

Monitoring The Effect of Damage in Bonded and Bolted T-Joints

Bonded and bolted joints are frequently expected to sustain static or cyclic fatigue loads throughout the service life of the joined system without any adverse effect on the load-bearing capacity or life expectancy of the structure . A major concern is that under dynamic fluctuating loads, joints will often fail at stress levels much lower than the static strength of the joint. Failure is generally preceded by damage initiation and propagation in regions of high stresses and strains, which can occur at relatively low loads and early in the service life of the component. The onset and accumulation of damage will often be accompanied by changes in structural properties of the joined system (i.e. loss of stiffness and strength). The design of safe and cost effective, structurally efficient joints is a major challenge that requires a good understanding of the effects on long-term performance of damage accumulation on joint stiffness and strength under cyclic fatigue loading conditions.

This Measurement Note examines the use of strain gauges and linear voltage displacement transducers (LVDTs) for monitoring local and global changes in stiffness of bonded and bolted aluminium and glass fibre-reinforced epoxy (GRP) T-joints under monotonic loading. It also examines the relationship between stiffness loss and residual life of these joined systems under cyclic fatigue loading conditions. The joints were subjected to direct tension and transverse or lateral loads. The bonded aluminium and GRP T-joints were joined using rubber-toughened epoxy adhesives. Finite element analysis (FEA) was used to predict the location and mode of failure for the different T-joint configurations under monotonic loading.

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INTRODUCTION

Safe and reliable design of joined structures is dependent on the availability of reliable measurement methods that can be used to detect the onset and propagation of damage in bonded and bolted structures under fluctuating dynamic loading conditions, and to relate changes in joint properties (i.e. stiffness) resulting from damage accumulation to residual life of the system. Currently, there are no well-established design procedures for predicting failure behaviour of bonded structures under monotonic and cyclic fatigue loads [1-6].

This Measurement Note examines the use of strain gauges and linear voltage displacement transducers (LVDTs) for monitoring local and global changes in stiffness of bonded and bolted aluminium and glass fibre-reinforced epoxy (GRP) T-joints under monotonic loading. It also examines the relationship between stiffness loss and residual life of these joined systems under cyclic fatigue loading conditions. The joints were subjected to pull-off (i.e. direct tension) and transverse (or lateral) loads. The bonded aluminium and GRP T-joints were joined using rubber-toughened epoxy adhesives. High strength bolts with a tensile strength in excess of 1,000 MPa were used for the bolted configurations. Finite element analysis (FEA) was used to predict the location and mode of failure for the different T-joint configurations under monotonic loading.

STATIC TESTS

A series of experiments were conducted on bonded and bolted T-joint configurations to measure the load-displacement response of the joints under monotonic load. Tests were also conducted on T-joints with strain gauges bonded at key locations to monitor local deformation. The aluminium T-joint configurations used in the study are shown in Figures 1 and 2. The GRP T-joints were similar in size and geometry to the aluminium joints (see Figures 3 and 4). The GRP joints were constructed of sections with a nominal thickness of 12.16 mm.

