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ORIGINAL ARTICLE

A comparative experimental study on blind-bolted beam connections to square steel tubular columns filled with polyurethane foam or concrete

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Abstract

In the last two decades blind-bolted connections have been developed to allow bolting of open section beams (e.g, I-beam) to steel hollow section (SHS) columns where access from all sides of the column is not possible. Filling the tubular column with concrete in the vicinity of the beam-to-column connection has been shown to improve the anchoring mechanism of the blind-bolted connection thereby increasing the strength and stiffness of the connection and reducing the column face deformation, however it adversely affects the joint ductility. This study introduces polyurethane foam filled steel tubular columns in combination with a new anchoring arrangement employing hollo-bolts to develop a novel connection between the SHS columns and open section beams that provides a better combination of stiffness, strength and ductility. To investigate the behaviour of the proposed arrangement, monotonic pull-out tests of blind bolted T-stub connections anchored to foam-filled steel tubular (FFT) and concrete-filled steel tubular (CFT) columns using holloBolts were conducted. Benchmark tests on unfilled SHS columns were also conducted for comparison. The FFT in conjunction with the proposed anchoring mechanism was shown to provide a good stiffness as the CFT columns, and almost similar ductility to that of the unfilled steel tube blind-bolted connection. Hence it is concluded that employing foam instead of concrete as an infill leads to favourable combination of strength and ductility, thus rendering FFT an attractive light alternative to CFT sections when ductility of the joint is an important design consideration.

Keywords

Blind bolted connections; Foam-filled steel tubes (FFT); Concrete-filled steel tubes (CFT); Hollow section face bending; Pull-out tests

1 Introduction

Traditional steelwork frames which comprise of open section profiles such as I-beam or H profile are one of the most commonly used construction techniques. This construction technique has been developed during the last century and steel hollow section (SHS) columns and open section beams (e.g I-beam) are implemented for multi-storey buildings due to their architectural reasons and favourable properties such as high strength-to-weight ratio and torsional stiffness. However, benefit of using this technique has complications due to difficulties of connection between the open section beams and closed form SHS columns.

Fully welded rigid connection is the first solution to connect closed form SHS columns and open section beam. On-site welding has negative effects on the construction programme and achieving the required standard quality is very difficult. Another solution is to weld some fittings to the SHS columns such as fin plates, T-stub and reverse channel in factory to enable the beams for bolted connection to the columns on site. Transportation of pre-manufactured welded columns are very difficult, and it might endanger the quality of the welding [1]. Bolted connection is the most preferred type of connection on site, but the standard dowel bolts are impossible to use for closed form SHS columns as access from inside of the steel hollow column is required to tighten the bolts. To overcome this issue new type of bolts without need of access from inside of SHS column for tightening was investigated and a type of bolt which is called blind-bolt was developed [2-4].

Concrete-filled SHS column [5] was suggested to improve the blind-bolted connection by increasing the strength and stiffness of the connection due to providing anchoring mechanism and reduction in column face deformation [6,7]. However, implementing concrete infill to improve the blind-bolted connection between SHS columns and open section beams may lead to produce connections with

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high rigidity and brittle behaviour. In addition to this issue, concrete infill increases the structure's weight. To date, large number of studies have been carried out on blind-bolted connection between concrete-filled SHS column and open section beam. This study aims to develop a semi-rigid connection between SHS columns and open section beams by introducing polyurethane foam as an infill into SHS columns. To achieve this aim, three experimental tests are carried out on blind-bolted connection between T-stub and polyurethane foam-filled SHS, concrete-filled SHS and unfilled SHS to compare the behaviour of each connection and develop a semi-rigid connection without increasing the structure weight.

2 Experimental study

2.1 Geometric configurations

All employed specimens are comprised of a S355 hot finished square SHS with 200mm width, 200mm height, 750mm length and 6.3mm thickness. Four holes have been embedded at the middle of the square SHS in two rows. They have been positioned with distance of 120mm along the width and 40mm along the length. These holes are considered to insert the blind bolts and position of the blind bolts on the SHS is called bolt pattern and one type of bolt pattern has been assumed in this experimental programme. This experimental test implemented the Lindapter Hexagonal M10 Hollo-bolt with strength class of 8.8 to connect the T-stub to the square SHS. A Hexagonal M10 Hollo-bolt is comprised of components such as sleeve with collar, threaded cone and bolt shank as it is illustrated in Figure 1. The arrangement of the implemented Hexagonal M10 Hollo-bolt components has been modified in each specimen as shown in Table1.

