Behaviour of fibre reinforced composite beams with mechanical joints

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Abstract

The fundamental behavior of the fibre reinforced composite beams with mechanical joints was examined using coupon and full-scale specimens. The effect of applied bolt torque, the contribution of adhesive bonding, and the number and configuration of bolts on the load capacity and failure mode of the double-lap bolted joints were investigated. The results showed that at different levels of applied bolt torque (10, 15, 20 and 25 N-m), little friction resistance developed. A slight increase on the load capacity was however observed with increasing tightening torque. On the other hand, the mechanical joints using bolts accompanied by adhesive bonding provided resistance against slipping. The flexural behavior of full-scale fibre composite beams with joints at midspan connected with bolts alone and a combination of bolts and epoxy was further examined. The beams connected using bolts and epoxy exhibited the same strength and stiffness as the beams without joints while using bolts alone resulted to a beam with only 65% of the stiffness of those without joints. This showed that the combination of bolts and epoxy adhesives could provide a reliable connection method for fibre reinforced composite beams.

Keywords: Composite beams, Mechanical joints; Fibre composites; Bolted joints; Bonded joints; Connections.

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1. Introduction

The advancement of fibre composite materials in civil engineering applications has resulted in the combination of two or more different fibers such as carbon and glass into a structure to improve its mechanical performance at very little additional cost [1]. This is commonly known as hybrid fibre composite structures. Recently, an effective application of fibre composite materials for bridge beams from the aspect of strength and cost was studied by Hai et al. [2]. The innovative feature of this composite beam is the combined use of carbon and glass fibre reinforced polymers in the top and bottom flanges. The carbon fibre (CF) is added to improve the mechanical performance of the beam because of its high modulus and high strength while glass fibre (GF) is the one only used in the web because it is relatively cheaper and it is expected that smaller stress is induced in this part. While structural components made up of fibre composite materials can be produced at almost any specified lengths, the limitations in the transportation and installation required them to be produced at manageable lengths to minimize weight and facilitate handling making the connections inevitable in the construction of composite structures.

The design of efficient connection system represents one of the major challenges in the development of fibre composite structures. According to Magness [3], the structural components must be joined such that the overall structure retains its integrity while performing its intended function. Unfortunately, there is limited knowledge on joining technology for fibre composite structures and only few research studies have been conducted in this area for civil engineering applications. In civil infrastructure, the structural members are usually joined by bolted connections [4]. This type of connection is relatively easy to assemble, has the ability to be easily removed when required, and is capable of transferring the high loads [5]. However, fabricating a hole for a bolted connection in composite materials may damage the continuous fibres through the components and compromises the strength of the members at the joint. Similarly, the mechanisms by which the damage initiates and propagates in the bolted joints for fibre composites can be different. Because of this, additional research and developmental works which aim at understanding the behavior of structural components with mechanical joints should be conducted to determine an effective and reliable jointing method for fibre composite beams.

In this paper, the mechanical behavior and the applicability of bolted joints in fibre composite beams for civil engineering applications were investigated. The effect of applied bolt torque, number and configuration of bolts, and the contribution of adhesive bonding on the strength and behavior of bolted joints were characterized through experimental investigation using coupons and full-size composite beam specimens.

2. Connections for fibre composite structures

Many types of connections for composite structures have benefited from research in automotive and aerospace engineering. For civil engineering applications where thicker members are generally used, only a number of research have been conducted so far. Hart-Smith [6] was the first to present the fundamental concepts of mechanically fastened joints for fibre composite materials. Based on his paper, fibre composites with bolted connections may fail due to tension, shear-out or bearing. It may also fail by cleavage of the laminate, the connector pulling through the laminate or by bolt failure either by single or double shear. Furthermore, he concluded that these failure modes largely depend on the geometry of the connection, i.e. width of the specimen (w), edge distance (e), diameter of the hole (d_h), side distance (s), gauge or transverse spacing (g), pitch or longitudinal spacing (p), diameter of bolts (d_b), thickness of the laminate (t_{pl}), and hole clearance (d_h-d_b). These geometric parameters are illustrated in Figure 1.

The effect of various geometric parameters on the capacity and failure mode of bolted joint has been studied by a number of researchers. Jurf and Vinson [7] had a study on the behavior of bolted joints in composite laminates using various geometric patterns. Results of their experimental investigation showed that the bearing strength increases with respect to s/d_b or e/d_b ratio independent of lateral restraint. Rosner and Rizkalla [8] on the other hand examined the effects of t_{pl}, w/d_h ratio, e/d_h ratio, and the fibre orientation with respect to load on the behavior of bolted connections for GF composite members. Their study showed that increasing the t_{pl}, w and e increased the load capacity of the connection. While changing the angle of the fibres with respect to the applied load from 0 to 90 degrees reduces the strength of the connection. Aktas and Dirikolu [9] investigated a pin loaded carbon epoxy composite laminate with different stacking sequences in order to determine its maximum bearing strength. Ekh [10] studied the multi-fastener single-lap joints in composite structures. He found out that the single lap-joints generate out-of-plane deflection and caused a non-uniform bolt-hole contact pressure through the plate thickness. Similarly, Sen et al. [11] investigated the failure mode and bearing strength of mechanically fastened bolted-joints in GF reinforced epoxy composite plates. The results showed that the failure modes and the bearing strength of GF laminated composites were considerably affected by the increasing preload moments applied on the bolts.

Lateral constraint due to clamping pressure can significantly increase joint strength [12]. Kishima and Meiarashi [13] investigated the effect of clamping pressure on the bolted joint strength in GF reinforced laminates applied to civil infrastructures. The results of their study showed that a higher clamping pressure and high strength adhesive increased the bolted joint strength. Similarly, Khasaba et al. [14] investigated the influence of the tightening torque and the washer's outer diameter on the strength of bolted joints in GF reinforced epoxy composites. Experimental results showed that the slope of the load-displacement curve of bolted joints increases with increasing washer size and the bearing strength increases with increasing tightening torque.

Currently, there is no distinct failure criterion for the experimentally tested mechanically fastened composite joints. Herrington and Sabbaghina [15] showed that the load displacement curve of bolted joint specimens had a linear behavior up to a certain point, followed by an unstable nonlinear behavior. They defined this point as the bearing failure, the maximum load just prior to the unstable, nonlinear behavior. On the other hand, the bolt bearing strength calculated by Hollman [16] was based on the ultimate failure load. In most studies, the ultimate strength and failure mode of bolted connections were investigated to determine the behavior of bolted connections. However, Allred [17] stated that it is desirable to obtain not only the ultimate values of bearing load but also the entire load deflection curve, because the material "yield strength" from such curve provides a better understanding of the behavior of the bolted connection than the ultimate bearing strength.

