BONDED SLEEVE CONNECTIONS FOR JOINING TUBULAR GFRP BEAM TO STEEL MEMBER: NUMERICAL INVESTIGATION WITH EXPERIMENTAL VALIDATION

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ABSTRACT

This paper investigates an innovative bonded sleeve connection for joining tubular GFRP and steel members. Experimental results focused on mechanical responses of beam-to-column specimens using bonded sleeve connections and conventional steel angle connections are used to set the benchmark for detailed finite element (FE) modelling. In the detailed FE analysis, bolt geometry including head, shank and washer were accurately modelled. Paired contact elements were used for simulating the contact and slip behaviour between bolt shanks and holes, washers and steel or GFRP. The pretension force in the bolts was also taken into account by implementing pretension elements. The FE models developed were first validated against the experimental results in terms of failure mode, moment–rotation curves and strain responses. Parametric studies were then undertaken to investigate the structural behaviour of the bonded sleeve connections considering the effects of major design parameters such as endplate thickness, bonding length, number of bolts, etc. It was found that the endplate thickness dominates the initial stiffness and the elastic moment capacity of the bonded sleeve

connection and the presence of central blind bolts improves the elastic moment capacity of the bonded sleeve connection.

KEYWORDS: Fibre-reinforced composite; Pultrusion; Beam column connection; Bonded sleeve connection; Detailed modelling

1. INTRODUCTION

Glass-fibre-reinforced polymer (GFRP) profiles have been increasingly used in civil applications due to their high-strength to low-weight ratio, low maintenance costs, excellent corrosion resistance, and low energy consumption during manufacturing process [1]. GFRP profiles have not been often employed in frame and building applications as there is lack of good connection systems between GFRP beams and columns. Pioneering research has revealed the problems of simply mimicking steel beam-to-column connection details on GFRP profile [2], such as the delamination of GFRP connection elements, and separation between web and flange of GFRP profiles. These challenges were all unique to GFRP materials. Therefore numerous studies have focused on developing better connection systems for GFRP structures. A comparative investigation on the behaviour of connections using GFRP I-shaped profiles and GFRP tubular sections as beams and columns is conducted by Smith et al. [3]. With the similar strong axis bending properties and same connecting elements, the merits of using pultruded close sections (e.g. tubular sections) over pultruded open sections (e.g. I-shaped sections) were demonstrated, with considerable improvement in connection stiffness and strength. This is because tubular sections generally have improved torsional rigidity and improved weak axis strength and stiffness over open sections. The effects of GFRP connecting elements and steel connecting elements used for pultruded I-shaped profiles has been also studied by Smith et al. [4]. The results showed that both connection strength and stiffness were increased when using steel connecting elements. An

innovative cuff connection concept was further proposed by Smith et al. [4], which integrates connection design into a single monolithic connection element and utilizes the entire column section as a part of connection system and avoids bolts in GFRP beam. Such a cuff connection was fabricated later on using vacuum assisted resin transfer moulding by Singameshthi et al. [5]. It was found that the cuff connection using purely adhesive bonding was stiffer and strong. All above studies highlighted the benefits of using tubular members, steel connecting components and cuff geometry when joining GFRP profiles.

For modelling the connection performance of GFRP structures, many studies have focused on simple versions of plate-to-plate connections, e.g. double-lap or single-lap connections, and limited results have been reported for member connections such as beam-to-column connections. Early work was done by Bank et al. [6] who conducted FE analysis of several connection configurations for I-shape profiles including angle connection (flange or web cleats), gusset plate connection and wrapped angle connection. Modelling results for the initial moment–rotation behaviour of those tested connection configurations have been obtained but with discrepancies from the experimental results. Numerical analyses of angle connections for I-shaped GFRP profiles have been also performed by Harte and McCann [7], where all profiles were simulated via two-dimensional (2D) solid plane stress elements using ANSYS software package. Contacts between different components were modelled via applying a spring element with assigned stiffness between nodes along the contact surface. Two methods were considered for modelling bolts. The first approach was to use 2-node link elements to represent the positions of the bolt head and nut. The second approach was to use quadrilateral plane stress elements to represent the bolt shank. The pretension of the bolts was modelled via reducing their temperature. Reasonable results were obtained for the initial stiffness of the flange cleat connections (when the plane elements was used for simulating bolts), but not for combined flange and web cleat connections.