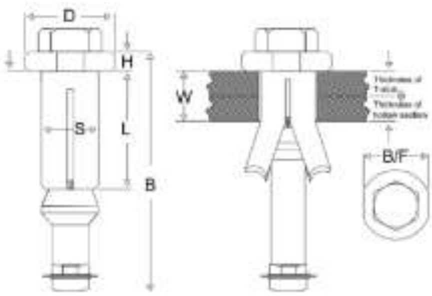


Figure 1: The anchored hollo-bolt view

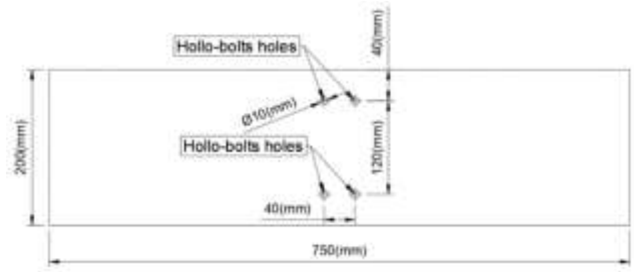
Table 1: Details of the hollo-bolt HB10

Bolt Length B (mm)	Clamping thickness W (mm)	Sleeve Length (L) (mm)	Sleeve Outher (Ø) (mm)	Sleeve Height (H) (mm)	Tightening Torque Nm
140	36	48	17.75	6	45

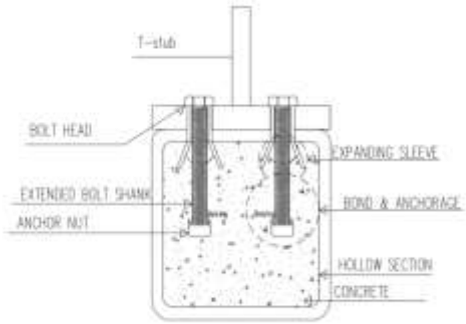
2.2 Description of the specimens

The main test comprises of three tests which are the unfilled tube section (UT), the concrete-filled tube section (CFT) and the foam-filled tube section (FFT). The geometry of the Hollo-Bolted connections was established in the experimental programme based on the minimum gauge and edge distances which was taken by Lindapter's Brochure recommendation [8]. Figure 2a shows the proposed bolt pattern of the employed SHS.

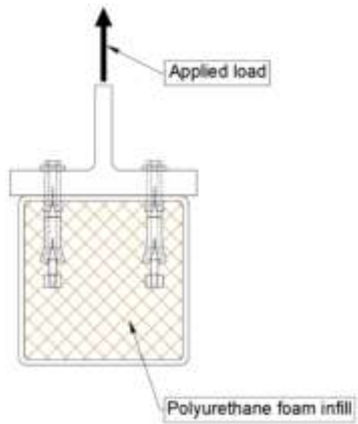
To prepare anchorage in CFT hollobolt, a Hexagonal M10 Hollo-bolt with extended bolt shank and a middle nut was used for this test. The length of the bolt shank is 146mm and the arrangement of proposed hollo-bolt is illustrated in Figure 2b. The nut has been designed to produce an anchorage mechanism.



(a)



(b)



(c)

Figure 2: The cross-sectional view of the specimens: (a) the UT specimen; (b) the CFT specimen; (c) the FFT specimen.

To prepare anchorage in FFT hollobolt, extended bolt shank with a length of 146mm, an additional middle sleeve, unthreaded cone and end nut have been implemented as shown in Figure 2c. The sleeve with collar was located at the top, unthreaded cone located after this sleeve and then middle sleeve and threaded cone was positioned to the extended bolt and finally an end nut is added at the end of the bolt shank. By tightening this type of bolt, the threaded cone pushes up the middle sleeve and unthreaded cone and because of this both sleeves would be expanded. The required torque to tighten the bolt is 45Nm. The cross-section of the specimen, T-stub, hollo-bolt arrangement after tightening and direction of the applied load is illustrated in Figure 2c.

