Composite Structures 157 (2016) 51–61

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Bonded sleeve connections for joining tubular GFRP beam to steel member: Numerical investigation with experimental validation

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ARTICLE INFO

Article history:
Received 29 March 2016
Revised 15 June 2016
Accepted 10 August 2016
Available online 10 August 2016

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

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.

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

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http://dx.doi.org/10.1016/j.compstruct.2016.08.016
0263-8223/

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 × depth × thickness), and the steel column had an I-shape section with dimensions of $158 \times 153 \times 9.4 \times 6.6$ mm (width × depth × flange thickness × 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 × depth × 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 × depth × 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.