A large part of the literature on mechanically fastened joints presented the effect of stacking sequence, geometric properties, clearance between the hole and the pin, and the degree of lateral clamping pressure on the strength of bolted connections. However, most of these research deal only with thin laminates and made up of the same type of fibres. In view of the very large number of variables involved, complete characterization of the joint behavior is impossible. In this paper, the behavior of double-lap bolted connections for composite beams consisting of glass and carbon fibres was investigated experimentally.

3. Experimental program

This section presents the preparation and procedure for laminate and full-scale tests to determine the behavior of fibre composite beams with bolted joints.

3.1 Material properties

The mechanical properties of each lamina and the stacking sequence of the plies which made the fibre reinforced composite beams tested in this study can be found in Hai et al. [2]. The effective mechanical properties in the longitudinal direction of the flanges and the web of this composite beam were determined following the test of coupon specimens and are reported in Table 1.

3.2 Tests of composite laminates with bolted joints

Fibre composite laminates with double-lap bolted joints representing the flanges and web of the composite beams were tested to failure to characterize its strength and behavior. A double-lap joint with 2, 4 and 8 bolts was considered as the experimental model. This corresponds to specimens 2b, 4b and 8b respectively. The description of the specimens for coupon test of composite laminates with bolted joints is listed in Table 2. The nominal thickness of the laminates is 14 mm and 9 mm for the flanges and web, respectively. All of the specimens were prepared following the minimum recommended geometric configurations for bolted joint connections by Bank [18]. Stainless steel bolts with a nominal diameter of 10 mm and yield strength of 600 MPa were used.

In the specimen preparation, the holes in the composite laminates were made using a diamond-tipped drill. The specimen was clamped with the bolt through 9 mm thick SS400 splice plate and the torque was applied to the bolts using a presetting torque wrench at 10, 15, 20 and 25 N-m. Sandpaper with a grit size of 60 was provided on the aluminum plate to increase the resistance against slipping at the gripping end. Figure 2 shows the geometrical configuration of the fibre composite laminates with 8-bolted joints. The specimens with epoxy adhesives and those without had the same configuration. The epoxy was applied on both sides of the composite laminates before the torque was applied on the bolts. Washers were also provided between the composite laminates and the splice plates to maintain the thickness of the epoxy. The epoxy adhesives were allowed to harden for a week before the specimens were tested.

The experimental test set-up for composite laminate with bolted joints is shown in Figure 3. Angular aluminum bars were attached on both sides of the composite laminate and the splice plates. Linear and draw-wire displacement transducers (LVDT) were then provided on these aluminum angular bars to measure the relative displacement between the composite laminate and the splice plates. Displacement transducers were also used to determine if slipping would occur at the metal grips during the initial tests. Each specimen was instrumented with back-to-back strain gauges attached on the splice plates to measure the load distribution on the bolt rows. The specimens were gripped at both ends in a 500 kN capacity universal testing machine and tension force was applied at the top end while keeping the bottom end fixed. All specimens were loaded at a rate of approximately 0.5 kN/sec and all the measurements were obtained using a data logger. The test was discontinued after a drop in the applied load was observed and the specimen was removed from the testing machine to observe and record the final failure mode.

3.3 Full-scale test of composite beams with mechanical joints

The flexural behavior of the full-scale fibre composite beams with mechanical joints at midspan was determined. The composite beam has a total length of 3700 mm and a clear span of 3000 mm. In the preparation of the full-scale specimen with bolted joints, the composite beam was cut into halves with lengths of 1850 mm each. The location of the bolt holes was marked and the holes were made on each beam using a diamond-tipped drill bit. The cut beams were joined at the flanges using 10 mm diameter stainless steel bolts and 9 mm thick SS400 splice plates, while 4 mm thick splice plates were used to connect the web. A gap of 5 mm was provided between the beam end faces. A torque of 20 N-m was applied to the bolts.

The beam with bolted and epoxy bonded joints had the same configuration as the beam without epoxy. In order to maintain the thickness of the epoxy adhesives, washers were provided between the laminates and the splice plates. The epoxy adhesives were allowed to harden for a week before the beam was tested. A similar full size beam without joints is subjected under four-point bending test to verify the difference in behavior of fibre composite beams with and without bolted joints. Table 3 summarizes the description of the full scale specimens and Figure 4 shows the details of the composite beams with mechanical joints.

The fibre composite beam with mechanical joints at midspan was tested under four-point loading. Figure 5 shows the test set-up and instrumentation for specimen FC2. The beam was simply supported and the load was applied manually by hydraulic jack at third points through a spreader beam. Displacement transducers were installed to measure the displacement at the loading points and at the midspan of the beam. Strain gauges were attached on the top and bottom flanges of the composite beams and the splice plates to evaluate the strain during loading and until failure. Data logger was used to record the strains with the load–deflection curve displayed in real time during testing to monitor the beam behavior.

4. Results and discussions

The experimental results for the fibre composite laminates with different bolted joint configurations are presented in the following sections. The behavior of the full-scale composite beams with bolted joints at midspan under static bending test is also discussed.

4.1 Effect of applied bolt torque on joint strength

The effect of the applied bolt torque on the strength of bolted joints in fibre composite laminates was determined. Figure 6 shows the failure load of composite laminates with 2 bolts at different levels of applied bolt torque (10, 15, 20, and 25 N-m). In the range of the investigated tightening torques, it was observed that the strength of bolted joints increased slightly with increasing tightening torque. The bolted joints with 25 N-m tightening torque has the highest average failure load while the bolted joint specimen with 10 N-m tightening torque has the lowest. A more consistent result was also observed for bolted joints with a higher applied bolt torque. This could be due to the higher lateral constraint provided by the higher clamping pressure in the splice plates which suppressed the out-of-plane deformation in the composite laminates. For specimens with higher applied bolt torque, the damaged laminates due to bearing accumulated between the splice plates and the specimens were able to carry a higher load before the final failure. However, it was observed that the specimens with 20 and 25 N-m applied bolt torque failed at almost the same level of applied load. In order to determine the optimal amount of applied torque to be used in the succeeding tests, the behavior of composite laminates with 8-bolted joints using 20 and 25 N-m applied torque was examined.

Figure 7 shows the load-bolt displacement relationship of laminates with 8 bolts at 20 and 25 N-m applied torque. In the figure, the load is the resistance of the specimen while the displacement is the difference of the averages in the readings on displacement transducers attached on both sides of the specimen which includes the hole elongation and the bolt deformation. The load-displacement behavior indicated that with the different levels of bolt torque applied there was very little friction resistance, since slipping of the connections occurred at the initial loading stage. The little resistance against slipping provided by the bolted joint can also be due to the stress relaxation due to creep in the through the thickness direction as observed by Caccese et al. [5]. This relieves some of the clamping pressure provided by the applied bolt torque in thick fibre composite laminates. After slipping, the load displacement relation curve was almost linear indicating that the bolts already slipped into bearing with the composite laminates. This linear load-bolt displacement behavior occurred up to an applied load of around 300 kN and a displacement of 3 mm. After this point, the load displacement curve became non-linear until final failure. This non-linear behavior is due to the initiation of bearing failure in the fibre composite laminates combined with bending of the bolts. The load reduction occurred gradually as the crushing damage at the contact surface between the bolts and the bolt hole continues to grow. The load then suddenly dropped after excessive displacement. It was also observed that the specimens with 20 N-m applied bolt torque showed a higher stiffness and failed at a slightly higher load. The specimen 8b-20t failed at an average load of 420 kN while the specimen 8b-25t failed at 410 kN. It was then concluded that an applied torque of 20 N-m is reasonable for bolted connections of the full scale fibre reinforced composite beams. This is almost similar to the optimum bolt clamping pressure of 22 MPa for CF reinforced laminates as recommended by Coolings [19].