Three-dimensional (3D) FE modelling on a series of beam-to-column connections was developed by Smith et al. [8] using ABAQUS. 3D 8-node shell elements were used to represent GFRP beams and columns which were connected via node coupling along the interface. Similar 3D FE modelling approaches were used by Singamsethi et al. [5] to predict the connection behaviour of proposed composite cuff connections. In that work, the composite cuff and GFRP beams and columns were considered to be perfectly bonded using the adhesive (modelled via node coupling method again). Such modelling approaches commonly presented linear elastic responses of the connection and thus were unable to track material damage initiations of GFRP profiles. Another FE study was performed by Carrion et al. [9] on the composite cuff connections similar to [5], but taking into account the material failure of GFRP profiles. In their modelling approach, to cope with the difficulty of selecting the reference surfaces (i.e. contact surfaces) when using shell elements, 20-node quadratic solid elements were used to model tubular GFRP profiles. Material damage of GFRP members was indicated by employing Tsai-Wu failure criterion [10]. The resulting failure region matched well with the observed material damage in the tests. However, no bolts were used in the composite cuff connection investigated, as the composite cuff and GFRP beams and columns were connected via adhesive bonding. Therefore, application of this node coupling approach might not characterise the interaction of bolted joints at the connected locations.

On the other hand, as bolts are commonly used in steel connections, published results from the modelling of steel bolted endplate connections may provide valuable information. Among the considerable FE modelling work on bolted endplate connections, the study by Shi et al. [11] using ANSYS software package demonstrated good comparisons and convenient implementation of predicting moment–rotation behaviour, the mode of failure and the load capacity of connection systems. In their modelling approach, 3D 10-node solid elements were

used to represent all components including bolts and nuts; pretension of bolts was considered in the model via applying pretension elements; the contacts between different components were modelled through contact pairs. This modelling approach was successfully applied for predicting the structural responses of the connection systems in GFRP lattice frames [12] and in GFRP space frames [13].

A sleeve connection, where a steel tube is inserted as a sleeve into GFRP profiles, was recently proposed for connections between tubular GFRP and steel members. Prior experimental study on the proposed sleeve connection for joining tubular GFRP and steel showed promising performance [14], with significant improvement in both connection stiffness and moment capacity in comparison with use of steel seated angle connections. However, only limited parameters such as different connection type (angles versus sleeve connector) with predetermined geometries were examined. Experimental studies become costly and time-consuming if parametric study is required. Modelling techniques, on the other hand, are preferable for developing full understanding of the effects of major design parameters on overall structural responses. Furthermore, from the above review of modelling techniques, it can be concluded that 3D detailed modelling should be developed in order to take into account elements such as bolts and nuts. It also becomes possible to model in detail the bolt interaction with other components, contact and slip between different components (such as shanks and holes), and pretension forces in bolts. Tsai-Wu failure criterion is a useful option for indicating possible damage of GFRP members.

This paper therefore presents a detailed numerical investigation of the proposed bonded sleeve connection for joining tubular GFRP and steel members, with consideration of the aforementioned merits. The modelling approach developed was further validated by experimental results introduced in [14], in terms of moment–rotation response, failure modes and local strain responses. With the validated modelling approach, a parametric study was

then performed to investigate design parameters including endplate thickness, bonding length, number of bolts, and the presence of central bolts for connecting the centre of the steel endplate to the flange of the steel column. The effects on the overall performance of the proposed bonded sleeve connection were thus clarified.

