Cabrera et al. (2021) A Review and Analysis of Testing and Modeling Practice of Extended Hollo-Bolt Blind Bolt Connections. Journal of Constructional Steel Research. 183, 106763. https://doi.org/10.1016/j.jcsr.2021.106763

A Review and Analysis of Testing and Modeling Practice of Extended Hollo-Bolt Blind Bolt Connections

Manuela Cabrera[a,*], Walid Tizani[a], Jelena Ninic[a]

[a] *Department of Civil Engineering, The University of Nottingham, Nottingham, UK*

Abstract

Steel Hollow Sections (SHS) offer many structural, economical and architectural advantages in multi-storey and high-rise construction. However, their use is not suitable for a wide range of applications due to the difficulties of site bolting as there is limited access to the inner part of the steel section for tightening of standard bolts. Blind bolts have been developed to overcome these difficulties in view of extending the application of SHS in construction. Special attention has been paid to blind bolts that could potentially be used in rigid or semi-rigid connections. This is the case of a modified blind bolt, termed the Extended Hollo-Bolt (EHB), which has shown to be able to achieve the required performance for its use in moment resisting connections. This paper critically reviews published work concerning the blind fastener, describes the loading procedures used for testing and failure modes produced, lists the assessed parameters with their respective applicability ranges, and summarises the analytical models developed for the EHB components. Additionally, a global sensitivity analysis is performed using information of two representative studies for the purpose of detecting key design parameters that influence the response of the connection in terms of strength and stiffness. The analysis shows that the

---

[*] Corresponding author: M. Cabrera, Email: manuela.cabrera@nottingham.ac.uk

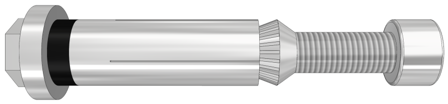
concrete strength has the most influential effect on both the stiffness and strength of the column component as well as bolt component stiffness, while the bolt grade highly influences the bolt component strength.

Keywords: Extended Hollo-Bolt, Tubular Connection, Concrete-Filled Steel Hollow Section, Experimental and Analytical Review, Sensitivity Analysis

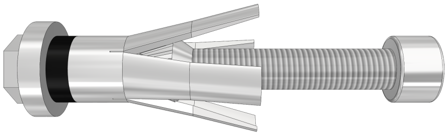
---

1. Introduction

The use of Steel Hollow Sections (SHS) in multi-storey and high-rise construction has grown over the years allowing the structural industry to explore new design concepts. SHS members (e.g., rectangular, circular profiles) are desirable as columns from architectural and structural points of view. They have superior axial load carrying capacity, higher strength-to-weight ratio, increased fire resistance and an excellent torsional resistance compared to steel open section profiles (e.g.,I-shaped, T-shaped profiles) [1]. Some alternatives to connect open beam-to-SHS involve welding of fittings, threaded studs or diaphragms onto the face of the column to provide access for bolting, or direct welding of the beam to the column [2]. However, welded components are prone to damage during transportation, could be impractical to install [3], and have quality and inspection issues when done on-site [4]. Welded



(a) Shape before tightening.



(b) Shape after tightening.

Fig. 1. Extended Hollo-bolt (EHB).

connections have also exhibited brittle failure under seismic events [5–7]. Therefore, bolting is broadly the preferred method, unless special circumstances dictate.

Blind bolts have been developed to overcome these limitations as they can be assembled and tightened from one-side only. There is an extensive range of commercial blind bolts which, along with endplate connections, allow to connect open to closed steel members. Each type of blind bolt has a particular geometry and installation technique defined by the maker which allows on-site installation such as the Blind Bolt [8], Huck BOM [9], Molabolt [10], Flowdrill system [11], Ajax-Oneside fastener [12], and Lindapter Hollo-Bolt (HB) [13].

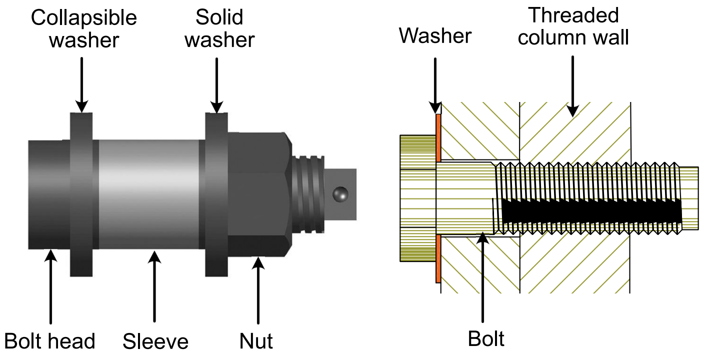
Connections using the fasteners mentioned above provide sufficient shear and tying resistance to satisfy structural integrity checks. However, such connections tend to have low moment–rotation stiffness which is usually controlled by the inherent flexibility of the SHS column face hindering the use of blind bolts in moment resisting connections. One of the effective ways to mitigate this problem is filling the SHS with concrete [14]. The advantages of this technique have been highlighted by many authors. For instance, the load carrying capacity, ductility and rotation capacity of Concrete-Filled SHS (CFSHS) columns are enhanced by the confinement provided by the column walls to the concrete which in turn limits concrete fracture [15]; the fire resistance of CFSHS members is higher than that of bare SHS since the infill concrete absorbs part of the heat reducing the temperature increment rate of the steel tube [16]; the bolt pull-out is limited by the anchoring effect produced by the concrete around the bolt [17]; additionally, excessive localised deformation in the column walls is prevented by the support provided by the concrete, specially in the compression zone of the connection [18–20].