4.2 Contribution of epoxy adhesives

The contribution of epoxy adhesives on the strength and behavior of bolted joints for fibre reinforced composite laminates was examined using specimens with 4 and 8-bolt configurations at 20 N-m tightening torque. Figure 8 shows the load-bolt displacement relationship of the specimens with and without epoxy adhesives. The results show that the slipping of the bolted joints in all specimens without epoxy occurred at a lower load. A linear load displacement curve was then observed up to approximately 140 kN and 320 kN for specimens 4b-20t and 8b-20t, respectively. The curve then became non-linear until final failure. On the other hand, the contribution of epoxy adhesives is similar for specimens 4b-20t-e and 8b-20t-e. The bolting accompanied by adhesive bonding provided resistance against slipping between the splice plates and the fibre composite laminates. There was no observed slip until an applied load less than the resistance developed between the two surfaces with the bolts carrying little load until the adhesives failed. Slipping occurred at an applied load of around 150 kN and 200 kN for specimens 4b-20t-e and 8b-20t-e, respectively. This shows that a higher resistance against slipping can be attained in bolted joints with epoxy adhesives. An abrupt drop in load was observed after debonding of the epoxy adhesives. After which, the load again increased indicating that the applied load was transferred to the bolts. The connection then behaved similar to the bolted joints without epoxy adhesives until final failure.

The specimen 4b-20t with and without epoxy failed at almost the same level of load and similar failure mode on the composite laminates. All of the specimens tested failed an applied load of around 205 kN. On the other hand, the 8-bolted specimen with epoxy failed at a lower load capacity compared to that of without epoxy. The maximum load that the specimen 8b-20t carried is 420 kN while the specimen 8b-20t-e is only around 400 kN with the failure mode also different for both specimens.

4.3 Effect of number and configuration of bolts

4.3.1 Failure load

The capacity of the composite laminates with 2, 4, and 8 bolts at an applied bolt torque of 20 N-m is shown in Figure 9. The results showed that the strength of bolted joints in the flange specimen increased linearly with increasing number of bolts. The average maximum loads measured were 103.5 kN, 205.2 kN and 419.2 kN for 2, 4, and 8 bolted joints, respectively. On the other hand, the web specimen failed at almost the same amount of applied load even with increasing number of bolts. The average load capacity of the web specimens with different number of bolts is only 67.7 kN. This result also shows that the capacity of the bolted joints depends on the type of fibre composite laminates being joined.

4.3.2 Load and strain relationship on the splice plates

Figure 10 shows the typical load-strain relationship on the splice plates for the specimen 8b-20t. In can be observed from the figure that the measured strain increased with the load up to almost 300 kN. After which, a decrease in strain was observed which indicates that the fibre composite laminates started to fail. The results also show that the measured strains from back to back strain gauges attached on both splice plates were almost equal. This means that the bolts were loading the hole uniformly throughout the specimen thickness. On the other hand, a higher strain on the bolts close to the application of the load was measured than those bolts located farther back indicating the unequal distribution of load among the bolts. Using these strain readings, the load distribution among the bolts was determined and compared with the load distribution factor in the fastener group for fibre composites suggested by Mottram and Turvey [20].

4.3.3 Distribution of load between bolt rows

The load distribution between bolt rows based on the result of the experiment was compared to the load distribution factor for multirow bolted lap joints suggested by Mottram and Turvey [20]. The load distribution factors suggested by these authors are for GF composite profiles connected to steel plates. Figure 11 shows the distribution of load in the 4-column bolted connections for hybrid FRP composites. In the figure, the bolt row number 1 in specimen 8b-20t carried almost 50% of the applied load while the second row carried almost 30%, the third row almost 15% and the last row only 5%. These results verified that in multi row joints, the row of bolts closest to where the tensile load is applied carries the most load than those farther back. A higher load distribution factor was observed in the experiment for bolted specimens compared to the recommended values. The addition of epoxy adhesives further increased the load carried by the bolt rows closest to the applied load. In specimen 8b-20t-e, the bolt row number 1 carries almost all the load and the last row carries almost no load. The high load carries by the bolts closest to the application of load also explains the reasons why net-tension failure occurred in row 1 in the tested laminates from the web and also on the GF side of the flange with 4 and 8 bolts. In both specimens 8b-20t and 8b-20t-e, the load carried by bolt rows 1 and 2 is higher compared that of the suggested value of only 42% and 25%, respectively.

4.3.4 Failure of composite laminates with bolted joints

The splice plates were removed after every test to examine the damage in the fibre composite laminates. Figures 12 and 13 show the failure modes in the composite laminates representing the flanges and the web of the beam, respectively. In Figure 12a, the specimen 8b-20t failed due to bearing of the laminates in both the CF and GF with initial signs of shearing out in the CF. However, no shear out failure was observed in the GF side as it has a higher shear resistance than the CF due to the glass fibres oriented at $\pm$45 degrees. The stainless steel bolts were also bent in specimen 8b-20t.

In flange specimen with bolts and epoxy adhesives, the specimen 8b-20t-e failed due to the net tensile failure in the GF, bearing failure with shear out in the CF and all the bolts in double shear as shown in Figure 12b. Delamination between the CF and the GF laminates was also observed which resulted in the net tensile failure in the GF laminates and initiated the shear out failure in the CF as the CF and the GF laminates acted separately in resisting the applied load. Similarly, the bearing failure in the specimen 8b-20t is more obvious compared to specimen 8b-20t-e. This could be due to the slipping to the bolts which occurred at the early stage of load application for specimen without epoxy adhesives and resulted in a more gradual failure behavior than that of specimens with bolts and epoxy.

The bolted connections of the web specimens failed in a sudden manner due to net-tension failure as shown in Figure 13. This was the expected mode of failure since the laminates containing 90^{o} and/or $\pm 45^{o}$ plies has a lower tensile strength but perform well under bolt bearing conditions [12]. A crack parallel to the applied load propagating from the end of the specimen towards the bolt holes and cracks near the net section can be seen in all web specimens. In web specimens with 4 and 8 bolts, the net-tension failure occurred at the bolt rows near the applied load.