2. EXPERIMENTAL SUMMARY

The mechanical behaviour of bonded sleeve connections for joining tubular GFRP and steel members has been experimentally examined through four specimens with comparison to conventional steel angle connections [14]. Fig. 1 shows the details for the bonded sleeve specimens and the steel angle specimens. The GFRP beam was a square hollow section with dimensions of $102 \times 102 \times 9.5$ mm (width $\times$ depth $\times$ thickness), and the steel column had an I-shape section with dimensions of $158 \times 153 \times 9.4 \times 6.6$ mm (width $\times$ depth $\times$ flange thickness $\times$ web thickness). The sleeve connector was made by welding a 175 mm-long cold formed steel tube of $80 \times 80 \times 10$ mm (width $\times$ depth $\times$ thickness) with a 10 mm-thick steel endplate. The steel tube was inserted into the GFRP beam and they were bonded using epoxy adhesive (Araldite 420), thereby achieving a bond length of 160 mm and allowing a 15 mm gap for the welding. The steel endplate was connected to the steel column using M12 steel high-tensile (Class 8.8) go-through bolts and four M8 blind bolts (BB) as shown in Fig. 1a. In the angle specimens, the GFRP beam and the steel column were connected by two steel angles with dimensions of $150 \times 90 \times 10$ mm (width $\times$ depth $\times$ thickness). The two angles were connected via the same M12 go-through bolts as in the bonded sleeve connections (Fig. 1b).

Two beam lengths (600 and 1700 mm) were adopted to enforce the shear and bending dominant loading conditions. So a total of four beam-to-column specimens have been tested. The specimens are referred to as “S” for shear dominant loading or “B” for bending dominant

loading; the second part of the specimen name describes the connection method, either “A” for steel angle connections or “B” for bonded sleeve connections.

All specimens were tested in a cantilever set-up (see Fig. 2) where the steel column was fixed on the ground while a displacement-controlled loading (achieved by Instron actuator with 250 kN capacity) was applied at the end of the GFRP beam. To accommodate the large rotations expected in the connections, a loading mechanism was developed to ensure free rotation at the end of the GFRP beam. The static test of each specimen was stopped until extensive damage to the connection was observed or until the ultimate stretch (200 mm) of the load cell was reached.

3. DETAILED FE MODELLING

The FE package ANSYS was employed to model the bonded sleeve specimens and steel angle specimens in detail. ANSYS parametric design language (APDL) tools were adopted [15] for the subsequent parametric study.

3.1 Material Properties

Three different materials were used, GFRP, steel and adhesive. Table 1 summarises the material properties used in the modelling. To represent the elastic-plastic behaviour of the steel components a bilinear model was applied, considering a linear isotropic hardening stage after the yield stress was reached. The tangent slope (E_t) of the linear hardening stage was assumed to be 2% of the corresponding Young’s modulus [11]. The Young’s modulus (E_s), Poisson’s ratio (ν_s), and yielding strength (f_y) of the steel tube, steel endplate and steel column were determined through coupon tests according to ASTM E-8/E-8M [16]. The properties of the steel go-through bolts and blind bolts were adopted from references [17]. Young’s modulus (E_a) of Araldite 420 epoxy is 1.9 GPa and Poisson ratio (ν_a) is 0.3 according to [18].

Its tensile strength is found to be 28.6 MPa and shear strength is 25 MPa according to the test results reported by Fawzia et al. [19]. In the FE model, Araldite 420 epoxy was considered as an elastic isotropic material where its E_a and ν_a were the inputs. The adhesive layer was defined with a thickness of 1.5 mm between GFRP beam and steel tube.

GFRP was assumed to be transversely isotropic in the study. For such materials, only five independent constants were required as input [20], i.e. Young's modulus (E_1, E_2), shear modulus (G_{12}) and Poisson's ratio (ν_{12}, ν_{23}) where '1' represents the pultrusion direction, '2' represents the in-plane transverse direction and '3' represents the through-thickness direction. In this study, E_1 was determined through tensile coupon tests according to ASTM D-3039 [21]. The other four required constants were estimated based on the properties of constituents and the fibre volume fraction (V_f). V_f was tested and determined as 46.7% according to ASTM D-3171 [22] as the density of E-glass fibres is 2.57 g/cm³. The constituent properties, matrix (polyester) and fibre (E-glass fibre) were taken as typical values according to [23, 24]. As such, ν_{12} could be determined using micromechanics relations [9], E_2, G_{12} were determined through the Halpin-Tsai method [25] and ν_{23} was estimated according to [26]. The resulting values for the GFRP properties are presented in Table 1.

