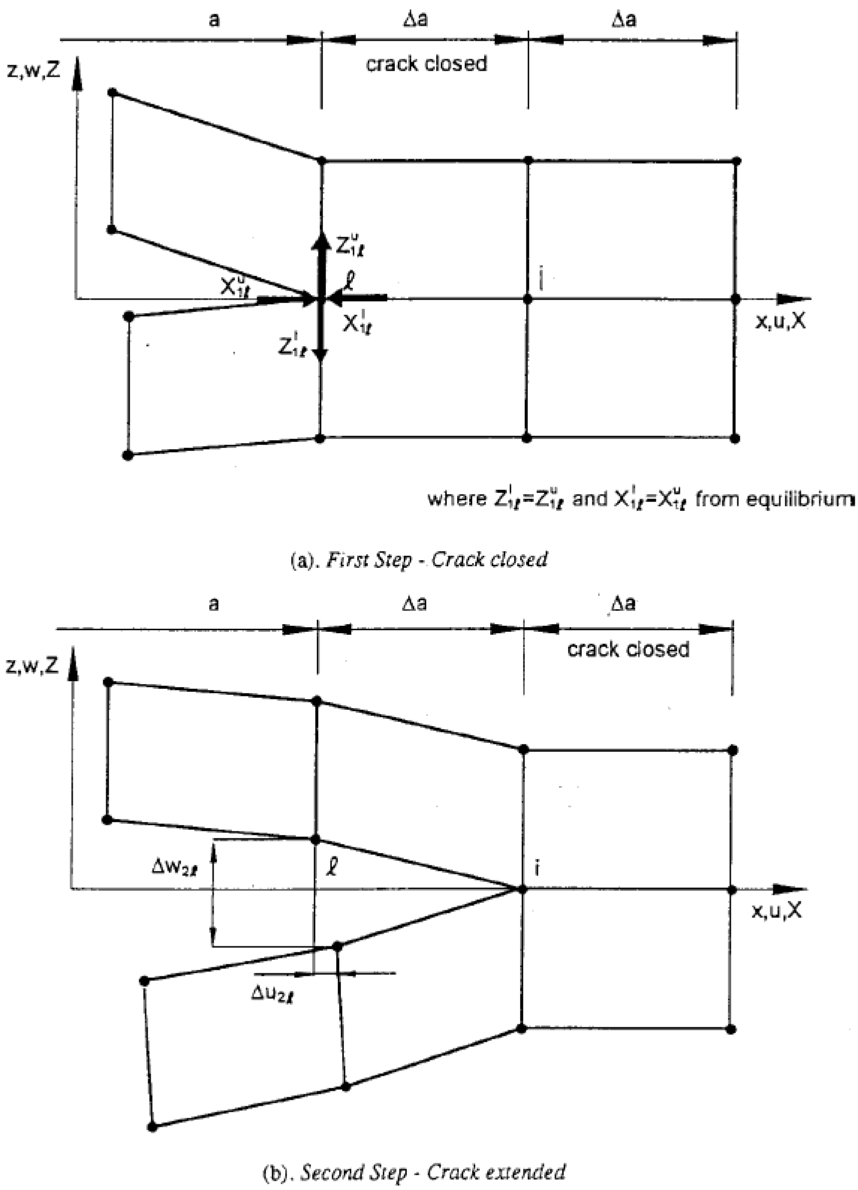


Figure 11. Crack closure method (two-step method) [5].

FE models of centre-notched flat plates with different mesh sizes (coarse 1 mm, normal 0.5 mm and fine 0.1 mm), notch tip shapes and of the same material properties (Table 2) are compared as shown in Figure 12. It was found that the calculated SIF according to Equations 1 to 2 is not sensitive to mesh sizes with infinitely sharp cracks. Additionally, blunt notches converge to infinitely sharp notches quickly from larger than 2 mm crack growth. Therefore, infinitely sharp notches and less than 1 mm mesh sizes were used.

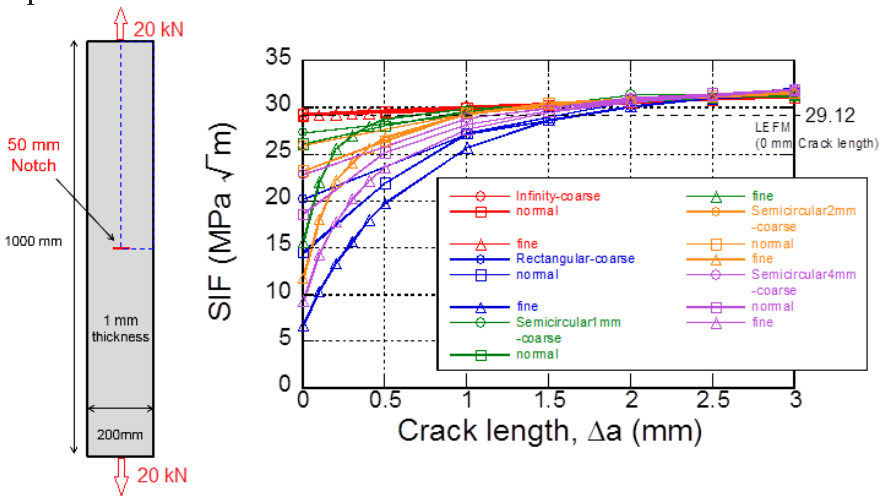


Figure 12: Mesh size and notch radii effects.