4.4 Behavior of full scale beams with mechanical joints

4.4.1 Load-displacement relationship

The load and midspan deflection relationship of beams FC1, FC2 and FC3 under four-point loading test is shown in Figure 14. According to the result, the beam FC1 behaves linear elastic up to failure. The beam failed at an applied load of 94.9 kN and a midspan deflection of 39.1 mm. The slope of the load-midspan deflection of beam FC2 is the same with that of beam FC1 only up to an applied load of 5 kN. With the continuous application of load, the beam showed a slight yet steady decrease in the stiffness. This could be due to the slipping of the bolts and the gap provided between the beam end faces which allowed the specimen to rotate. The specimen was loaded up to 97.9 kN with a midspan deflection of 56.3 mm. This applied load is slightly higher compared with the load capacity of the hybrid FRP girder without joints. However, the beam deflected to a greater degree than expected. At this point, the test was stopped and the load was released. There were no signs of failure observed in the bolts and in the composite laminates when the splice plates were detached. It was then concluded that if the test was continued, the beam FC2 might have carried a higher load before its final failure. Using the same beam, epoxy adhesives were provided in the bolted splice joints and the flexural behavior of this beam was examined under the same loading condition.

In the fibre composite beam with bolted and epoxy bonded joints, the load increases linearly with deflection until final failure. There was no decrease in stiffness observed at every initiation of epoxy debonding at the splice plates. The beam FC3 failed at an applied load of 93.9 kN with a midspan deflection of 36.9 mm. It is noteworthy that the stiffness of beam FC3 is slightly higher than that of specimen FC1 mm even though the load levels at failure are almost identical for the two specimens. The difference in observed stiffness can be attributed to the contribution of the steel splice plates on the bending resistance of the beam. Similarly, the epoxy filling the gap between the beam ends might have prevented it to rotate.

Overall, the beam FC3 exhibited the same strength and stiffness as the beam FC1 while beam FC2 has only 65% of the stiffness of specimen FC1. This result suggests that the use of combined bolts and epoxy adhesives provided a reliable connection method for fibre reinforced composite beams.

4.4.2 Load-strain relationship

Figure 15 shows the relationship between the load and strain of the top and bottom flanges at midspan section of the fibre composite beams with and without splice bolted joints. Result showed that the strains in both tension and compression increased linearly with load for all beams. This suggests that the composite beams with and without bolted joints behaved linearly elastic during the test. An average maximum strain of around 4,500 microns in tension and 4,600 in compression were measured for all beams at failure. It is interesting to note that the failure in all beams occurred at a level of compressive strain comparable with the established critical strain value of 4,000 microstrains determined from the test of coupons while the maximum tensile strain measured was only 30% of the failure strain.

4.4.3 Load-strain relationship of the splice plates

Figure 16 shows the location of the strain gauges attached to the splice plates while Figure 17 shows the load and strain relationship of the splice plates at the top and bottom flanges of the composite beams. In Figure 17a, the strain measured in beam FC2 increased linearly with load up to 5 kN. At this point, the bolts might have slipped in contact with the splice plates hence a gradual but steady increase in the strain followed. In Figure 17b, the load and strain relationship in beam FC3 showed a linear increased in strain up to an applied load of 20 kN. A decrease in strain was then observed with the continuous application of the load at different levels. This showed that there was a progressive debonding of epoxy in the joints of beam FC3. At every initiation of epoxy debonding, a sudden decrease in strain at the outer part of the splice plate was observed but increased again which indicates that the bolts at these locations started to carry the load.

The results also showed that the measured strains from the strain gauges attached on the opposite ends of the splice plates were almost equal indicating that the bolts were loading the hole uniformly at both ends of the beam. As expected, a higher strain reading on the bolt rows closest to the beam ends than those located farther back were measured showing that there is unequal distribution of loads among the bolt rows. In general, higher strains were measured in the splice plates of beam FC2 than in beam FC3. This shows that the bolts in beams without epoxy are more stressed compared to the beams with epoxy. Furthermore, the results show that the presence of epoxy in beam FC3 resulted in a more uniform load distribution in the bolted joints than the beam FC2.

4.4.4 Failure of full scale beams with bolted joints

Figure 18 shows the failure mode of fibre composite beams with and without bolted joints. As the load was applied, a sound was heard caused by epoxy debonding between specimen and the metal stiffener. The final mode of failure of beam FC1 was the delamination between the CF and GF laminates in the compression flange at the midspan followed by shear failure at the web (Figure 18a). This failure was the expected failure mode as the fibre composite laminates in the flanges has higher tensile than compressive strength.

The beam FC2 exhibited large amount of deflection when the test was stopped at an applied load of 97.9 kN. However, no signs of failure in the bolts and the composite laminates around the bolt holes was seen when the splice plates were removed. For beam FC3, the failure did not occur at the bolted joints but at the compression flange between the loading point and the splice plate. The failure mode was the delamination between the carbon and the glass fibre laminates as shown in Figure 18b. The splice plates and the bolts also showed no signs of damage after the experiment. Visual inspection also showed no sign of debonding failure in the epoxy adhesives. This type of failure was expected since the beam was designed to fail outside the joints. Accordingly, the results showed that if the joint is sufficiently designed, the flexural behavior of the fibre composite beams with and without mechanical joints is governed by the strength of the compressive flange.

5. Theoretical strength of bolted joints

5.1 Mechanics based equations for bolted joints

Theoretical mechanics based equations were used to analyse the strength of the bolted connections. In bolted joints, the bolts are subjected to shear while the fibre composite laminates and the splice plates are subjected to bearing stress. The load-carrying capacity of the bolted joints due to bearing can be calculated using the equation 1. The load capacity is computed as the bearing strength of the FRP composite multiplied by the number of bolts, bolt diameter and the thickness of the FRP laminate. According to Bank [18], if the bearing strength of the fibre composite materials is not available, the material compressive strength can be used for approximate calculation.

$$P_b = \sigma_b n d_b t_{pl} \quad (1)$$

where P_b is the load capacity due to bearing of the laminates, σ_b is the bearing or compressive strength of fibre composites, and n is the number of bolts in the bolted joint configuration. On the other hand, the load carrying capacity of the joint connection due to the net tension at the critical section of the fibre composite laminate can be calculated using equation 2:

$$P_t = \sigma_t A_{net} \qquad (2)$$

where P_t is the tensile load transferred by the entire lap joint consisting of a number of column of bolts, σ_t is the tensile strength of fibre composites, and the net area, A_{net}, is taken as equation 3:

$$A_{net} = t_{pl}(w - nd_h) \qquad (3)$$

The load capacity of the bolted joints in double shear, P_v is given as equation 4. In this equation, P_v can be determined as the shear strength of the bolt, τ_b (which can be approximated as $0.60f_y$ where f_y is the yield strength of the bolt) multiplied by the total cross-sectional area of the bolt shank:

$$P_v = 2\tau_b A_b \qquad (4)$$

and A_b can be computed using the equation 5:

$$A_b = n(\pi d_b^2 / 4) \qquad (5).$$

5.2 Comparison with experimental results

Table 4 shows the comparison between the load carrying capacity of the composite laminates with bolted joints obtained from the experimental investigation and the predicted values using the theoretical equations. In view of the difficulty in determining the load at which failure of the bolted joints occurred, the maximum load carried by the specimen was used as the measure of the joint strength.