Various authors have proposed modifications to the commercial blind bolts in order to increase their tensile stiffness, and increase the bending stiffness of the face of the hollow section. This is the case of the Extended Hollo-Bolt (EHB) developed by Tizani and Ridley-Elis [21] as a modified version of the commercially available Lindapter Hollo-Bolt (HB). The modified fastener, Fig. 1, has an extended bolt shank and an additional nut at the end of the bolt which creates an anchoring effect taking advantage of the concrete around the bolt.

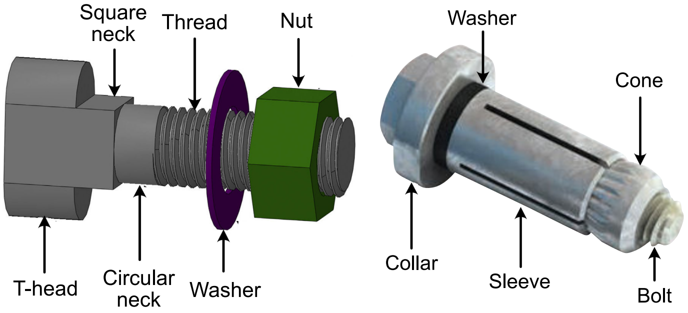
This paper presents a review of previous and ongoing research regarding the EHB connection zones under different load types. Also, it describes the studied parameters and their impact on the connection response. A systematic literature survey has been conducted to assess the effects of modifying the HB to the EHB, and to identify the steps required to fully characterise the EHB. Three databases are chosen for the paper retrieval, namely Scopus, Web of Science, and American Society of Civil Engineers (ASCE) Library, among which ASCE is the core collection. Search results are then selectively reviewed based on refining topics to concentrate on the EHB connection. For example, there are a total of 32 publications on this topic ranging from 2012 to 2021 (data accessed from Scopus on 28/10/2020) using the query strings in Scopus as TITLE-ABS-KEY (”Extended Hollo Bolt” OR “Anchored Blind bolt”).

The purpose of this paper is to review all available information regarding the EHB connection in order to identify aspects that have not been addressed in the present body of research and are required for deeper understanding of the EHB connection such that design guidance can be produced. The development of a rigid bolted connection system will allow for the use of open-section beams connected to hollow sections as columns which represent a clear advantage for the building industry.

The remaining of the paper is organized as follows: Section 2 presents the state of the art of different blind bolts which are under current investigation; Section 3 presents a review of the available experimental and analytical information of the EHB connection zones (i.e. tension, compression, and both); a sensitivity analysis



(a) Ajax-Oneside fastener [22] **(b)** Thread-Fixed One-Side [23]



(c) T-shaped One-side Bolt [24] **(d)** Lindapter Hollo-bolt [13]

Fig. 2. Different blind bolts under research.

is presented in Section 4; and finally, the conclusions of the work are presented in Section 5.

2. Blind Bolted connections background

Multiple studies have been conducted regarding blind bolted in steel and composite beam to column connections. Some studies have addressed the static behaviour of CFSHS column connections with various blind fasteners, e.g: Loh et al. [25, 26], Liu et al. [27], Ataei et al. [28, 29], highlighting the benefits of using blind bolts in terms of joint ductility, strength, and stiffness. Other researchers have investigated the cyclic performance of blind bolted end plate connections to CFST columns, such as

Li et al. [30], Wang et al. [31–33], Waqas et al. [34], demonstrating that these blind bolted connections perform satisfactorily in terms of yielding, maximum strength capacity, and ultimate displacement under seismic events.

These experimental studies have shown these connections to have a promising prospect in practical engineering and to be an effective solution for modern structures. Four blind bolts under current investigation at different institutions are reviewed in this section for illustration, these are the Ajax-Oneside fastener, Thread-Fixed One-side Bolt, T-shaped One-side Bolt, and Lindapter Hollo-bolt.

2.1. The Ajax-Oneside fastener

The Ajax-Oneside fastener is a blind bolt comprised of a high strength bolt, a split step-washer that expands once inside the hollow section, a solid step-washer, and a structural nut, see Fig. 2a. This blind bolt can reach the full structural strength of high strength bolts under AS4291.1 specification, according to Ajax Fasteners Innovations [35].

The Cogged Anchor Blind Bolt (CABB) is a modification of the Ajax-Oneside fastener developed by Gardner and Goldsworthy [36]. This bolt has been studied under cyclic tension by Gardner and Goldsworthy [37], and Yao et el. [20] studied groups of CABB to concrete-filled circular hollow sections. The studies showed that the modified bolt has a higher connection failure load and initial stiffness compared to the original bolt.

However, this modification was found impractical for manufacturing and installation, and therefore another modification was introduced by Yao et al. [38], the Headed Anchor Blind Bolt (HABB), which used the same method for anchorage as the EHB. Yao et al. [38], Oktavianus et al. [39, 40] performed a series of monotonic tensile tests and parametric studies using FE analysis to assess the performance of individual and groups of HABBs and compared them to the conventional Ajax-Oneside bolts. The results indicated that the modified bolts could be suitable for moment-resisting connections with a high degree of strength and stiffness. Agheshlui et al. [41] concluded that placing the HABBS close enough column corner prevents full concrete cone failure and therefore the full tensile capacity of the bolt can be used.

Further modification of the HABB, the Double-Headed Anchored Blind Bolt (DHABB), was introduced by Oktavianus et al. [4] who added a second embedded head within the infill concrete. The individual and group behaviour of DHABB under cyclic loading was studied by Oktavianus et al. [4, 22], respectively. The authors concluded that the DHABB exhibit higher secant stiffness if the extra embedded head is installed in the appropriate location and the thickness of the T-stub flange has most influential effect on the secant stiffness of the connection.

The cyclic behavior of groups of DHABBs was experimentally and numerically evaluated by Pokharel et al. [42]. The authors proposed the use of through bolt along with the DHABBs and the test results show that stiffness of the connection is increased while the cyclic deterioration is decreased. From parametric analysis, the variation of the flange thickness of the T-stub has shown to have the largest effect on the tensile behavior of the DHABB connections.