2.3 Setup and instrumentation

Experimental tests were carried out by using Avery 60T testing machine in the civil engineering's laboratory of University of Birmingham. Avery 60T machine is displayed on Figure 3 and it is able to resist a force up to 600KN safely. There are two grips in Avery 60T test machine which have been used to hold the T-stubs. The T-stub which was tightened by four hollo-bolts was installed in the top grip and the T-stub which was tightened by six normal bolts and nuts was installed in the bottom grip. During this test the bottom grip was fixed without any movement, but the top grip set to apply controlled displacement with the rate of 0.5 (mm/sec) to model the pull-out force. This displacement was continued until a clear drop of applying load was observed. To determine the deformation of the connection, two Linear Variable Differential Transformers (LVDTs) were employed. These LVDTs were installed to observe the deflection of the T-stubs on the top and bottom. The top LVDT illustrates the top T-stub movement which identify the hollo-bolt displacement and bottom LVDT identify any slippage of the specimen at the bottom grip. To identify the displacement of the top T-stub, the difference of the measured values of the top and bottom LVDTs were used.

Figure 3: The experimental setup

2.4 Material Properties

2.4.1 Hollow section plate

Mechanical properties of the square SHS were obtained by carrying out a tensile coupon test. Mechanical properties of the Lindapter Hexagonal M10 Hollo-bolt with strength class of 8.8 were extracted from Table 4 of EN-ISO 898-1:2013 (F_y = 640 MPa and F_u = 800 MPa) [9]. In this experimental programme T-stub on the top has been employed to transfer the load and T-stub at the bottom of the specimen has been used to enable the specimen to be installed in the testing machine, therefore the T-stubs considered to have very high stiffness to perform as a rigid element without any deformation. Mechanical properties of the square SHS are illustrated in Table 2. Through testing the test pieces for the mechanical properties, it enabled the determination for the properties of the SHS.

Table 2: Material Properties of the hollow section

E (MPa)	F_y (MPa)	ε_y	F_u (MPa)	ε_u	ε_f
196042	406	0.036	509.27	0.197	0.345

2.4.2 Concrete

Employed concrete for this test is Carlton HP-ECOFIX which was supplied by Carlton Manufacturing Ltd. The individual components of this product are complied with the requirement of BS EN 206-1 [10]. This type of Carlton HP-ECOFIX provides a strength class of C32/40. Mechanical properties of concrete have been obtained by carrying out a compressive test on a 100mm cubic samples of concrete and the mean compression strength value of concrete samples displayed in Table 3.

Table 3: Compression strength of the infilled concrete

f_c (MPa)	Mean strength (MPa)
43.22	
40.35	42.26
43.21	

2.4.3 Polyurethane foam

Onsalung et al. (2016) [11] carried out an experimental study on the crush characteristic of foam-filled steel tubes. An experimental test was performed on polyurethane-filled SHS and unfilled SHS specimens. In according with observed results, polyethylene foam-filled (SHS) improves the energy absorption capacity. Ammons et al. (2021) [12] carried out an experimental investigation on performance of polyurethane foam-filled circular hollow section (CHS) braces under cycling loading. Significant energy dissipation was observed in foam-filled specimens in compared with unfilled specimen.

Due to limited information about the mechanical properties of polyurethane, this study investigated the polyurethane characteristics in more details. ALCHEMIX PU 3617 [13] has been used to prepare the polyurethane foam. This material is comprised of two components of Formulated polyol blend (PU 3617A) and Isocyanate (PU 3617B). Typical density of this foam for free raise condition is between 240 (kg/m^3) to 260 (kg/m^3) and this density is increased to 280 (kg/m^3) for overpacked condition of FFT specimen. Required amount of each component has been determined by the desired density and implementing the following Equation (1):

$$\text{Amount of PU 3617 (kg)} = \text{Desired Density (kg/m}^3\text{)} \times \text{Cavity Volume (m}^3\text{)} \qquad (1)$$

The mix ratio of the PU3617A:PU3617B is 100:85 by weight and weight of each component is determined according to the specimen volume. Desired density for polyurethane foam infill of this specimen has been considered to be 280 (kg/m3). In accordance with the dimensions of the specimen, the cavity size is 0.03m^3. To achieve 280 (kg/m3) density and according to the recommended required amount of PU3617 and mixing ratio, 4.54(kg) of PU3617A and 3.86(kg) of PU3617B has been used. Each of required components were weighed in separate clean containers. Then PU3617A was poured in the square SHS and after that PU3617B was poured into the square SHS. These two components were mixed with a metal paddle at a speed of above 2000rpm and it was continued to achieve a cream/brown colure mixture. Polyurethane foam preparation should be processed at a temperature between 18°C to 25°C. 72 hours is required to cure this foam, but it can be cut after 2hours if it is required.