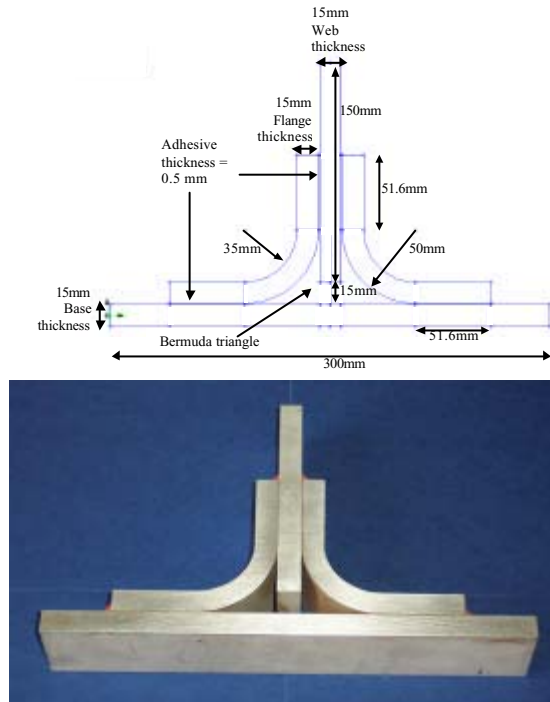


**Figure 1: Bonded aluminium T-joint.
(width = 50 mm)**

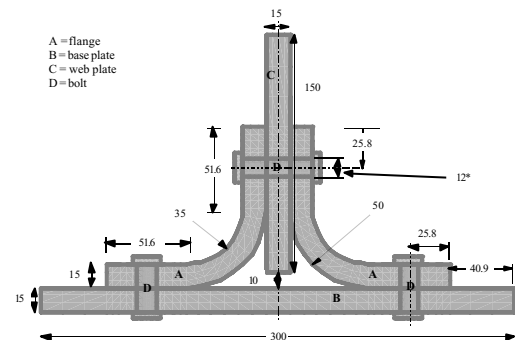


**Figure 2: Bolted aluminium T-joint.
(width = 50 mm)**

The aluminium joints were constructed from 2014-T6 aluminium alloy. For the bonded T-joints, the adhesive was XD4601, a one-part epoxy with a cure temperature of 180°C (supplied by Dow chemicals).



Figure 3: Bonded GRP T-joint.



Figure 4: Bolted GRP T-joint.

The laminated sections used to construct the GRP T-joints consisted of a combination of unidirectional (UD) plies (layers) and biaxial woven plies (double bias biaxial woven fabric where the glass fibres are oriented at $+45^\circ$ and -45° to the section edges) as shown in Table 1. SP Systems supplied the GRP prepreg material. The adhesive used for bonding GRP sections was DP460, a two-part room-temperature curing epoxy supplied by 3M, UK.

The bonded and bolted T-joints were tested under standard laboratory conditions ($23^\circ\text{C}/50\%$ relative humidity) using a 4507 Instron test frame at a cross-head displacement rate of 0.5 mm/min .



Figure 5: Direct tension loading of bolted aluminium T-joint (with strain gauges).

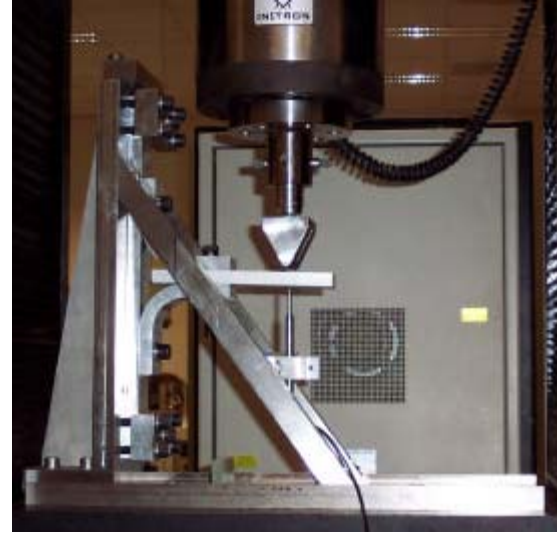


Figure 6: Lateral loading of bonded aluminium T-joint.

The loading arrangements used for applying pull-off and lateral loads to the T-joints are shown in Figures 5 and 6. An RDP spring return LVDT with an operating range of 0 to 25 mm was used to measure displacement in the direction of applied load. Strain gauges were bonded to key locations on three T-joints (bonded aluminium, bolted aluminium and bolted GRP).