2.2. The Thread-Fixed One-side Bolt (TFOB)

The Thread-Fixed One-side Bolt (TFOB) is similar to the Flowdrill system extended to thicker plates. In these bolts, a thread is created in the column wall holes and a bolt without nut can be installed and tightened, see Fig. 2b.

The TFOB has been studied by Iu et al. [43] under monotonic load to evaluate the tension yield resistance of the connected T-stubs. Two failure modes were identified from the experimental tests and a series of design methods were proposed. Zhu et al. [44] found that using backing plates in combination with these kind of bolts improves the tension resistance of the connection. Using a validated FE model, Wulan et al. [45] conducted parametric studies and concluded that threaded T-stubs provide enough tensile capacity to fix the high strength bolt, preventing pre-mature thread failure. Wang et al. [46] studied the TFOB on lap connections under shear load. Finite Element Analysis (FEA) were also performed and conclusions show that the studied bolt and screwed shear plate could replace the traditional bolt and nut in engineering applications.

The monotonic and cyclic loading response of the connection was investigated by Wulan et al. [47]. It was observed that the cyclic loading caused the threads on the wall become more vulnerable to failure compared to the monotonic case. Additionally, the authors concluded that available design methods for monotonic load can be applied under cyclic loading as well.

Wang et al. [48] subjected beam to SHS connections using TFOBs to static bending moment. Strengthening methods were also used to improve the initial stiffness and bending moment capacity. Test results showed that the yielding bending moment, the ultimate bending moment and the ultimate rotation of a TFOB strengthened with backing plate were similar to those of traditional Nut-fixed bolts, and the initial stiffness was enhanced. The yielding bending moment, the ultimate bending moment and the initial stiffness were also improved, but the ultimate rotation decreased. Additionally, all tested specimens met the seismic ductility requirements.

2.3. T-shaped One-side Bolt (TOB)

The T-shaped One-side Bolt (TOB), developed by Sun et al. [49], consists of a bolt shank with T-head, a nut, and a washer, as illustrated in Fig. 2c. The authors evaluated numerically the behaviour of the end plate connection of SHS to I-beam. The numerical results showed that the bending moment capacity of the proposed TOB connection is higher than that of Standard High-strength Bolts.

Wang et al. [24] conducted tensile tests on TOB connections with vertical and horizontal slotted bolt holes. It was concluded that compared to standard high strength bolt connections, the initial stiffness of TOBs with vertical slotted bolt holes was increased, while in the case of horizontal slotted bolt holes, it decreases. Theoretical models for calculating the bending yield strength were proposed.

2.4. Lindapter Hollo-bolt

The Lindapter Hollo-Bolt (HB) is comprised of a thread bolt, a collar, a sleeve, a cone, and a rubber washer, as in Fig. 2d. Design guidance for simple joints using the HB fastener is currently available in Eurocode 3 [50]. In order to extend the use of blind fasteners to moment resisting connections, the HB has been investigated in combination with CFSHS.

Wang et al. [51] tested beam to concrete-filled column connections under symmetrical monotonic loading using HBs. According to the moment-rotation response, the tested specimens were classified as semi-rigid and of partial strength according to the EC3 specification. A similar test programme was conducted by Wang et al. [31] to evaluate the hysteretic performance of the connection. The authors concluded that rotation capacities of this type of joint satisfied the ductility requirements for earthquake resistance in most seismic regions.

Wang et al. [32] carried out experimental and analytical analysis of CFSHS to steel beam connections using HBs. Similar to [51], the specimens were classified as semi-rigid and partial strength, and the rotation capacities satisfied the ductility requirements suggested by FEMA-350 [52].

In spite of the advantages mentioned above, the use of HBs in combination with CFSHS does not provide the required moment resistance and rotational stiffness to be classified as moment resistant. This is because the concrete filling only addresses the flexibility of the tube face and the improvement is not sufficient to attain significant moment resistance.

A modification of the HB, the Reverse Mechanism Hollo-bolt (RMH) [1], has an inverted expanding sleeve that clamps directly to the underside of the joint. [53] tested the RMH a using back to back T-stubs test arrangement. Conclusions show that the use of this fastener in moment resisting connections is feasible. However, undesirable sudden failure occurs and the flexibility of the SHS may limit the moment capacity of the connection. Tizani and Ridley-Elis [21] presented the results from experimental tests carried out to RMH using SHS with and without infill concrete. It was concluded that the RMH connection without infill concrete has sufficient stiffness to classify as moment-resisting but lower tensile strength than standard bolts. It was also found that the insufficiency in strength can be improved by the use of concrete infill.

Tizani and Ridley-Elis [21] proposed to add a nut at the end of an extended bolt shank in order to create an anchoring effect, take advantage of the infill concrete, and improve the flexibility of the column face. Ellison and Tizani [54], and Tizani et al. [14] compared the tensile behaviour of the modified blind bolt, termed the Extended hollo-bolt (EHB), with standard bolts. The test results showed that both strength and stiffness are enhanced by the modified EHB configuration. The use of infill concrete changes the failure mode from bolt pull-out to bolt shank tensile fracture improving the strength of the connection. It also provides additional bending stiffness to the face of the hollow section and the stiffness is enhanced by the embedded anchor nut. This fastener has shown to have the potential to be used in moment-resisting

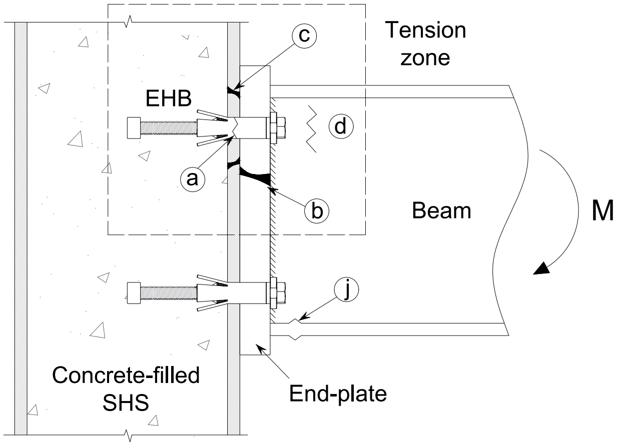


Fig. 3. Joint components of an open section to CFSHS joint with an EHB flush end-plate connection. See Table 1 for component key.