In the current models of the stiffened panel and scaled-down coupons, the effect of the damage zone on *G* could be accounted for as equivalent to an additional crack length of the same size being added to the initial crack length. Namely, the initial G-curves could be shifted to the left by the estimated full damage zone size as shown in Figure 13 for the assumed size of 5 mm. *G* values from the three configurations at the previously defined failure loads from VCCT are similar at the new origin, consistent with a trans-laminar fracture toughness for initial crack propagation of approximately 90 kJ/m^2, with the estimated fully developed damage zone at the size of about 5 mm. *G* values would be even closer with a full damage zone of 4 mm in Figure 13, however, the corresponding loads would be unknown with no strain gauges attached between 1.5 mm and 5 mm from the notch tips.

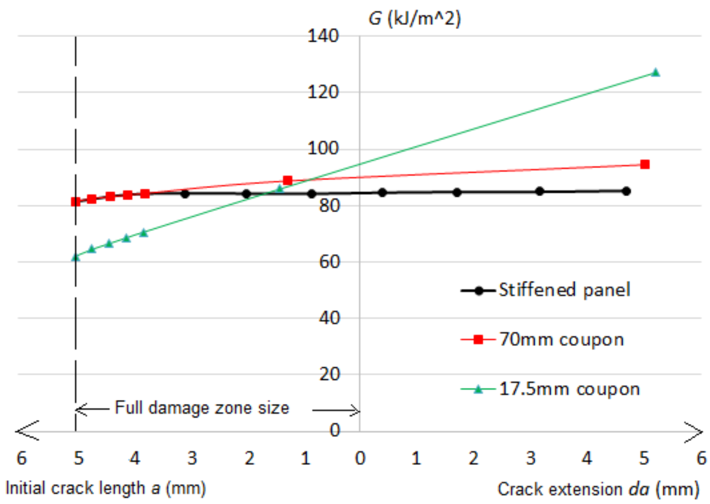


Figure 13: Predicted G-curves with 5 mm full damage zone and loads from failure of strain gauges 5 mm from notch tips.

By contrast, there is a large discrepancy between the *G* values from the three configurations at the failure loads at which the strain gauges 1.5 mm away from the notch tips fail, as shown in Figure 14.

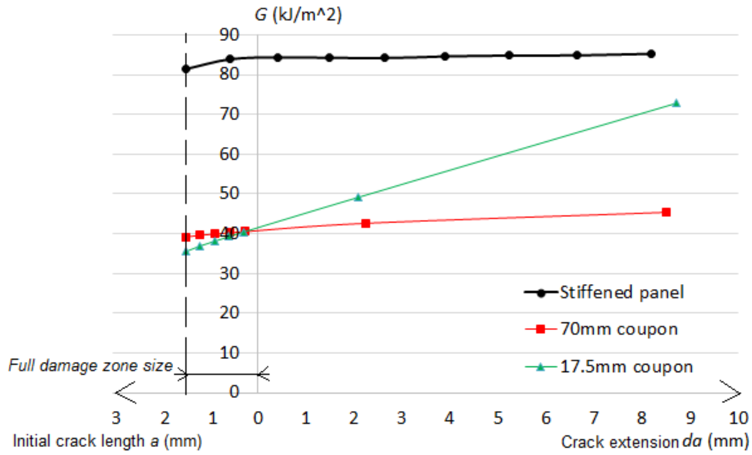


Figure 14: Predicted G-curves with 1.5 mm full damage zone and loads from failure of strain gauges 1.5 mm from notch tips.

6 DISCUSSION

In the present study, the full damage zone size of 5 mm is an estimated value, which is limited by the locations of the strain gauges. According to Figure 13, the real size is likely to be between 4 and 5 mm. More accurate measurements of the damage zone could be taken through X-ray or Digital Image Correlation (DIC) in the future.

The G-curves for the large stiffened panel and the 70 mm coupon are rather flat as shown in Figure 13, which may result in more stable fracture propagation than that in the 17.5 mm coupon if there exists an R-curve. This is because the flat G-curves may cross the R-curve during initial fracture propagation, so more energy (load) would be needed to propagate the fracture after its initiation.

Implications for potential engineering applications are: First of all, it is crucial to estimate the full size of the damage zone. According to Ref. [1], the centre-notched coupons need to be large enough to generate a fully developed damage zone at the notch tips, or unstable fracture may occur before the formation of the full damage zone. Additionally, the notches need to be long enough to ensure the fully developed damage zone is relatively small scale compared to the notch size, or the problem will exceed the scope of linear elastic fracture mechanics. The failure of the strain gauges, for example, near the notch tip is not necessarily an indication of initial fracture propagation, but could rather be the development of a damage zone. Only when the damage zone is fully developed, can the consequent trans-laminar fracture toughness be considered as a material property for initial fracture propagation [7]. Furthermore, in the case where an R-curve may exist, the measured trans-laminar fracture toughness for initial fracture propagation would still yield a conservative prediction.

7 CONCLUSIONS

There is a discrepancy between the G values of the large stiffened panel and coupons if using the failure loads at which the strain gauges closest to notch tips (1.5 mm) are broken in the tests. Such a discrepancy is largely reduced by taking the failure loads at which the strain gauges 5 mm away from notch tips are broken in the tests, consistent with a damage zone size of about 5 mm.

If the calculated G-curves from VCCT are shifted by the assumed damage zone size (5 mm), the trans-laminar fracture toughness values from the three configurations are close to 90 kJ/m^2.

Trans-laminar fracture toughness is the key to the prediction of the failure of large stiffened panels. According to this paper, the notched tensile strength of the large stiffened panel could potentially be predicted from small coupon tests if the trans-laminar fracture toughness and the full damage zone size can be measured in small coupon tests. The coupons need to be large enough to ensure the damage zone is fully developed, and the notches need to be long enough to ensure the full damage zone is relatively small scale compared to the notch size.

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