The results showed that the values predicted using the equation 1 for the flange specimen is 7-9% higher than the actual failure load. On the other hand, the failure load calculated using equation is very conservative compared to the actual failure load. This is due to the high tensile strength of the fibre composite laminates in the flanges eliminating the possibility of net tensile failure. Using the equation 4, the estimated joint capacities based on the strength of the bolts in double shear are 5-7% higher than the experimental results. Based on the predicted values, it can be concluded that the flange of the fibre composite beams with bolted joints should be designed to fail due to bearing in the laminates. Bearing failure is the crushing of the fibre composite material supporting the bolt which is a desirable form of failure for due to its progressive nature [21]. This result also showed that the strength of the bolted joints in the flanges can reliably be designed based on the compressive strength properties of the materials determined from the test of coupons. Furthermore, the result showed that an edge distance of 30 mm is sufficient for the fibre composite beams with mechanical joints since the bearing failure occurred.

The predicted load of the web specimen with bolted joints due to bearing and double shear (of the bolts) is 1.3 to 6.4 times higher than the actual failure load. However, the failure load estimated based on the tensile strength of the web using the equation 2 is only 10-12% higher compared to the failure load obtained from the experiment. A failure load of almost 76 kN was computed for the web to fail in net tension but all the web specimens failed due at the critical section at a load of around 68 kN. The lower failure load could be due to the presence of the bolt holes which might have damaged the $\pm 45^o$ GF fibers thus reducing its strength.

6. Conclusion

Experimental investigation on the behavior of fibre composite materials made up of carbon and glass fibres with bolted joints was conducted using test of coupon specimens and full-scale beams. The effects of applied bolt torque, contribution of epoxy adhesives and the number and configurations of bolts on the strength and the failure mode of bolted joints were examined.

The results of test using fibre composite laminates with double-lap bolted connections showed that at different levels of applied bolt torque, little friction resistance developed between the splice plates and the composite laminates but increased significantly with the addition of epoxy adhesives. A slight increase in the failure load was however observed with the increasing tightening torque. The flange specimens with bolted joints failed due to bearing failure with initial signs of shearing out while the web specimen failed due to net-tension failure. It was verified that the strength of the fibre composite laminate with bolted joints can be approximated using the mechanical properties obtained from the coupon tests.

The combination of bolts and epoxy adhesives was determined to be a better connection for the fibre composite beams than bolts alone. The beam with this type of connection at midspan exhibited the same strength and stiffness as the composite beam without joints while connecting with bolts alone resulted in a beam with only 65% of the stiffness of those without joints. The final failure of the composite beams with and without joints was the delamination between the stiff composites of the combined CF and GF and the comparatively soft GF at the top flange. This shows that if the joint is sufficiently designed, the strength and behavior of the composite beams with joints is governed by the compressive strength of the flange.

Further investigation on the behavior of full-size beam with joints not at the midspan should be conducted. Similarly, studies on hybrid FRP beams with bolted connections which will fail at the joints should be carried out in order to fully examine the behavior of this type of connection. The results of these studies could provide a better understanding on the behavior of bolted connection leading to the practical application of fibre composite beams investigated in this study for civil infrastructure.

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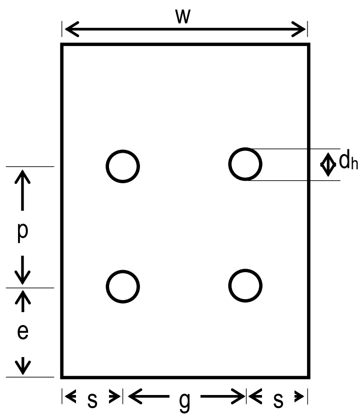
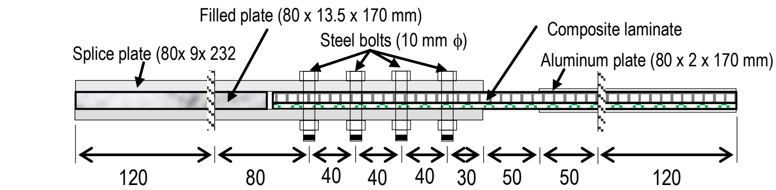
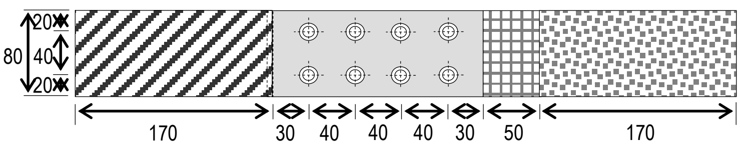


Figure 1. Geometric parameters for multi-bolt joint connection

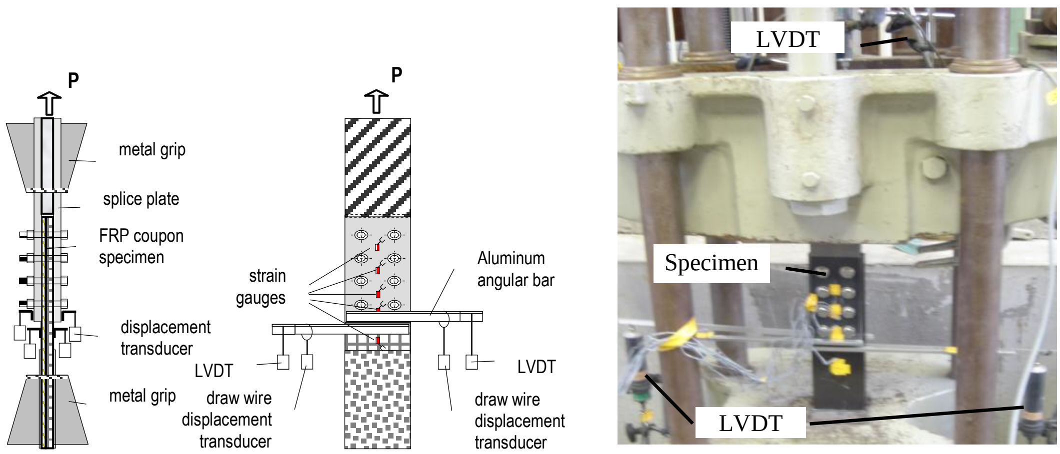


(a) Side view



(b) Top view

Figure 2. Double lap bonded/bolted connections with 8 bolts (all units in mm)