3.2 Failure Criteria

The yielding of steel is governed by Von Mises yield criterion [27], i.e. the steel is deemed to yield when the Von Mises stress reaches its yield strength. In the FE modelling, the stress state ratio (R_Y) was used as the ratio of Von Mises stress to the yield strength. For the assessment of the material failure of GFRP profiles, Tsai-Wu failure criteria was adopted in the form of the inverse of Tsai-Wu strength ratio index (I_F) and failure occurred for the GFRP material if it was greater than 1. Since the GFRP material is considered to be transversely isotropic, I_F was then dependent on non-zero strengths including its tensile strength in

pultrusion direction, its transverse tensile and compressive strength as well as its interlamimar shear strength. The tensile strength in the pultrusion direction was 306.5 MPa as per the coupon test results according to ASTM D-3039 [21]. The compressive strength in the pultrusion direction was determined as 277.2 MPa through short column compression tests in [28]. The transverse tensile strength was taken as 44 MPa according to the Eurocomp manual [25] based on materials with similar constituent and fibre architecture. Its transverse compressive strength was adopted as 110 MPa as a conservative estimation, considering the transverse compressive strength of commercially produced pultruded E-glass/polyester profiles ranging from 110 to 140 MPa suggested in [24]. Interlaminar shear strength was determined through short-beam tests in [14] as 26.7 MPa according to ASTM D-2344 [29].

3.3 Model Set-up

The components of the specimens, including GFRP and steel members, sleeve connector, steel angle (with the root radius), steel go-through bolts, steel blind bolts and adhesive layer, were established first according to their geometries and then meshed using solid elements SOLID45 (see Fig. 3a for bonded sleeve specimens and Fig. 3b for angle specimens). SOLID45 is a 3D 8-node solid element with three degrees of freedom (DOFs) per node and allows for stress stiffening, large deflection and large strain capabilities [30]. The bolt geometry including bolt head, shank and washer was also meshed using SOLID45. To achieve accuracy with less computational processing time, partition and mapped mesh techniques were used (see Fig. 3c). The meshing size in the connection zone was controlled to be no more than 5 mm, while the meshing size away from the connection zone was around 10 to 20 mm.

Previous studies [5, 9] have evidenced that the node coupling method can effectively simulate the adhesive bonding between different components. As illustrated in Fig. 4a, nodes

at the outer face of the steel tube and those at the inner face of the adhesive layer, and nodes at the outer face of the adhesive layer and those at the inner face of the GFRP Beam shared the same location. The DOFs of these coincident nodes were coupled in the x, y and z directions. The contact/slip behaviour between shanks and holes, washers and endplates/angles, endplates/angles and column were modelled via surface-to-surface contact elements with predetermined friction coefficients, i.e. CONTA174 and TARGA170. The former was a 4-node surface element and the latter was an 8-node surface element with extra midnodes. The friction coefficient between GFRP and steel was 0.25 and the coefficient between steel components was 0.44 [11, 31]. CONTA174 elements were located as the surface of solid elements and had the same geometric characteristics as the solid element with which they were in contact. They overlay the solid elements describing the boundary of a deformable body and were potentially in contact with TARGA170. Such contact occurred when the surface of the CONTA174 element penetrated one of the target elements TARGA170. Fig. 4b illustrates how contact pairs were created between a hole in the steel column and the bolt shank, which was done by selecting the inner face of the hole to be target surface and selecting the outer face of the bolt shank to be the contact surface. In addition, the pretension force of a bolt was taken into account in the detailed modelling approach. This function technically defined a meshed bolt into two parts and generated the pretension elements (PSMESH) between these two parts (see Fig. 4c). The magnitude of the pretension force could be specified according to the torque applied in this study [14], i.e. 100 N.m for steel-to-steel components and 30 N.m when GFRP was involved.

All the nodes at the steel base were restricted in all directions to represent the fixed boundary condition. There were two load steps in the FE analysis. The first load step was to apply the pretension forces to the bolts. The second load step was to apply the vertical displacement at the beam end to start the static loading. The Newton-Raphson iterative

method with a force convergence criterion of 0.01 was used in the solution process.