Table 1. Key to Fig. 3. EHB joint components and evaluation rules availability.

Ref in Fig. 2	**Component**	**EC3 availability**	**Rotational stiff. contribution**
	Tension		
a	Bolt tension	No	Yes
b	Endplate bending	Yes	Yes
c	Column face bending	No	Yes
d	Beam web tension	Yes	No
	Compression		
j	Beam flange compression	Yes	No

connections and therefore, the following sections are focused on this type of blind bolt.

3. Review of studies on the EHB connection behaviour

Structural steel and composite joint systems are complex to characterize as a whole due to their material and geometric non-linearities, residual stress conditions, and complex geometrical configurations. Therefore, simplified mechanical models such as the component method in Eurocode 3 [50] have been developed to facilitate the joint design procedure. In the component based approach, joints are decomposed into a set of rigid and flexible components which contribute to the joint structural properties and therefore constitute a powerful tool for the evaluation of the stiffness and/or resistance properties of joints under different loading conditions [55]. The assembly of these individual basic components into a mechanical model can be used to predict the response of any joint geometry as long as the behaviour of its components (stiffness, resistance, and ductility) is fully characterized [19].

To extend the application of the component method to EHB blind-bolted connections between open and hollow sections, Pitrakkos et al. [55] reviewed the available data in terms of the relevant components of a single-sided joint between an open section beam (I profile) and a CFSHS column connected using a flush endplate and two rows of EHBs fasteners, one in tension and one in compression. The joint components which contribute to the resistance and/or rotational stiffness of the EHB joint and the availability of evaluation rules for each of them in Eurocode 3 [50] are presented in Fig. 3 and Table 1. The identification of these components is based on the following assumptions:

- The beam flange carries all compression and therefore, the beam web in compression is not considered.
- Due to the infill concrete stiffening action, the following components do no need to be taken into account: bolts shear, column face compression, side column faces compression/tension, and punching shear failure around the bolt heads in compression.
- The weld components do not contribute to the rotational stiffness of the joint (CEN 2005). However, their resistance must be checked against the existing rules available in Eurocode 3 Part 1-8.

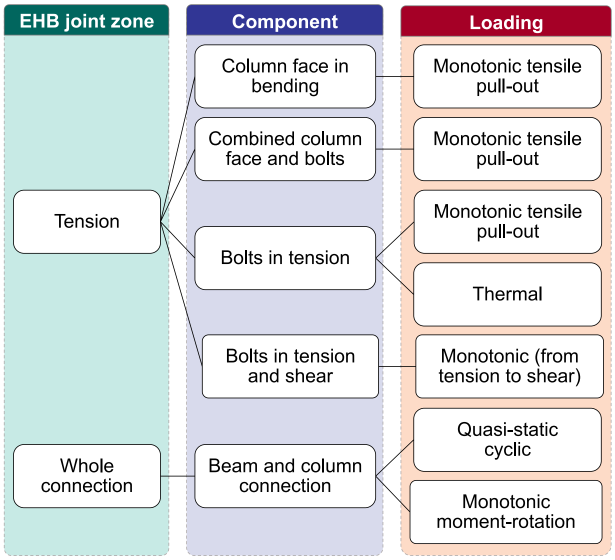


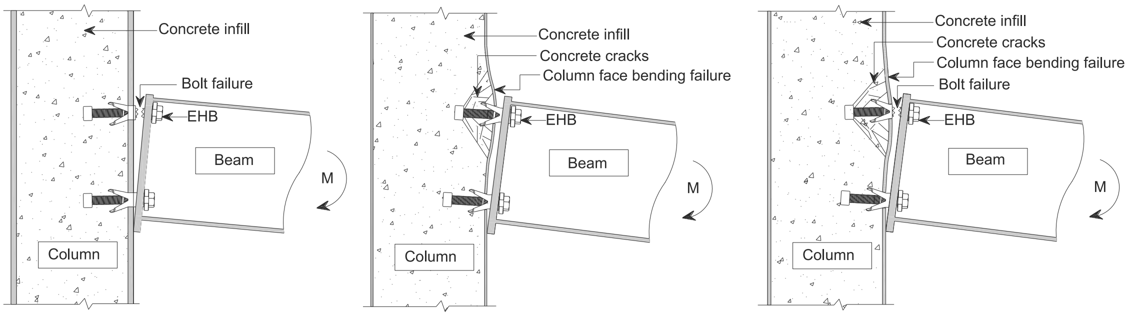
Fig. 4. Summary of available literature regarding the EHB

Different authors have contributed to the existing gap in the knowledge regarding the two components unavailable in Eurocode 3: bolts in tension and column face in bending. Different studies addressing these components are presented below.

The study of the EHB connection behaviour have been made as a whole (beam and column connections) or dividing it into zones. Special attention has been paid to the tension zone since the extension of the component method to the EHB connection has been limited due to the lack of knowledge regarding the behaviour of two components in this zone. A summary of the studied components and load types applied for each zone is presented in Fig. 4.