(a) Schematic illustration (b) Actual test set-up

Figure 3. Test set-up for fibre composite laminates with bolted joints

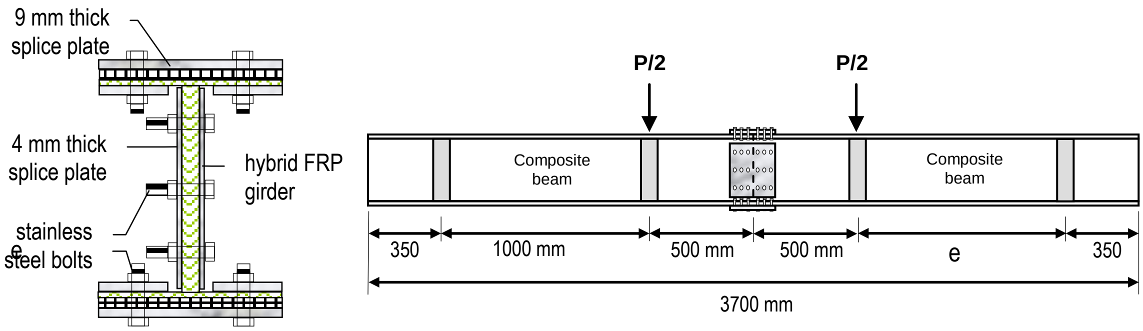


Figure 4. Details of full scale composite beam with bolted joints

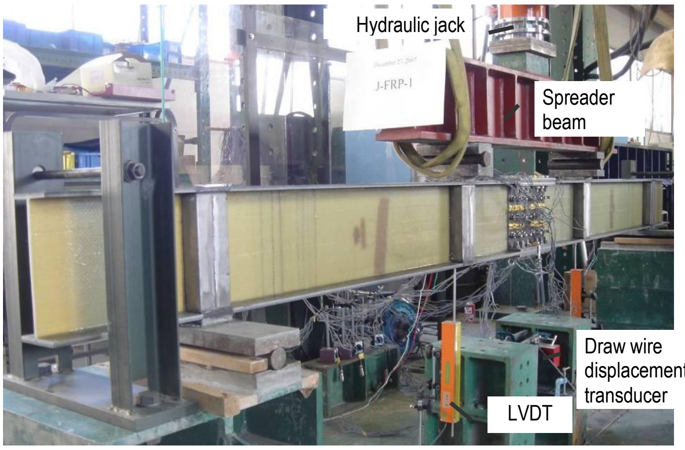


Figure 5. Test set-up and instrumentation of specimen FC2

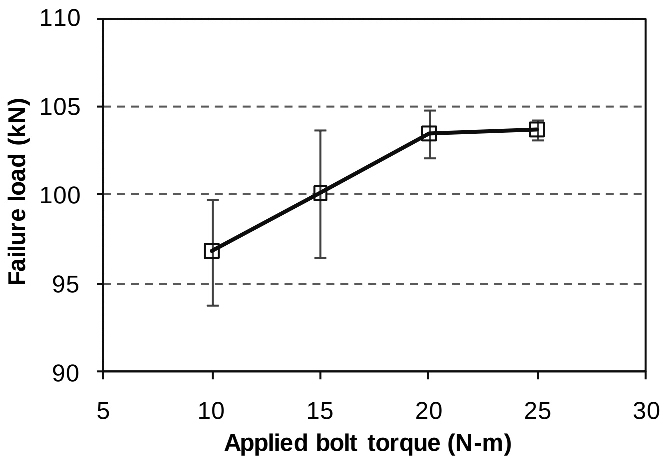


Figure 6. Failure load of specimen 2b at different levels of applied bolt torque

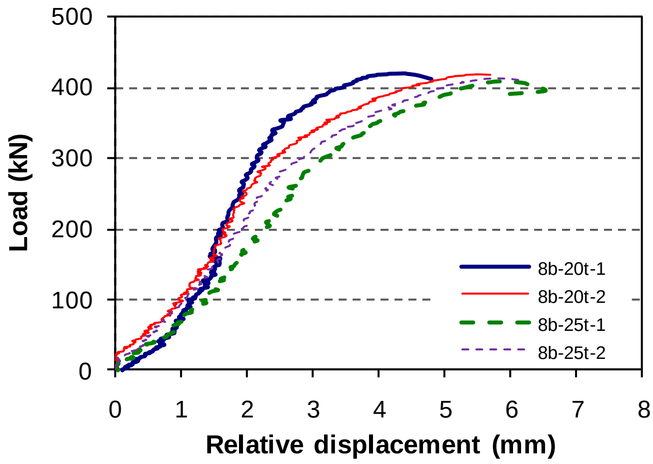


Figure 7. Load-displacement of specimen 8b with 20 and 25 N-m bolt torque

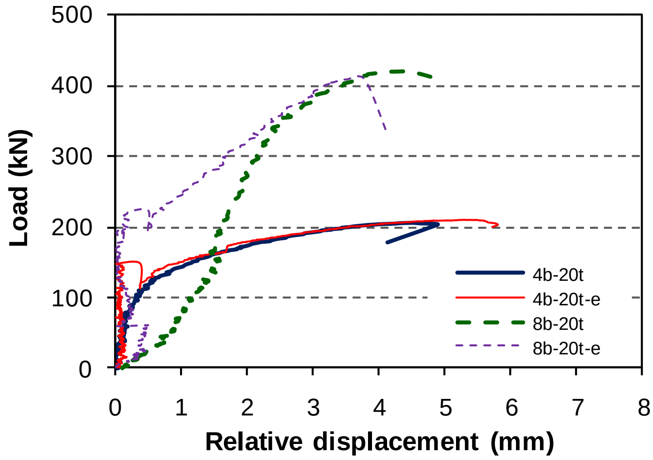


Figure 8. Load-displacement of flange bolted joints with and without epoxy