Compression tests have been carried out on the 3 polyurethane samples (100mm cubic) which were extracted from the FFT specimen, as shown in Figure 4a. These samples have been used to determine the density of the polyurethane foam and a compression test has been carried out on each sample. Stress-strain graph of the compression tests is illustrated in Figure 5. The behaviour of the foam was seen through linear elasticity with the progression of long plateau region which is associated with the foam crushing and then an immediate and sharp increase within the stress which is known as the densification region. Mechanical properties of the polyurethane foam samples are displayed in Table 5.

(a) Compression test

(b) Tension test

Figure 4: Compression and tension tests of the FFT foam

Six tensile tests were also carried out, as shown in Figure 4b according to ASTM (2014) [14]. The tensile strength of the foam coupons was found to be nearly 1.2 kN on average. This provides an approximate tensile stress equal to 4MPa. The failure of the foam under tension was brittle, as shown in Figure 4b.

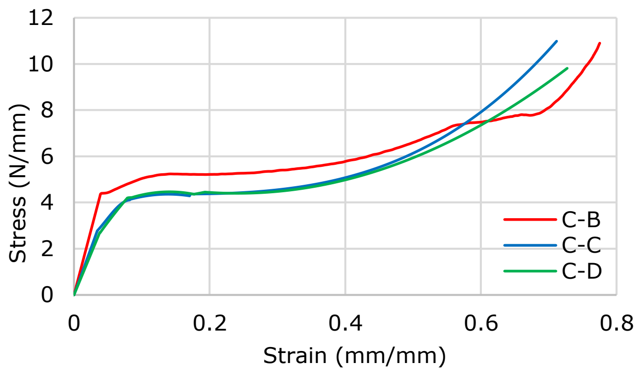


Figure 5: Stress-Strain graph of FFT polyurethane foam under compression

Table 5: Mechanical properties of polyurethane foam under compression

Specimen	Density (kg/m3)	0.2% proof stress (MPa)	Young's modules (MPa)
C-B	311.9	4.5	111.73
C-C	290.3	4.0	80.84
C-D	287.4	4.2	71.07

3 Results and Discussion

3.1 Load-displacement curves

Figure 6 illustrates the load-displacement diagrams of all specimens. The yielding strength of the UT connection occurred at approximately 112.3kN load and 7.1mm displacement. Ultimate strength of the connection observed at approximately 180kN and 18mm displacement and after this point the hollo-bolts' sleeves widen the holes on the tube and connection was failed due to fully yielding of the hollow section wall. As it is displayed the ultimate displacement of the connection is happened at 18 mm which means the connection is flexible.

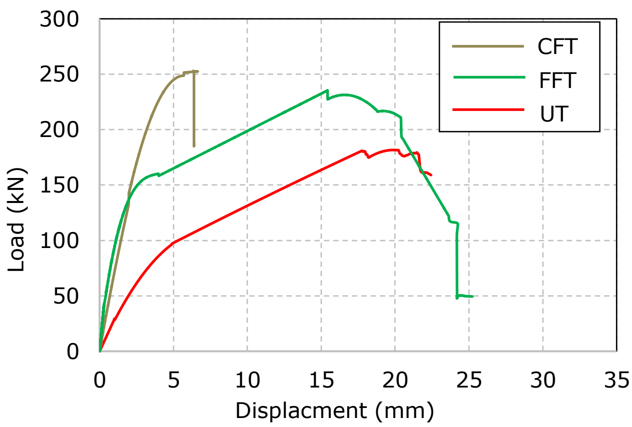


Figure 6: Load-displacement diagram of tested specimen

The yielding strength of the CFT connection occurred under approximately 240kN load and 4mm displacement. Ultimate strength of the connection observed under approximately 250kN and 5.7mm displacement and after this point the connection was failed due to slippage of hollo-bolts. Bonding between the hollo-bolts and concrete enabled the bolts to use their full tensile capacity and finally the bolts have been ruptured at the ultimate strength. As it is observed the ultimate displacement of the connection is occurred at 5.7mm providing almost three times lower ductility.

The yielding strength of the FFT connection occurred under approximately 134.6kN load and 1.9mm displacement. Ultimate strength of the connection observed under approximately 235kN and 16mm displacement and after this point the connection was failed due to the hollo-bolts slippage and hollow section wall yielding. As it is shown the ultimate displacement of the connection is happened at 16.4mm which suggests the connection is quite ductile.