3.1. Tension zone

In the tension zone of the connection, three possible failure modes have been identified: bolt failure in tension, Fig. 5a; column face failure in bending, Fig. 5b; and combined failure mode (both bolt and column face can contribute to failure),

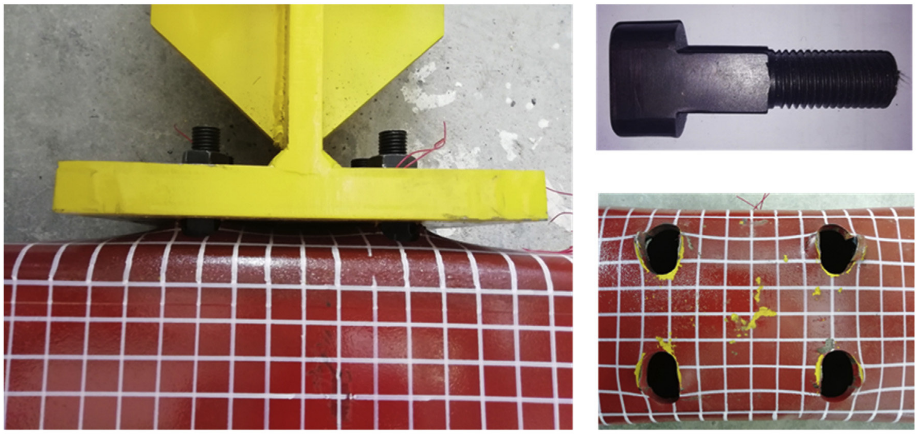


(a) Bolts in tension **(b)** Column face in bending **(c)** Combined failure

Fig. 5. Failure modes of the EHB connection [56].

Fig. 5c. The two extreme failure modes have also been identified and reported for other blind bolts, for instance, the TSOB with rigid T-Stub, displayed large column face deformation when a thin column is used Fig. 6a, while bolt fracture is reported for thick column face Fig. 6b [24]. Another example is the anchored Ajax-Oneside fastener, for which the failure modes are bar fracture Fig. 7b, and the tube wall yield and bar pullout Fig. 7a, depending on the bolt location (middle or side of the SHS), bolt diameter, SHS wall thickness, and compressive strength of the concrete infill [38].

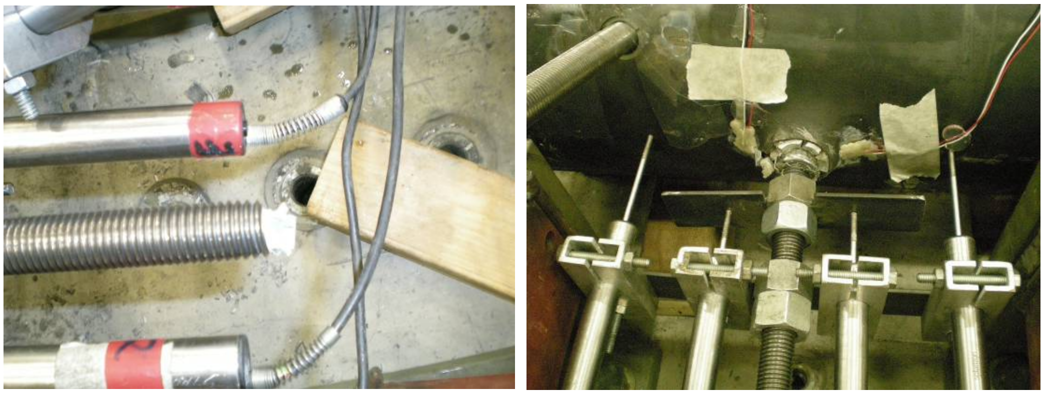
The first two EHB failure modes have been studied independently isolating the component of interest. The tension zone of an end-plate connection between open section members is modelled in Eurocode 3 [50] as a equivalent T-stub model, which represent the flange and web of the column, and the web and end plate of the beam for open section steel members [1, 57]. The component based approach and the T-stub model have been adopted to study open beam-to-hollow column, as illustrated in Fig. 8, in order to study the components in tension of the EHB connection. A review of the available literature per component is presented next.



(a) TSOB Tube wall yield and bar pullout

(b) TSOB Bar fracture

Fig. 6. TSOB failure modes [24].



(a) Ajax Bar fracture **(b)** Ajax tube wall yield and bar pullout

Fig. 7. Anchored Ajax-Oneside fastener failure modes [38].

3.1.1. Bolt component in tension

Extensive research has been carried out isolating the bolt component by means of a rigid column face arrangement, the studied configurations include single-sided and double-sided T-stub models under different loads.

Pitrakks [3] carried out 16 tests to evaluate the single EHB connection under a monotonic tensile pull-out test arrangement. The test set-up uses a reusable steel box assembly comprised of four rigid flat plates limiting the bending of the top plate and therefore isolating the bolt behaviour as illustrated in Fig. 9a. The authors identified and assessed individually three components that contribute to the deformability of the EHB component: 1) Internal bolt elongation, 2) Expanding sleeves, and 3) Bond and anchorage. Additional tests of EHBs without sleeves, and HBs with and without infill concrete were performed in order to identify the contribution of each individual component to the general behaviour of the connection.

It was observed that the EHB has better performance than the original version, the HB, as the anchored nut distributes the applied force over the surrounding concrete and therefore, concentration of stresses in the expanding sleeves is decreased, limiting their failure and eliminating concrete breakout. Concrete strength was found to have significant influence on the connection stiffness and negligible effect on its strength and ductility. Higher bolt grade improves the stiffness, strength, and ductility. The study concluded that the EHB component can be compared to an standard bolt as the failure mode corresponds to bolt shank necking and fracture, showing that it is able to develop the full tensile capacity of its internal bolt.