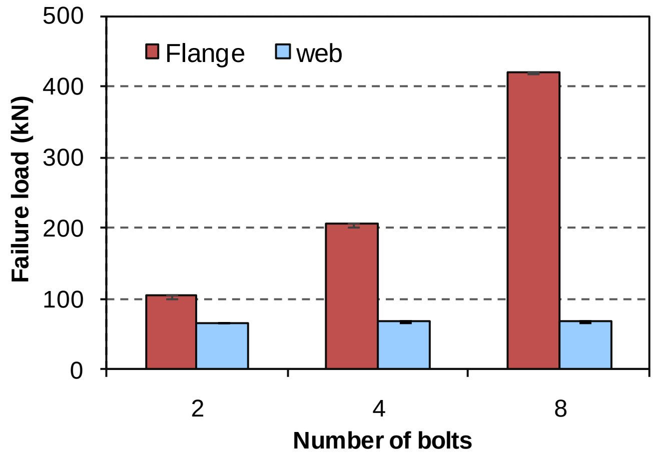


Figure 9. Failure load composite laminates with different number of bolts

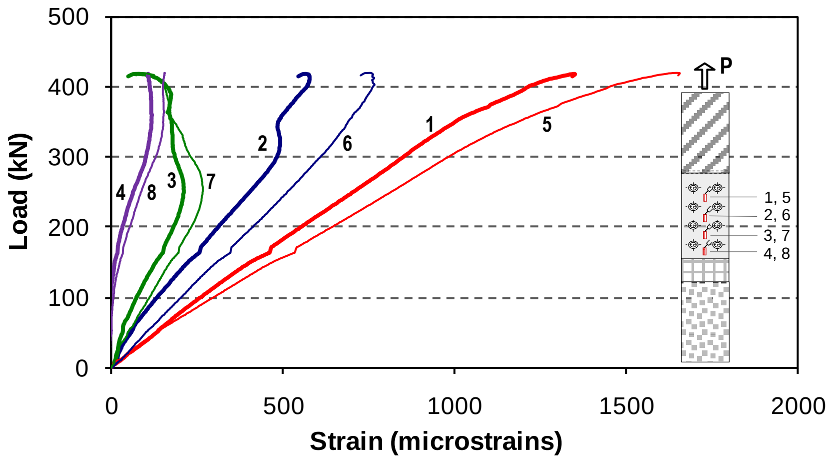


Figure 10. Load-strain relationship of splice plate for 4-column bolted joints

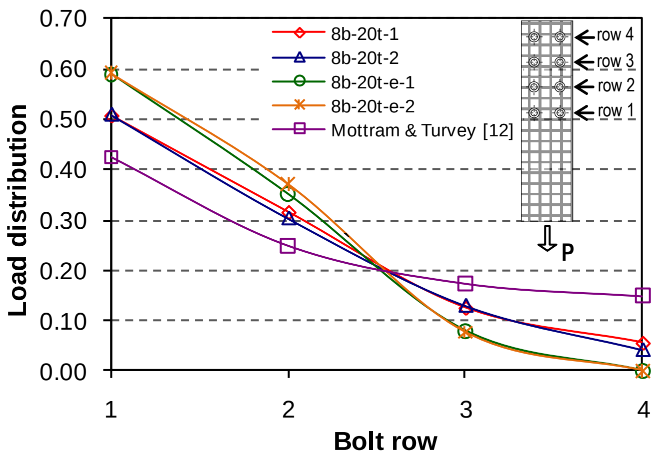
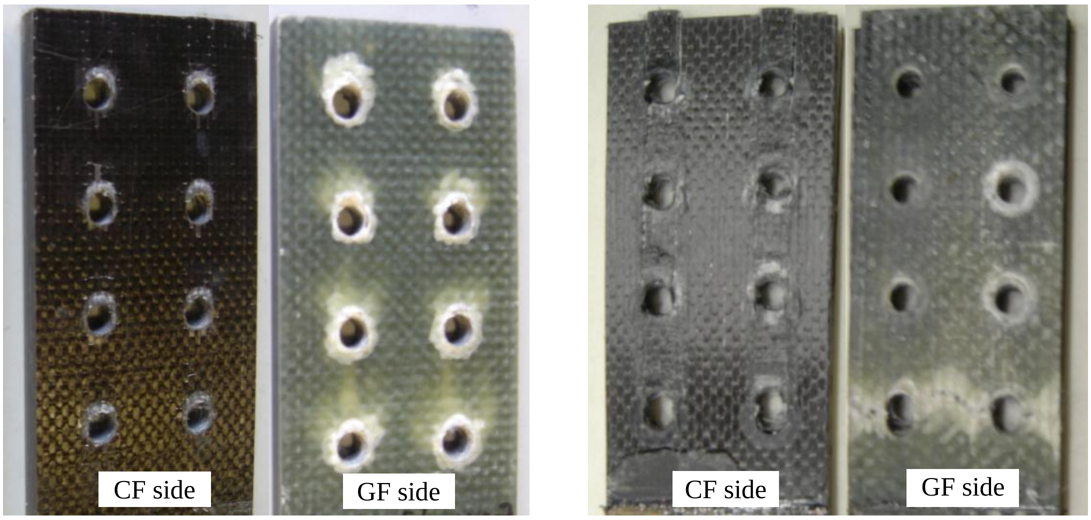


Figure 11. Distribution of load in the 4-column bolted joints



(a) 8b-20t (b) 8b-20t-e

Figure 12. Failure of the flange specimen with bolted joints

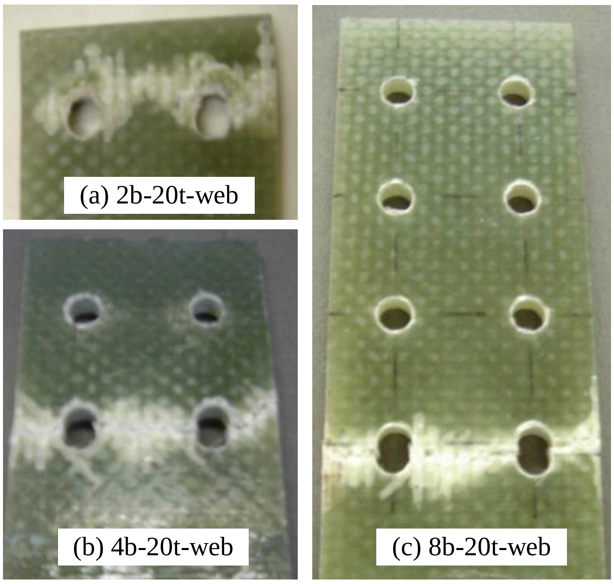


Figure 13. Failure of the web specimens with bolted joints

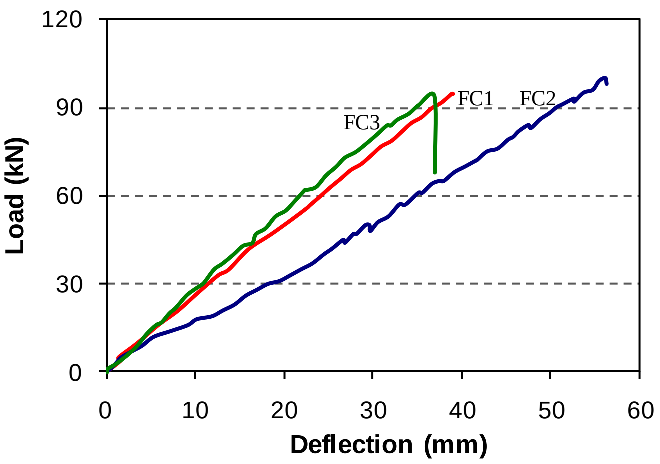


Figure 14. Load and midspan deflection of fibre composite beam with and without joints