Table 1: Basic Laminate Configuration

Layer Number	Ply Orientation	Total Thickness (mm)
1-6	0°	3.84
7-10	Biaxial Fabric	1.6
11-12	90°	1.28
13-16	Biaxial Fabric	1.6
17-22	0°	3.84

Note: 0° and 90° unidirectional layers consist of PG51-531 SE90/L/EGL/1200/1000/32%
Biaxial fabric layers consist of PG21-532 SE90/M/XE603D/1250/35%

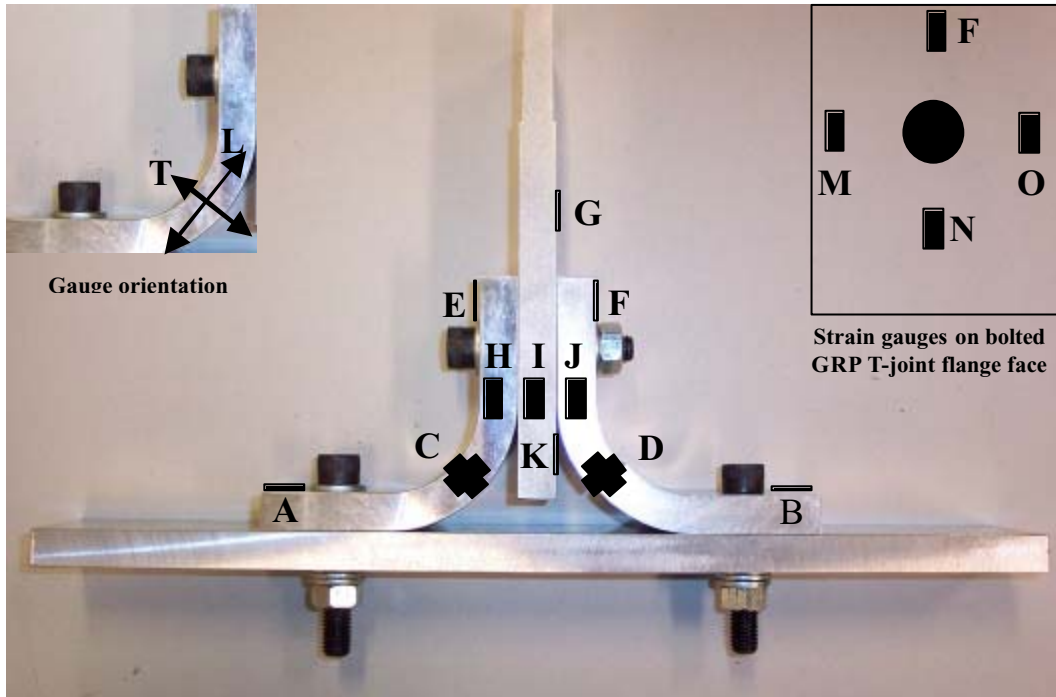


Figure 7: Schematic of strain gauge location on T-joints.
(strain gauges centrally located on either an edge or face of a flange or web section)

Figure 7 shows the location of strain gauges used for measuring local strain. Two types of strain gauge were used:

- 5 mm length uniaxial (Radio Spares)
- 2 mm length 0°/90° biaxial (Kyowa)

For the bonded aluminium T-joint, uniaxial gauges were centrally located at positions **E**, **F**, **H**, **I** and **J** on the two flanges and central web section. The distance between the gauge centre and the flange end was 7 mm for gauges located at **E** and **F**, and 45 mm for gauges located at **H**, **I** and **J**.

For the bolted aluminium T-joint, uniaxial gauges were located at **A**, **B**, **E**, **F**, **G** and **K** with biaxial gauges located at the apex of the flanges at **C** and **D**. The distance between the centre of the gauges located at **A** and **B**, and the flange end was 7 mm. The distance between the centre of the gauge at **G** and the flange end was 26 mm. The centre of the gauge at **K** was 25 mm from the bottom end of the web. The biaxial gauges at **C** and **D** were oriented perpendicular to the flange edge as shown in Figure 7. For the bolted GRP T-joint, uniaxial gauges were located at **E**, **F**, **G** and **K**, and biaxial gauges at **A**, **B**, **C** and **D**.

Uniaxial gauges were also located at 0° (**F**), 90° (**M**), 180° (**N**), and 270° (**O**) on the flat surface about the upper bolt securing the right hand side flange to the central web (see inset in Figure 7). The gauge centres were approximately equidistant (17 to 20 mm) from the centre of the bolt hole with the top gauge located at position **F**. The bolt hole diameter was 12 mm with the hole centre located 26 mm from the flange edge.