The mechanical properties of the bolts used in the testing programme were also reported in [3] for seven bolt batches. Tensile tests were performed on machined and full-size bolts in accordance with ISO 898-1:2009 [58]. Test results are summarised in

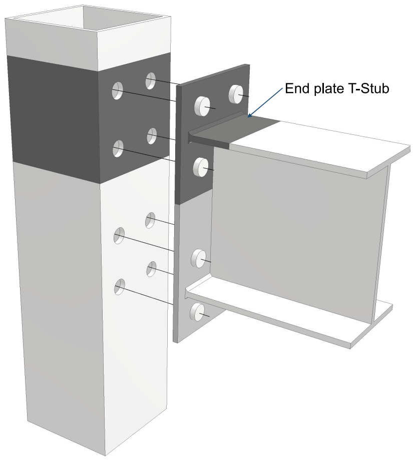


Fig. 8. T-stub to steel hollow section model.

Table 2. Mechanical properties of different bolt batches.

Bolt batch	**Diameter (mm)**	**Bolt grade**	f_{yb} **(MPa)**	f_{yu} **(MPa)**	**E (MPa)**
A	16	8.8	907	1003	205
B	16	8.8	725	900	210
C	16	8.8	873	981	209
D	16	8.8	836	931	207
E	16	10.9	1086	1127	209
F	20	8.8	785	935	207
G	16	8.8	828	917	212

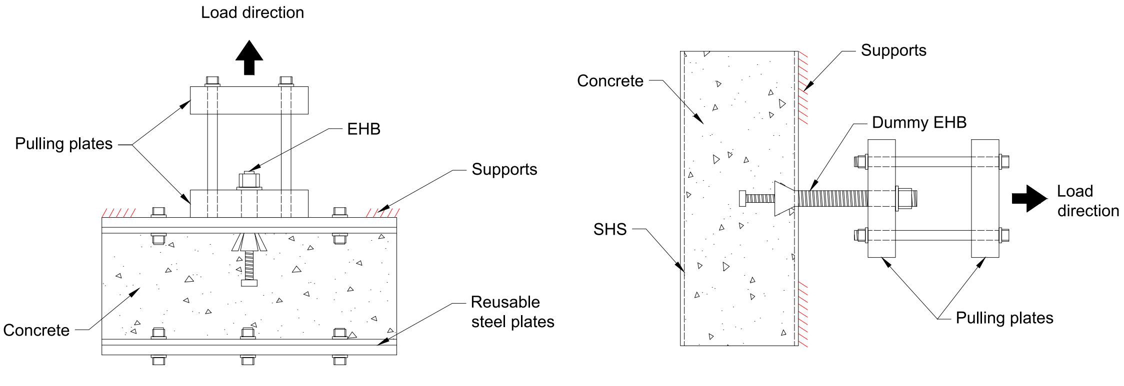
Table 2 where f_{yb}, f_{yu}, and E are the yield, ultimate strength, and Young's modulus of elasticity, respectively. Variations were observed in the bolt properties for the same bolt grade, which in turn caused some discrepancies in the yield and ultimate states for the tensile results when different bolt batches were used for identical specimens. The author highlighted the importance of considering the actual mechanical properties of the tested bolts as they influence the test results significantly.

Using the experimental results reported above, Pritrakkos et al. [55] developed an analytical model based on a system of spring elements. This model takes into account pre-load and deformation from the three components identified previously for both the elastic and inelastic behaviour of the component. The proposed model showed to accurately predict the response of the component and contributed to the development of a more detailed design method for the fastener. The analytical model is presented in Section 3.3.

The performance of a group of EHBs under a monotonic tensile force was also studied by Pitrakkos [3] using double-sided T-stub connections. Four bolts were used in each side of the CFSHS. The studied parameters included bolt grade, gauge distance, pitch distance, and concrete grade. Apart from the benefits raised by the use of concrete infill, high concrete strength, and bolt grade, it was found that the bolt group action does not compromise the strength of the system as the total connection strength is equal to the sum of the individual bolts.

Tensile fatigue tests were conducted by Abd Rahman [17] using a single EHB. The results indicate that the fatigue life and strength of an EHB were lower than those of a standard bolt, but higher than those of a HB. The failure mode of the connection was a fatigue fracture of the bolt shank which is comparable with that of the standard bolt.

Pascual et al. [59] evaluated the thermal behaviour of single unloaded HBs and EHBs through experimental and FEA. Connections to SHS with and without infill concrete were considered. It was concluded that the use of concrete has a noticeable effect on the thermal behaviour of the connection and bolt temperature reduction. On the other hand, the use of different section sizes and blind bolts (HB and EHB) has no effect on the thermal behaviour of the connection. Later, the same authors [60] developed a loaded numerical model to predict the fire behaviour of blind bolts in the tension zone of the connection. The failure occurred in the bolt shank near the bolt head. This section is critical as high temperature at this location caused



(a) Side view of bolt test setup **(b)** Side view of column test setup

Fig. 9. Experimental configuration by: (a) Pitrakkos [3], and (b) Mahmood [56]

softening of the steel. Similar to the unloaded tests, no significant effect on the fire resistance was caused by changing the bolt type in concrete-filled specimens. However, significant enhancement was observed from unfilled to concrete-filled SHS.

The group behaviour of the EHB connection was evaluated by Shamsudin [61] using a test arrangement similar to the one used in [3]. A total of 36 tests with one row of two EHBs were subjected to tensile loading. The effect of bolt gauge distance, concrete compressive strength, and embedment depth on the connection strength and stiffness was investigated. The author concluded that small bolt gauge distances lead to bolt interaction which results in low connection stiffness. The effect of the concrete grade on the connection strength and failure mode was found to be negligible, while the enhancement of the connection initial stiffness was significant up to 40MPa. The ductility of the connection was reduced with the use of small embedment depth.

