Tension analysis of bolted sleeve connection between pultruded GFRP tube and steel member considering adhesion

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Abstract. Pultruded Glass fibre reinforced polymer (GFRP)-steel hybrid structures have become increasingly popular in civil infrastructures. However, the connection between GFRP and steel members is one of the key issues limiting the development of the innovative structure. This paper presents tensile capacity of bolted sleeve connection between GFRP and steel members. With consideration of the pre-loaded bolt effect, the appropriate fastening torque was proposed by finite element investigation. The adhesive effect was also considered and investigated by cohesive zone method. The bolted sleeve connection provides a good solution for the tubular and large-span structures.

1. Introduction

Pultruded Glass fibre reinforced polymer profile, which has the advantage of high strength to weight ratio, good durability performance, ease of installation and lower life-cycle cost, has been attracting an increasing interest in the field of civil engineering. Hybrid steel and GFRP structure is a common practice in bridges [1,2], space frame [3] and other infrastructure [4]. For each application, connections are inevitable to make the two kinds of materials action together.

The connection between steel and GFRP could be classified as adhesive and mechanical joints. Keller conducted a series of static and fatigue experiments on adhesive connections finding that composite action between FRP bridge decks and steel girders can be expected and no damage was observed in the bond during fatigue tests [5-6]. The mechanical joints can be various, including clamps, bolts and shear studs, among which bolts are most common in FRP and steel connection. Du Peloux [3] made ultimate tests on GFRP tubes connected by pinned steel sleeve when design the gridshell of Ephemeral Cathedral in Paris as shown in Figure 1. Chakerlou found that with the clamping force increasing, the fatigue strength of FRP plates increase, but the fatigue life only improved at a low stress level [7]. Davalos investigated a non-grouted sleeve-type connection for stiffness, strength, fatigue resistance, and degree of composite action [8]. Satasivam used a novel blind bolt on steel-FRP composite beam systems and studied the effect of bolt rows and pultrusion orientation on the joints’ stiffness and capacity [9]. Dakhel studied energy absorption and load carrying capacity of steel-FRP connections in shear wall systems with various factors, for example bolt numbers [10]. Shahryariifard proposed a term named lamination cohesion rate [11], which was used to determine the failure mode of steel tubes connection by GFRP sleeve as shown in Figure 2.

In column-beam connection and space frame’s connection, hybrid steel and GFRP structures also have wide applications [12]. Ascione tested GFRP beam-column connection with adhesive [13], which was found that the adhesive beam-column connection presented reliable performance as well as bolted
connection. Shahhosravi [14] carried out fatigue experiment of GFRP laminates with drilled hole, which involved the delamination effect of drilling and presented an evident bending fatigue improvement of drilling hole in lamina. Experimental analysis on octatube steel joint of GFRP footbridge was made and it’s said that the joint’s capacity showed no decrease under 2.1 million fatigue load cycling [15]. Van Wingerde made a comparison between common bolt and bolt with epoxy under different fatigue ratio [16].

To the author’s knowledge, the understanding about tensile behaviour of the pultruded GFRP tubular member and its connection are limited. Especially, GFRP tubular member with hole easily took place stress concentration on the edge of the pre-loaded bolt’s hole. Encompassing the adhesive layer in the bolted sleeve and the pre-loaded bolt, finite element (FE) models were built and analysed to investigate the tensile performance of the connection.