Static Test Results - Bonded T-Joints

FEA indicated that elastic-plastic yielding would occur within the adhesive layer of bonded T-joints prior to failure with minimal effect on the linearity of the load-displacement response (see extended line in Figure 8). The test results indicated that failure was cohesive in the adhesive layer and that adhesive deformation had a small to moderate effect on the linearity of the load-displacement response of aluminium and GRP T-joints loaded in either mode. There was no clear evidence from the LVDT data to indicate imminent failure of the T-joints, although there seems to be a point of inflection at a load of ~22 kN. Failure was sudden and catastrophic.

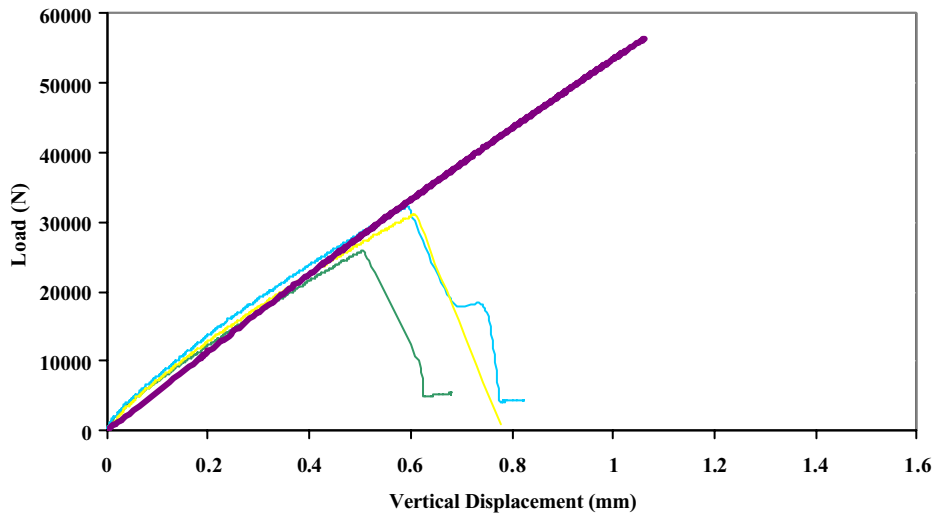


Figure 8: Direct tension load-displacement curves for bonded aluminium T-joints.

The maximum surface strains measured on the flange and central web sections were small (less than $200 \mu\epsilon$), which made data interpretation difficult. As expected, the strain at **I** (web) was approximately twice that for **H** and **J** (flange). Failure occurs within the adhesive fillets between the flanges and web, leading to separation of the adjacent sections. Onset of failure is manifested by a change in slope of the load-strain response of gauges at **H** and **J**, which occurs at ~ 22 kN.

Static Test Results - Bolted T-Joints

FEA has shown for bolted aluminium T-joints under direct tension that damage in the form of hole elongation would first initiate in the base plate and flanges at **A** (see Figures 9 and 10) followed by similar damage in the flanges and web at **B**. Ultimate failure was predicted to occur in the flange at **C** as a result of high stress and strain concentrations in this region. The sequence and form of damage predicted was also observed experimentally.

The load-displacement response measured using the LVDT showed that non-linearity occurs at ~ 49 kN, which agrees with the FEA prediction (see Figure 11). However, FEA also predicts localised damage initiation around the bolt hole at **A** when the load is ~ 38 kN. Hole elongation had minimal effect on the load-displacement response.

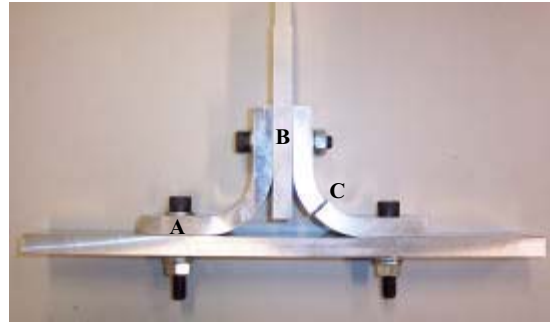


Figure 9: Tensile failure of bolted aluminium T-joint flange (location C).