From the bolts in tension assessment, it is concluded that when a rigid column wall is used, two failure modes are identified: bolt fracture and/or bolt pull-out. Different load types have been used for this component and a wide range of parameters studied.

3.1.2. Column face in bending

The column face component has only been assessed under tensile pull-out tests. These studies isolate the column face component by using a simplified rigid replica of the EHB usually denominated a dummy bolt. Dummy EHBs have a simplified geometry compared to the EHB and are fabricated with high strength steel. The test arrangement is illustrated in Fig. 9b.

Mahmood [56] investigated the effect of the slenderness ratio (column face width to its thickness ratio, $\mu = b/t$), anchorage length, bolt gauge distance, concrete type and strength on the bending behaviour of the connection using experimental and numerical methods.

In terms of slenderness ratio, it was concluded that increasing the column thickness increases both the ultimate load carrying capacity and the stiffness of the connection. However, the stiffness improvement is higher from thin to medium than from medium to thick column thickness, indicating a possible optimum combination between concrete strength and column face thickness.

Regarding the anchorage length, it was found that increasing the anchorage length significantly increases the component strength. For the bolt gauge distance, it was observed improvement of both the ultimate strength and the initial stiffness of the connection with the use of a larger bolt gauge distance. Besides, findings suggest that the use of small gauge distance leads to stress concentration in the concrete between bolts limiting the anchorage effect.

From the concrete analysis, it was observed that the failure starts with anchorage failure caused by concrete crushing in front of the anchor nut, followed by column face bending and finally pull-out of the bolts. An increase in the concrete strength resulted in improvement of the component stiffness and significant enhancement in the component strength. On the other hand, the use of self-compacting concrete affected neither the strength nor the stiffness of the component while the use of light weight concrete reduces both.

From the study summarised above, it can be seen that a wide range of parameters have been assessed under monotonic tensile load. However, other load types have not been considered.

3.1.3. Combined failure

Cabrera et al. [62] developed and validated a Finite Element (FE) model combining the results from research performed independently on the bolt [3] and column face components [56] in order to produce a combined failure. The effect of varying the column face thickness on the connection behaviour was assessed showing that components with small slenderness ratios (thick column walls) resist higher load before concrete failure. It was concluded that the first failure signs are caused by concrete crushing accompanied with SHS yielding. After this, the component strength is dependent mainly on the bolt properties in tension (bolt necking and rupture).

Debnath and chan [63] used the experimental results reported in [64] to validate a numerical model and perform parametric studies to evaluate the influence of design variables in the behaviour of the connection when using a single EHB under tensile load. Investigated parameters include bolt embedment length, bolt grade, bolt diameter, concrete grade, and tube thickness. The authors concluded the connection stiffness is influenced by slenderness ratio, concrete strength, bolt diameter, and embedment depth, while strength is dependent on bolt diameter (when high stength concrete is used), concrete grade, and embedment length.

From the tension zone assessment, it is observed that most studies have been carried out in the bolts in tension component, followed by the column face in bending component. Up to date, only numerical analyses have been carried out to assess the combined failure mode. Ultimately, this is the condition to which the connection would be subjected to in construction so further studies are required to complement the component method calculation for this kind of blind bolt.

3.1.4. Bolts in combined tension and shear

It is generally assumed in plastic design of bolted connections that shear forces are resisted mainly by bolts in the compression zone plus a small contribution (28% of the shear resistance) of bolts in the tension zone [65], and therefore some bolts are subjected to a combination of these forces. Pitrakkos et al. [66] studied the performance of a single EHB when subjected to various ratios of combined tension and shear forces. A total of 13 tests were conducted, from pure tension to pure shear, in order to propose an interaction curve for the studied blind bolt. The author found that the EHB behaves better than the HB as the concrete infill reduces the effect of bending in the bolt and prevents the pull-out failure. It was also observed that, at predominant tension angles, the load-capacity of the bolts has increased with respect to predominant shear due to the fact that the shear stress area is increased by the area of the sleeves

3.2. Beam and column connection

Tizani et al. [14] assessed the performance of the connection using connection stiffness classification methods from Eurocode 3 [50] and their suitability for use as moment-resisting connections. The test arrangement consisted of a point load applied to the beam 1m away from the column face producing a moment into the connection. A total of eight specimens were tested with the samples designed to fail by the EHB in tension either by its pull-out or bolt shank fracture.

The authors used the beam-line method and Eurocode 3 [50] to classify the connection in terms of stiffness and strength. The results showed that all the tested connections are classified as semi-rigid and partial strength and none performed as nominal pin demonstrating the capability of the fastener to provide semi-rigid connections. Since the stiffness of the tested connections is relative to the attached beam, the normalised moment–rotation data was analysed varying the beam section sizes. It was concluded the connection behaviour is mostly semi-rigid and that rigid behaviour can be achieved in braced frames.

The seismic behaviour of CFSHS column joints with EHB blind bolts was studied by Wang [67] and Tizani et al. [68]. The authors performed six full-scale connection tests under quasi-static cyclic loading in order to investigate the inelastic hysteretic behaviour of the connection. The parameters investigated were amplitude of cyclic loading procedure, bolt grade, tube wall thickness, and concrete grade. The authors identified two failure modes. Mode I ”weak bolt – strong column face” was observed in specimens with thick tube face and/or high strength concrete infill. Mode II ”strong bolt – weak column face” had either thin column wall face or low concrete strength.

Table 3. Design parameters and ranges assessed by different authors.