4. VERIFICATION OF MODELLING RESULTS

To validate the modelling approach developed, comparisons were made against experimental results in terms of the failure modes, the moment–rotation behaviour and the local strain responses.

In the tests, both bonded sleeve specimens (SB and BB) failed by extensive yielding of the steel endplates, which caused further bending of the steel go-through bolts. This is well captured in the FE results of deformed shapes as shown in Fig. 5. The location on the endplate of the initiation of yielding could be identified by checking the stress state ratio (R_Y). As indicated by Fig. 6a and Fig. 6b, yielding of endplate first occurred near the junction at the top flange of the steel tube with a load of 8.82 kN.m for SB and 8.98 kN.m for BB. Those load levels were therefore considered as the elastic moment capacity of the bonded sleeve specimens, indicating the moment at the yielding initiation. The modelling results of elastic moment capacity compared well (about 5% difference) to the measured value in [14] (8.3 kN.m for SB and 8.5 kN.m for BB). In addition, no damage of the GFRP beam was observed in either of the bonded sleeve specimens, indicated by Tsai-Wu failure criterion (as $I_F < 1$ for all regions on the GFRP member in SB and BB at the experimental ultimate loads). However, certain regions near the bolt holes of the steel angle specimens SA and BA were highlighted in yellow and red, corresponding to I_F values greater than 1. This result indicates that damage occurred to GFRP materials there. These damage regions compared well with those observed from experiments (see Fig. 7).

The experimental moment–rotation curves are compared with modelling results in Fig. 8, where overall satisfactory agreement is found for all specimens. For SB as shown in Fig. 8a, the moment linearly increased with the rotation angle until nonlinearity occurred at about

8.3 kN.m due to yielding of the steel endplate. Although the top rows of blind bolts failed in testing for the BB specimen (marked on the experimental curve in Fig. 8b), the load capacity of BB showed only a slight decrease (2.14% of the applied moment). Failure of blind bolts was not simulated in the modelling as such a slight drop in the applied moment was not present in the modelling results. The experimental results of the initial rotational stiffness for SB and BB were calculated using the initial slopes of the experimental curves as 911 kN.m/rad and 1019.9 kN.m/rad respectively. The values from FE analysis were 996 kN.m/rad for SB specimen (i.e. 8.53% discrepancy) and 1122.3 kN.m/rad for BB specimen (i.e. 9.12% discrepancy).

In the angle specimens SA and BA, the development of connection rotation with applied moment showed three stages during the loading process. After the initial linear stage, the tangent of the moment–rotation curve, i.e. the rotational stiffness, decreased at around 1.5 kN.m for both angle specimens. This was due to the contact and slip between the bolts and bolt holes. After the bolts came into full contact with the bolt holes, the rotational stiffness increased again. It is clear in Fig. 8c and Fig. 8d that such changes in the rotational stiffness of the experimental moment–rotation curves were captured by the FE modelling curves. The drop of load capacity in the experimental curves was due to failure of the GFRP beam in both specimens, and such failure initiation could be indicated by Tsai-Wu failure criterion as discussed previously.

Strain responses measured at key locations from experiments were used to further validate the modelling approach. The locations of interest (considering an indication of steel yielding) were the junction locations between the steel tube and the endplate for the bonded sleeve specimens, and the locations between the wall plate and the bottom plate of the top steel angle for the angle specimens. Reasonable agreement was found for the moment–strain curves obtained from FE analysis and experiments as evidenced in Fig. 9.

5. PARAMETRIC STUDY OF BONDED SLEEVE CONNECTIONS

The validated modelling approach is used in this section to evaluate the proposed bonded sleeve connection with various design parameters, including i) the thickness of the steel endplate; ii) the bonding length between steel tube and GFRP beam; iii) the number of go-through bolts; iv) the presence of blind bolts for connecting the centre of the steel endplate to the flange of the steel column. Such connection details were only applied to specimen BB with the length of 1700 mm, for more realistic bending moment dominant scenarios. Also, the parametric study below was applicable only to the yielding of steel or the material failure of GFRP according to the aforementioned failure criteria. As the steel tube and the GFRP beam were considered to be perfectly bonded (modelled via node coupling method), failure of the adhesive bonding was not considered in this study as no such failure occurred in either SB or BB specimens during experiments.