Figure 10: Bolt hole elongation at A.

The surface strain measurements (Figure 11) for the bolted aluminium T-joint also deviated from linearity at ~ 50 kN. The longitudinal strain at **C** (CL - see Figure 7) shows a marked deviation from linearity at ~ 50 kN as a result of localised yielding of the aluminium flange. Although local deformation occurred around the bolt holes at loads less than 50 kN, it was impossible to isolate hole elongation from global effects. At failure, hole elongation in the base plate was ~ 0.1 - 0.2 mm (1-2% of hole diameter).

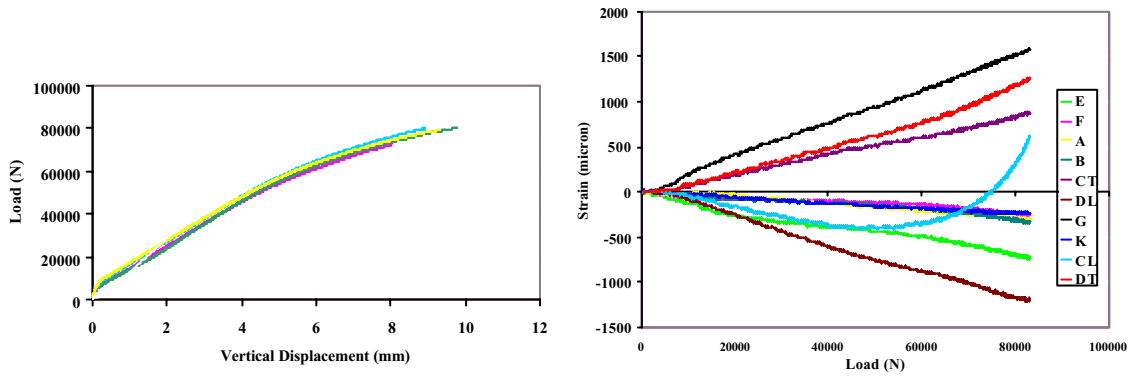


Figure 11: Direct tension of bolted aluminium T-joints.
(left: load-displacement curves; right: load-strain curves for a single T-joint)

Multiple modes of damage in the composite (i.e. longitudinal splitting and delaminations) were observed for bolted GRP T-joints in direct tension (Figure 12). As predicted, delaminations causing catastrophic failure of the joint, initiate in the vicinity of the bolts securing the flanges to the base plate at ~20 kN. These delaminations are a result of combined through-thickness shear and tensile stresses (see fractographic image in Figure 12). Delaminations originate in the upper half of the laminate at the interface between a biaxial fabric 45° ply and a 90° UD ply. The crack then propagates through the thickness to the laminate centre and around the flange circumference (NB. For lateral loads, failure results from high shear stresses at the flange apex). Although the LVDT data was insensitive to localised damage around the bolt holes, strain gauges in these regions detected changes at ~10 kN; as predicted by FEA.

CYCLIC FATIGUE TESTS

Constant amplitude (sinusoidal waveform) cyclic fatigue tests were conducted on bonded and bolted aluminium and GRP T-joints. The test regimes are described below.

Direct Tension-Tension Loading

- Bonded aluminium/XD4601
- Bonded GRP/DP460
- Bolted GRP

Lateral Tension-Tension Loading

- Bonded aluminium/XD4601
- Bolted GRP

The stress ratio R ($\sigma_{\text{MIN}}/\sigma_{\text{MAX}}$) was equal to 0.1 for direct and lateral tension-tension cyclic loading conditions.