2. Bolted sleeve joining GFRP tube and steel member
In tubular structures, pultruded GFRP tube could make full use of its light-weight material potential for a tendon as shown in Figure 1. In Figure 3, the GFRP tube’s end was fastened by bolt and adhesion, and the steel sleeve was welded to the gusset plate connecting to the chord. In space frames and bridges, the main skeleton made up of pultruded GFRP could be extended by the configuration as shown in Figure 4 [17]. After the tube was inserted in the sleeve, bolt was fastened to the prescribed torque with the existing epoxy layer on the tube. The GFRP tube has a relative low compressive strength than steel. The pre-loaded bolt yields stress concentration on the edge of the GFRP tube’s hole. Next, a connection was built by FE. The radius of the sleeve and GFRP tube was 36mm and 30mm respectively, the thickness of GFRP tube was 6mm the same as that of steel sleeve, the bolt was M12 in accordance with Chinese code.
3. FE model of bolted sleeve

The FE software Abaqus was employed to simulate the tensile behavior. GFRP material property was assumed to be anisotropic which required seven input parameters - Young's modulus of roving direction \( E_1 = 26 \text{GPa} \) and transverse direction \( E_2 = 16 \text{GPa} \), shear modulus \( G_{12} = 1.25 \text{GPa}, G_{13} = 1.25 \text{GPa}, G_{23} = 15.8 \text{GPa} \), Poisson’s ratio \( v_{12} = 0.3, v_{23} = 0.3 \). A bilinear material constitution was assumed for steel in which Young modulus and yield stress were defined as \( 2.1 \times 10^5 \text{MPa} \) and \( 345 \text{MPa} \) respectively. Bolt’s material property adopted the same model as steel while the yield strength was \( 1043 \text{MPa} \) [12]. All the models were meshed by reduced integration solid element C3D8r. The contact pairs were divided into two types. One is the standard penalty contact for GFRP tube, sleeve and bolt. The other is adhesive layer. Cohesive zone method (CZM) has been proved to be an efficient way to simulate the adhesive behavior [18]. When implementing CZM, maximum interfacial bond stress or separation needs to be determined. In this paper maximum interfacial bond stress was assumed to be \( 0.05 \text{MPa} \) [19]. The cohesive law was illustrated in Figure 5, in which the adhesive traction degraded as the separation developed. It evolved under the assumption of the fracture energy \( G_c \) of cohesive behavior.

![Figure 5. Adhesive constitution](image)

The bottom surface of the sleeve was fixed as shown in Figure 6. There were two load steps in FE, the first step is bolt fastening and the second is tension. Bolts were designed to be fastened to three kinds of torques in FE, which were 2.4Nm, 4.8Nm and 10 Nm. Pre-tension load was applied by bolt load in the software. FE models are listed in Table 1.

| Specimens | Bolt Number | Bolt’s torque(Nm) |
|-----------|-------------|-------------------|
| BSC1      | 2           | 2.4               |
| BSC2      | 2           | 4.8               |
| BSC3      | 2           | 10.0              |
| BSC4      | 3           | 4.8               |

Table 1. Specimens’ detail
4. Analysis results
All the specimens reached its peak load when the GFRP tube’s bolt hole failed due to compression, and the failure mode of specimens was GFRP tube’s hole bearing failure as shown in Figure 7. Typical load-displacement curves are plotted in Figure 8. The ultimate strength of the sleeve was determined by the number of the bolt as observed from Figure 8, in which the ultimate load of BSC4 with three bolts was much larger than that of specimens BSC2 with two bolts. Adhesion layer didn’t make significant effect since the smooth surface and the limited interfacial stress. With respect to the bolt’s torque, specimens BSC2 hole’s edge compressive stress due to fastening torque was 5.2 MPa, while BSC3’s stress was nearly 11MPa.

5. Conclusions
This paper presented a tension analysis of bolted sleeve joining GFRP tube and steel members. Incorporating the bolt’s pre-tension and adhesion in the numerical simulations, the following conclusions were drawn. The tensile strength of bolted sleeve is governed by the compressive strength of GFRP tube and the number of bolt. Maximum bolt fastening torque of M12 is suggested to set to 4.8N.m. The adhesive layer of the bolted sleeve doesn’t show a substantial effect on the ultimate
tensile strength of the connection. In the future work, the fatigue performance of the bolted sleeve connection between GFRP tube and steel member needs to be further evaluated.

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