5.1 Effect of Endplate Thickness

The steel endplate is a part of the sleeve connector that welds to the steel tube (sleeve) and connects to the steel column with bolts. To understand the effect of changing endplate thickness on the overall structural behaviour of the bonded sleeve connection, the other design parameters remained the same as those in the FE model of specimen BB. The thickness values selected in the parametric analysis were 6 mm (Model T6), 8 mm (Model T8), 10 mm (Model T10, the same model as in the experimental validation in Section 4) and 12 mm (Model T12).

The resulting moment–rotation curves of the bonded sleeve connection models with different endplate thicknesses are shown in Fig. 10a. The initial stiffness of the connection (taken as the linear slopes of the moment–rotation curves) was plotted against the endplate

thickness in Fig. 10b, showing the increase of rotational stiffness with endplate thickness. This trend is reasonable because the endplate is under prying effects and a large thickness provides an increased second moment of area for the bonded sleeve connection, which in turn improves its overall stiffness when subjected to such prying effects. More specifically, when compared with Model T6, a 60% increase in rotational stiffness was found when the thickness of the endplate was doubled (Model T12), compared to a 29% or 48% increase in initial stiffness for Model T8 or Model T10 respectively.

All models failed with extensive yielding of endplates and bending of bolts, as shown in Fig. 11, whereas no material damage on GFRP was observed according to Tsai-Wu failure criterion. At the same applied displacement at the beam end (200 mm, for example), more gaps were observed between the endplate and the column with a thinner endplate, as shown in Fig. 11. The yielding initiation in all models were found at the location of the steel endplate near the top flange of the steel tube. The corresponding elastic moment capacities at the yielding initiation were 10.86 kN.m for T12, 8.98 kN.m for T10, 7.42 kN.m for T8 and 6.95 kN.m for T6. An increase of 56% in elastic moment capacity was found in Model T12 compared with Model T6, but only a 7% increase from Model T6 to Model T8.

5.2 Effect of Bonded Sleeve Length

In a bonded sleeve connection, adhesive bonding between the GFRP beam and steel tube provides full composite action between these two components. The length of the steel tube thus determines the bonded sleeve length. The bond length was 160 mm in the FE model for specimen BB (Model L160). In order to investigate the effect of the bonded sleeve length on the overall performance of the connection, this length was selected as 80 mm (Model L80, equal to the outer width of the steel tube) and 240 mm (Model L240, three times the outer width of the steel tube) in the parametric study. The maximum shear stress at the adhesive

layer was about 17 MPa when the elastic moment capacity of Model L80 was achieved. It is understandable, therefore, that a bond length which is too short might cause premature debonding failure between the steel tube and the GFRP, while a length too long would certainly be a waste of material and create difficulties in assembly.

As shown in Fig. 12a, the moment–rotation response of Model L240 is similar to that of Model L160; both presented initial stiffness and elastic moment capacity higher than those of Model L80. It is clear from Fig. 12b that initial rotational stiffness increased with longer bond length, with a 58% increase in initial stiffness from Model L80 to L160 but only 14% increase from Model L160 to L240. The increased initial stiffness was due to the improved second moment area of the composite section of GFRP and steel sections with a longer length, resulting in a stiffer beam end engaged in the connection. The elastic moment capacity of the connection system was found to be similar for bonded sleeve connections with different sleeve lengths (7.77 kN.m for Model L240; 7.73 kN.m for Model L160 and 7.63 kN.m for Model L80), with a 1.31% increase from Model L80 to L160 and a 1.84% increase from Model L160 to Model L240. The reason is that the elastic moment capacity was determined mainly by the yielding of the endplate and its thickness was 10 mm for all the models in this study.