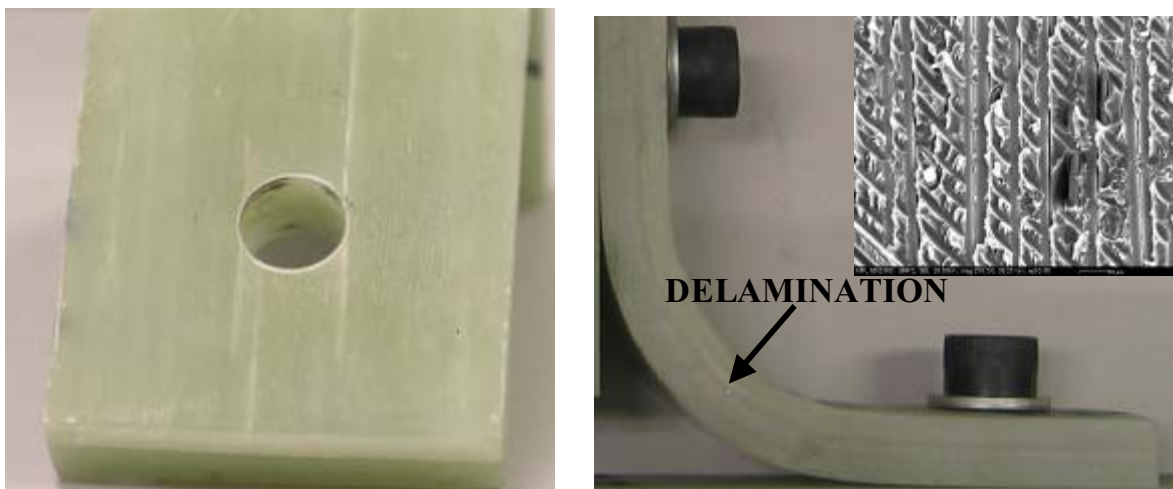


Figure 12: Damage induced in a bolted GRP T-joint resulting from direct tension loading.
(left: longitudinal splitting in around bolt hole; right: delamination in flange)

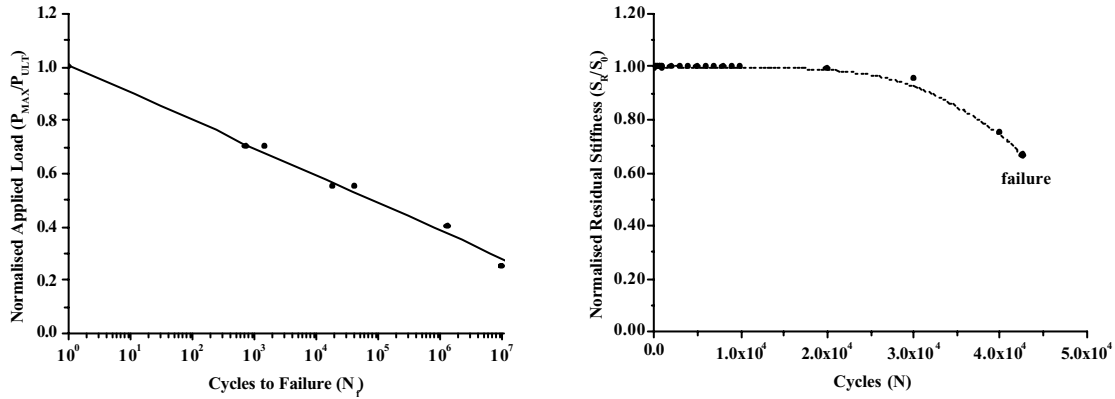


Figure 13: Direct tension-tension cyclic loading of a bonded aluminium T-joint. (left: normalised S-N data; right: normalised residual stiffness at $P_{MAX} = 0.55 P_{ULT}$)

The T-joints were tested in load control using an 8501 Instron servo-hydraulic test machine at a frequency of 3 Hz under standard laboratory conditions. Tests were carried out at four different stress levels ($P_{MAX} = 70\%$, 55% , 40% and $25\% P_{ULT}$). The ultimate strength P_{ULT} was measured at a displacement rate equivalent to the test frequency.