It is observed the CFT has the highest ultimate strength, but its connection behaviour is less ductile as the failure has been occurred in less than 6mm displacement. As it is expected the UT specimen has got the lowest yielding and ultimate strength due to lack of anchorage, but the connection is flexible. As it is displayed in Figure 6, FFT yielding strength was increased compared to that of UT, while its ultimate strength was very close to the one provided by the CFT. The developed anchorage between the hollo-bolts and foam infill material provided the same elastic stiffness as the concrete-filled hollow section. This behaviour means the hollo-bolts arrangement in foam successfully enhanced the UT connection to perform stronger without sacrificing ductility.

3.2 Failure mechanism

The infilled material affects the strength of the connection by providing the bonding between the hollo-bolts and the infilled material as well as interaction between the hollo-bolts' anchorage mechanism and the hollow section wall. Impact of the bonding between the infilled material and the hollo-bolts depends on the strength of the infilled material and hollo-bolt arrangement which means stronger infilled material and more effective hollo-bolt arrangement provide stronger bond to the hollo-bolts and enable the hollo-bolts to achieve their ultimate tensile strength capacity.

Pull-out load forms a cone failure line between the hollo-bolt's anchorage and hollow section wall. Confined infilled material between the cone failure line and hollow section wall creates an interaction between this confined infilled material and hollow section wall and its magnitude depends on the ductility of the infilled material. In other word, if the infilled material has more ductility, the connection could benefit more from the infilled material by employing the hollow section wall tensile capacity.

In accordance with the experimental test on CFT specimen and Figure 7, it is observed the connection was failed due to rupture and slippage of the hollo-bolts. Figure 7 illustrates the hollo-bolt slipped through the concrete (left picture) and the hollo-bolt has been ruptured (right picture). As it was observed from the result, due to the negligible ductility of the concrete, the connection behaviour was brittle and infilled concrete between the hollo-bolt anchorage nut and hollow section wall was not able to improve the connection in this respect. Concrete enabled the hollo-bolts to reach their ultimate tensile strength and then fracture.

Figure 7: Failure mechanism of the CFT specimen

Figure 8 illustrates the failure mechanism of the FFT specimen. As it is clear the cone failure line was formed (left picture) and hollo-bolts have been slipped (right picture). Figure 9 illustrates the hollow section wall deformation of the specimen. By considering the test results the connection was ductile, and it suggests the infilled polyurethane has high ductility characteristics. The yielding strength of FFT specimen has been happened due to slippage of the hollo-bolt through the polyurethane foam and yielding of hollow section wall because of interaction between polyurethane foam and the hollow section wall.

Figure 8: Cone failure line and hollo-bolt slippage of the FFT specimen

Figure 9: Hollow-section wall deformation of the FFT specimen

Finally, regarding the results of UT test, this specimen has the lowest stiffness as it has not been provided with an anchorage. In this connection the tube wall deformed, and connection failed due to the widening of the holes on the tube wall by hollo-bolts' sleeves and fully yielding of the hollow section wall, as shown in Figure 10. Moreover, inward buckling was observed in the tube webs, a failure that was not observed either in CFT or FFT specimens.

Figure 10: Failure mechanism of the UT specimen

4 Conclusions

This study carried out pull-out experimental tests on blind-bolted beam connections to square steel tubular columns filled with polyurethane foam or concrete. Benchmark tests on unfilled columns were also conducted for comparison. Test results revealed the behaviour of each type of connection in regard to employed infilled material and hollo-bolts arrangement. The main findings of this investigation are summarised in follow.

- By implementing the polyurethane foam as an infilled material into the empty hollow section, the strength of the blind-bolted connection was improved and still can provide robust design against extreme load impacts with increased ductility requirements.

- The adopted hollo-bolt arrangement in foam-filled specimens led to a cone failure line between the hollo-bolt's anchorage in foam and the hollow section wall. It was found that this failure mechanism of foam assists to employ more segment of hollow section wall at the location of beam-to-column connection to increase the capacity of the conventional unfilled connection.

- Concrete-filled hollow section provides high elastic stiffness and the highest yielding and ultimate strength. The connections behaviour relies upon the strength and stiffness of hollo bolts alone.

- The developed anchorage between the hollo-bolts and foam infill material provided the same elastic stiffness as the concrete-filled hollow section, while it successfully enhanced the unfilled connection to perform stronger without sacrificing ductility. This indicates the efficiency of the foam-filled connection as an alternative, light infill material in steel hollow sections.

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