5.3 Effect of Number of Go-through Bolts

The number of go-through bolts connecting the steel endplate to the steel I-shaped beam is another design parameter. Eight steel high-strength go-through bolts were used in four parallel rows (Model N8) in specimen BB (see Fig. 1b). In this parametric analysis, four go-through bolts in two rows (Model N4) and 12 go-through bolts in six rows (Model N12) were comparatively studied. It should be noted that the depth of the steel endplate had to be adjusted according to the steel design requirements for accommodating the corresponding

number of bolts. This resulted in depth of the steel endplate of 183 mm for Model N4 and of 303 mm for Model N12.

It appears in Fig. 13a that moment–rotation responses were scarcely affected by the number of bolt rows for the models with 10 mm endplate and 160 mm bonding length. The initial stiffness of these three models was found to be almost the same (1122 kN.m/rad). The elastic moment capacity of these three models was also found to be similar, at 8.73 kN.m for Model N4 and 8.98 kN.m for both Model N8 and Model N12. This result can be supported by looking at the stress state ratio in each go-through bolt in Fig. 13b. Most loads were carried by the two rows of bolts close to centre of the connection, while the other rows of bolts did not contribute much in Model N8 and Model N12. Thus, adding more rows of bolts with a diameter of 12 mm in this connection detail did not contribute much to the overall stiffness of the connection system. The modelling results showed that the endplates yielded prior to the bending of the first row of bolts (which was close to the top surface of the steel tube) in all three models. Again, the elastic moment capacity was dominated mainly by the thickness of the steel endplates.

5.4 Effect of central blind bolts for connecting endplate

Four blind bolts were applied for connecting the centre of the steel endplate to the flange of steel I section in specimen BB (see Fig. 1a). In order to understand the effects of the blind bolts on the connection performance, a FE model for the bonded sleeve connection without the blind bolts was developed and analysed.

The resulting moment–rotation responses are shown in Fig. 14a, indicating that the presence of blind bolts introduced minor effects on the initial stiffness of the bonded sleeve connection (1123.2 kN.m/rad with blind bolts and 1109.4 kN.m/rad without blind bolts). However, the effect of blind bolts was significant on the elastic moment capacity of the

bonded sleeve connection. The elastic moment capacity (when the endplate started to yield) dropped significantly (from 8.98 kN.m to 3.72 kN.m) if no blind bolts were applied. This is because the blind bolts could provide the endplate with additional constraint to the column section and such constraint could effectively reduce the prying effects of the endplate. This mechanism is clearly illustrated in Fig. 14b, where a much smaller gap is evident in the model with blind bolts in comparison to the model without blind bolts at the same applied displacement at the beam end.

6. CONCLUSION

This paper has presented a numerical analysis with experimental validation of the bonded sleeve connection for GFRP beam to steel. A parametric study was conducted to investigate the effects on initial stiffness and elastic moment capacity of major design parameters, including the steel endplate thickness, the bonding length between steel tube and GFRP beam, the number of go-through bolts and the presence of blind bolts at the centre of the endplate. The following conclusions can be drawn:

1) The modelling approach proposed was found to be able to describe the failure mechanism of the yielding of steel endplates and the bending of go-through bolts (taking into account the pretension of bolts) as observed in the experiments. It produces close estimations of the initial stiffness and elastic moment capacity of both bonded sleeve specimens and steel angle specimens. It can describe the contact and slip of bolt shanks and holes, washers and steel or GFRP, and thereby accurately present the change of rotational stiffness due to such effects. It is limited to indicating material failure in the forms of steel yielding and GFRP material damage only.

2) The parametric study clarified the dominant effects of endplate thickness on both initial stiffness and elastic moment capacity of the bonded sleeve connection. A 60% increase

in stiffness and a 56 % increase in elastic moment capacity was found when the endplate thickness was increased from 6 mm to 12 mm. This was because the endplate was under prying effects and a larger thickness provided an increased second moment of area for the bonded sleeve connection.

3) Longer bonded sleeve length resulted in an improvement in initial stiffness of the bonded sleeve connection, with a 58% increase if the length of the bonded sleeve was increased from 80 mm to 160 mm. This improvement became limited (only 14%) when the bonding length was further increased to 240 mm. The increase in the bonded sleeve length showed no effects on the elastic moment capacity of the bonded sleeve connection.