The normalised stress-fatigue life (S-N) data for all the T-joints tested in cyclic fatigue (see Figure 13) is independent of mode of joining, material or bading mode and can be represented by the following relationship:

$$P_{MAX}/P_{ULT} = 1 - k \log N_f \quad (1)$$

where P_{MAX} is the maximum applied load, P_{ULT} is the joint failure load, k (the slope) is the fractional loss in strength per decade of cycles and N_f is the number of cycles to failure. The value of k for the bonded and bolted aluminium and GRP T-joints under the two loading configurations varied from 0.08 to 0.11 (see Table 2).

Residual stiffness S_R was monitored throughout the fatigue test. Figure 13 shows a typical normalised residual stiffness (S_R/S_0) plot for a bonded aluminium T-joint under tension-tension fatigue (S_0 is the initial stiffness at $N = 0$). The onset of localised damage (e.g. mode I cracking in the internal fillet of a bonded T-joint) coincides with a reduction in residual stiffness. For bonded aluminium T-joints under lateral tension fatigue loading, S_R/S_0 decreases linearly with N with the rate of decrease dS/dN dependent on P_{MAX}/P_{ULT} (see Figure 14).

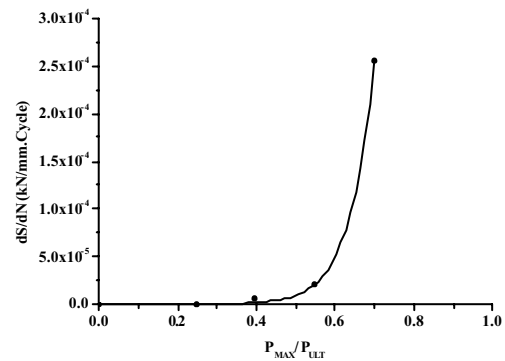


Figure 14: Rate of stiffness loss versus P_{MAX}/P_{ULT} for transverse tension fatigue of bonded aluminium T-joints.

Table 2: Joint Efficiency Factor and Normalised Residual Stiffness (S_R/S_0) at Failure

T-Joint Configuration	k	Average S_R/S_0 at Failure
Direct Tension - Bonded Aluminium	0.104	0.70
Direct Tension - Bonded GRP	0.106	0.78
Direct Tension - Bolted GRP	0.078	0.74
Lateral Tension - Bonded Aluminium	0.111	0.75
Lateral Tension - Bolted GRP	0.112	0.80

Normalised residual stiffness S_R/S_0 for bonded T-joints under direct tension fatigue can be estimated for N cycles using the following function:

$$S_R/E_0 = 1 - Ae^{N/B} \quad (2)$$

where A and B are empirical constants dependent on P_{MAX}/P_{ULT} . The normalised residual stiffness at failure tends to be approximately the same for different values of P_{MAX}/P_{ULT} (Table 2). Preliminary trials indicate that the normalised residual strength (monotonic loading) after N cycles tends to mirror the normalised residual stiffness value (i.e. $\approx S_R/S_0$).

CONCLUSIONS

The results of the study show that it is possible to monitor the effects of damage on the stiffness of bonded and bolted T-joints. Although, it is difficult to detect the onset of localised damage, which can lead to eventual failure of the structure. Strain gauges in some cases proved effective in detecting the onset of localised damage. Non-contact full field strain techniques (e.g. Digital Image Correlation (DIC) and electronic speckle pattern interferometry (ESPI)) may prove more successful in detecting localised strain concentrations and damage onset in joined systems (see Figure 15). Empirical relationships can also be used to determine the life expectancy and residual stiffness of these bonded and bolted structures subjected to fatigue loading conditions.

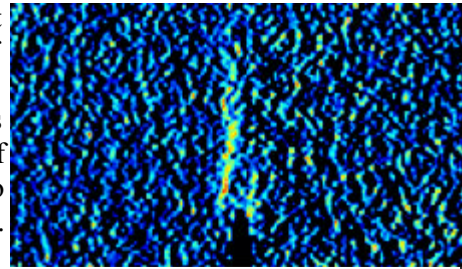


Figure 15: DIC map showing strain concentration in adhesive layer between flange and web.

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