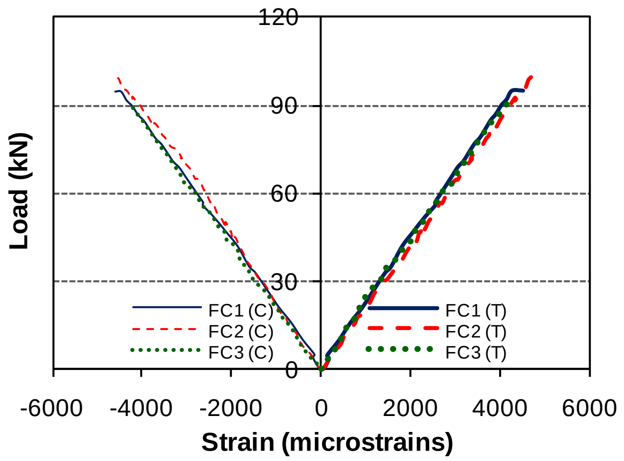
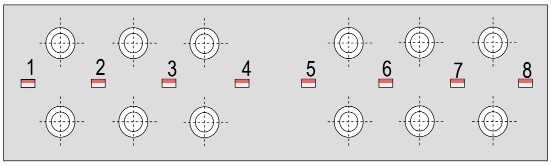
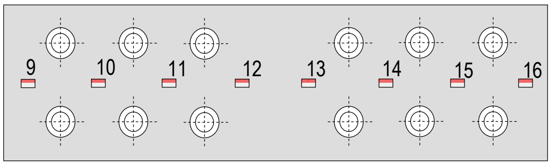


Figure 15. Load and strain relationship of composite beam with and without joints

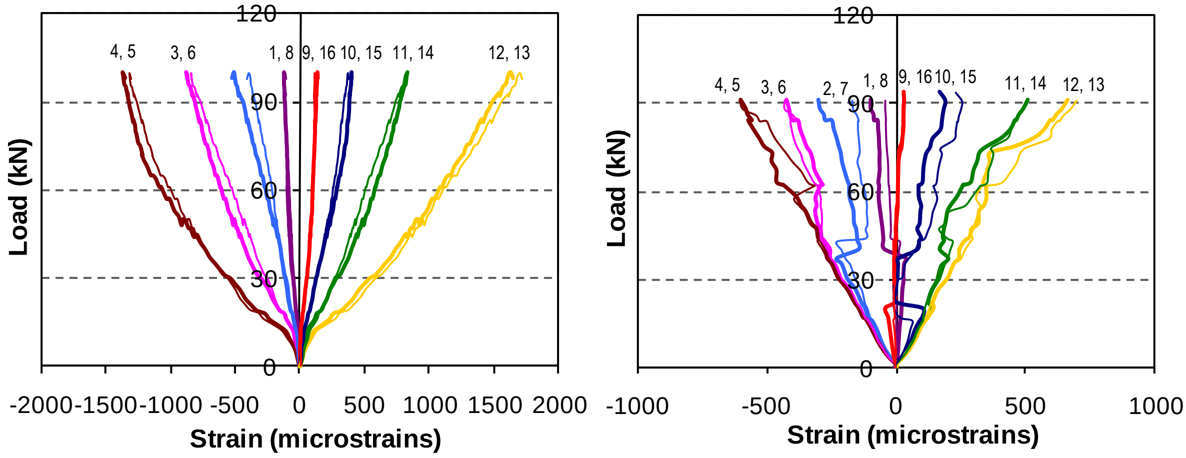


(a) Top flange



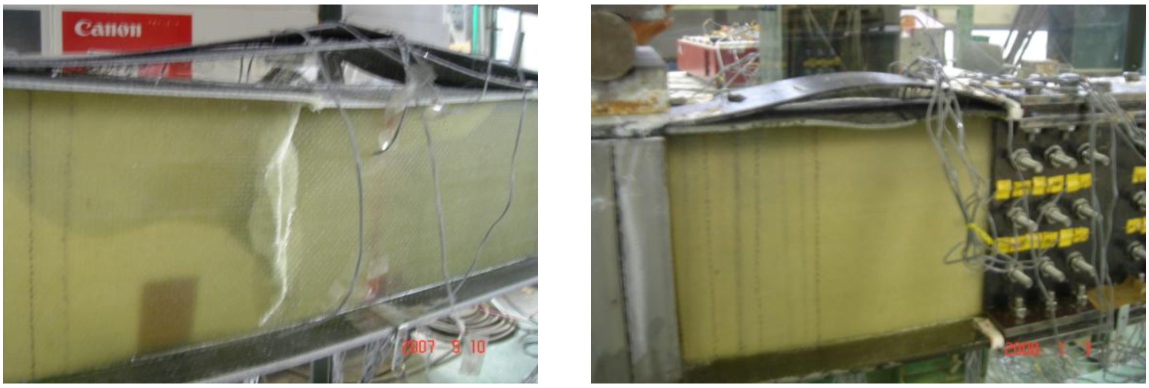
(b) Bottom flange

Figure 16. Location of strain gauges in splice plates at the top and bottom flanges



(a) FC 2 (b) FC3

Figure 17. Load and strain relationship of splice plates at the top and bottom flanges



(a) Beam FC 1 (b) Beam FC 3

Figure 18. Failure mode of full scale composite beams with mechanical joints

Table 1. Effective mechanical properties of composite laminates in the longitudinal direction

Parameters	Tension		Compression	
	Flange	Web	Flange	Web
Modulus, GPa	50.67	15.30	48.35	19.78
Poisson's ratio	0.23	0.27	0.26	0.29
Failure stress, MPa	884.11	155.53	367.17	263.21
Failure strain, %	1.40	1.40	0.40	1.00

Table 2. Description of specimen for coupon test of bolted joints

Specimen name	Number of specimens	Number of bolts	Applied bolt torque (N-m)	Epoxy adhesives
2b-10t	3	2	10	without epoxy
2b-15t	5	2	15	without epoxy
2b-20t	5	2	20	without epoxy
2b-25t	4	2	25	without epoxy
4b-20t	2	4	20	without epoxy
8b-20t	2	8	20	without epoxy
8b-25t	2	8	25	without epoxy
4b-20t-e	2	4	20	with epoxy
8b-20t-e	2	8	20	with epoxy
2b-20t-web	2	2	20	without epoxy
4b-20t-web	2	4	20	without epoxy
8b-20t-web	2	8	20	without epoxy

Table 3. Description of specimens for test of full scale beams with bolted joints

Specimen	Description
FC1	Fibre composite beam tested without mechanical joints
FC2	Fibre composite beam with bolted joints
FC3	Fibre composite beam with bolted and epoxy bonded joints

Table 4. Predicted and actual failure load of composite laminates with bolted joints

Specimen name	Failure load, kN			
	Actual	P_b	P_t	P_v
2b-20t	103.5	96.3	818.8	109.5
4b-20t	205.2	187.2	816.4	219.1
8b-20t	419.2	386.5	818.2	438.3
2b-20t-web	66.61	86.2	73.2	109.5
4b-20t-web	68.29	169.4	76.2	219.1
8b-20t-web	68.36	331.1	76.5	438.3