4) An increase of the number of go-through bolts from 4 to 12 bolts had little effect on either the initial stiffness or the elastic moment capacity for the configuration details of the bonded sleeve connection in this study. This was because the use of 4 go-through bolts in two parallel rows appeared sufficient to connect the steel endplate and steel in the bonded sleeve connection, and most load was carried by the two rows of bolts close to centre of the connection.

5) The effect of central blind bolts on the initial stiffness of the bonded sleeve connection was minor. However, their effects on the elastic moment capacity of the bonded sleeve connections were considerable. This is because the blind bolts were able to provide the endplate with additional constraint to the steel member, which could effectively reduce the prying effects of the endplate.

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TABLES

Table 1: Material properties used in FE modelling

Components	Young's modulus (GPa)	Poisson's ratio	Yielding strength (MPa)	Tangent slope (MPa)	Shear modulus (GPa)
Steel column	216.4	0.33	361.8	4328	-
Steel endplate	218.8	0.3	332.4	4376	-
Steel tube	216.9	0.3	326.2	4338	-
Steel angle	220.7	0.28	349.7	4413.6	-
Steel go-through bolt	235	0.42	1043	4700	-
Steel blind bolt	200	0.42	640	4000	-
Epoxy adhesive	1.9	0.3	-	-	-
GFRP beam	30.2 (E_1) 11.9 (E_2) 11.9 (E_3)	0.29 (ν_{12}) 0.41 (ν_{23}) 0.29 (ν_{13})	-	-	3.65 (G_{12}) 4.22 (G_{23}) 3.65 (G_{13})

FIGURES

Fig. 1: Experimental specimens with (a) bonded sleeve connection (L of 600 mm for SB, of 1700 mm for BB); (b) steel angle connection (L of 600 mm for SA, of 1700 mm for BA)

Fig. 2: Set-up for experimental specimens

Fig. 3: Detailed FE model after meshing for (a) angle specimens (SA and BA); (b) bonded sleeve specimens (SB and BB); (c) illustration of mapped meshes of a steel endplate.

Fig. 4: Illustration of (a) node coupling method for bonding; (b) creating contact pairs (TARGA170 and CONTA174) between bolt shank and bolt hole; (c) creating pretension element in a bolt.

Fig. 5: Comparison of failure modes between experimental observations and FE modelling for (a) SB; (b) BB (green arrows indicate yielding of steel endplate; red arrows indicate bending of steel go-through bolts)

Fig. 6: Contour plot of stress state ratio (R_{γ}) on sleeve connectors for (a) SB at load level 8.82 kN.m; (b) BB at load level of 8.98 kN.m

Fig. 7: Contour plots of inverse of Tsai-Wu strength ratio index (IF) for bolt hole regions indicating material failure of GFRP in (a) SA and (b) BA, with comparison to observed GFRP material failure from experiments

Fig. 8: Comparison of moment–rotation curves between experimental and FE results for (a) SB; (b) BB; (c) SA; and (d) BA.

Fig. 9: Comparison of moment–strain curves between experimental and FE results for (a) SB; (b) BB; (c) SA; and (d) BA.

Fig. 10: (a) Moment-rotation curve and (b) initial rotational stiffness for bonded sleeve connection models with different endplate thicknesses

Fig. 11: Deformed shapes of bonded sleeve connections with 160 mm bonding length and eight go-through bolts and different endplate thicknesses for (a) Model T12; (b) Model T10; (c) Model T8; and (d) Model T6

Fig. 12: Effect of bonded sleeve length on (a) moment–rotation curve and (b) initial rotational stiffness for bonded sleeve connections with 10 mm endplate thickness and eight go-through bolts

Fig. 13: Effect of different number of bolts on (a) moment–rotation curves and (b) stress state ratio of 4 bolts at rotation of 0.04 rad, for bonded sleeve connections with 10 mm endplate and 160 mm bonding length

Fig. 14: Effect of presence of blind bolts on a) moment–rotation curve and (b) deformed shape for bonded sleeve connection with 10 mm endplate thickness and 160 mm bonding length and eight go-through bolts