Ref.	Analysis type*	Benchmark			Variables	
		N°	Bolt specimen**	Column	Name	Range
Bolt component						
[3]	Exp	1	M16-8.8-NA-90-C40	200x10	Bolt diameter	16 & 20
					Bolt Grade	8.8 & 10.9
					Anchored length	85, 90 & 130
					Concrete strength	C40 & C60
		4	Double sided connection M16-8.8-120-90-C40-P100	200x10	Bolt grade	8.8 & 10.9
					Gauge distance	90 & 120
					Pitch distance	100 & 140
					Concrete strength	C30, C40 & C50
[17]	Exp	1	M16-8.8-NA-NR-C40	200x12.5	Load range (kN)	50, 60, 70 & 90
					Frequency	0.2 to 5 Hz
[59]	Exp & Num	1	M16-8.8-NA-120-C30	220x10	Tube section	150x8, 250x150x10, 220x10 & 350x150x10
[61]	Exp & Num	2	M16-8.8-120-82-C20	240x180 x20	Gauge distance	120, 140 & 180
					Anchored length	82, 92 & 102
					Concrete strength	C20, C40 & C80
					Concrete type***	NW & LW
Column component						
[56]	Exp & Num	2	M16-RIG-80-80-C40	200x6.3 200x8 300x10	Tube thickness	5, 6.3 & 8
					Concrete strength	C24, C36 & C90
					Concrete type***	NW, NWSC, LW & LWSC
					Gauge distance	80, 140 & 180
					Anchored length	80, 103 & 112
Combined component						

Table 3. Design parameters and ranges assessed by different authors.

Ref.	Analysis type*	Benchmark			Variables	
		N°	Bolt specimen**	Column	Name	Range
[62]	Num	2	M16-8.8-80-80-C40	300x10	Tube thickness	5, 6.3 & 8
[63]	Num	1	M20-8.8-NA-90-C40	250x8	Embedment depth	0,60, 72, 80 & 90
					Bolt grade	8.8 & 10.9
					Bolt diameter	12, 16 & 20
					Concrete strength	C40, C50, C60 & C70
					SHS cross section	250, 275 & 300
					Tube thickness	6, 10 & 12
Beam and column connections						
[14]	Exp & Num	2	M16-8.8-120-NR-C40-P100	200x10	Tube thickness	5, 6.3 & 8
					Concrete strength	C40 & C60
					Pitch distance	100 & 140
					Endplate type	Flush & Extended
[67]	Exp & Num	2	M16-8.8-120-NR-C50-P100	200x8	Tube thickness	5, 6.3 & 8
					Bolt grade	8.8 & 10.9
					Concrete strength	C20 & C50
					Beam section	UB356×171×67 UB457×152×52
[69] [70]	Exp & Num	2	M16-8.8-120-90-C40-P100	250x5	Tube thickness	5 & 12
					End plate thickness	12 & 24
					Beam section	HN350×175×7×11 HN300×150×6×9
					Bolt grade	8.8, 10.9 & 12.9
					Pitch distance	80, 100 & 120
					Bolt diameter	16, 18 & 20

***Analysis type:** Exp: experimental; Num: numerical.

****Specimen index:** Bolt (1)-(2)-(3)-(4)-(5)-(6), where: (1) Bolt shank diameter; (2) bolt grade, RIG: rigid bolt; (3) gauge distance, NA: not applicable; (4) anchored length, NR: not reported; (5) concrete grade; (6) pitch distance (optional). Column (1)x(2), where: (1) SHS width; (2) SHS thickness. N°: number of bolts per sample. All dimensions in millimeters.

*****Concrete types:** (NW) Normal Weight; (LW) Light Weight; (NWSC) Normal Weight Self Compacting; (LWSC) Light Weight Self Compacting.

It was concluded that the EHB connection provides stable hysteretic behaviour with appropriate level of strength and stiffness, and rigid behaviour can be achieved. The connection behaviour was suitable for seismic applications as it offered adequate energy dissipation capacity and ductility. This is particularly true for connections that exhibited failure mode II (flexible column face) which have high ductility and relatively low strength degradation under cyclic loading. It is suggested to control the connection failure mode in practice by designing for relatively thin tube face and/or low strength concrete.

Even though the performance of the connection when using both column face and bolt real mechanical properties was evaluated in [67], the failure modes reflect the extreme cases of either the bolt failure or the column face failure.

Wang et al. [69] tested six EHB flush endplate connections and developed a nonlinear FE model to assess the performance of the connection under quasi-static cyclic loading. The test results showed the capability of the EHB connection to effectively limit the deformation of the column face walls since the anchor nut transmitted the tensile force to the concrete. These results were closely examined in a FE model which allowed to identify the transmission path as: beam - endplate - bolt - concrete

- column wall. The influence of bolt grade, endplate thickness, pitch distance, bolt diameter, and pretension was assessed by means of FEA. The authors concluded that all the studied configurations can be classified as semi-rigid connections.

Wang et al. [70] conducted cyclic loading tests on seven extended-plate joints between CFSHS columns and open section beams. The authors investigated the effect of welding C-channels to locally strengthen the tube walls combined with the EHB fastener. It was found that this combination allows the joint to fully utilize the bolt strength and enhance its performance in terms of strength and strength degradation. Studied parameters included the end-plate thickness, steel tube wall thickness, beam section size, local strengthening connection method, blind bolt anchorage method, and the inclusion of stiffeners.

Table 3 summarises the parameter ranges considered in the studies mentioned in this chapter and grouped according to the studied component.

3.3. Analytical modelling review

Based on the results from experimental and FEA, different authors have proposed equations to describe the global force-displacement response of the EHB connection and its components. Table 4 summarises the proposed equations found in the literature.

The numerical model developed by Pitrakkos [3] for a single EHB assumes three sources of deformability for the bolts in tension component: elongation of the internal bolt shank (k_b), slippage of expanding sleeves (k_{HB}), and slippage of the mechanical anchorage (k_M). The massless spring model proposed in Fig. 10 is used for the assembly of these individual components to estimate the EHB global force-displacement behaviour.

A regression analysis including a 95% prediction band was used to assess the reli-

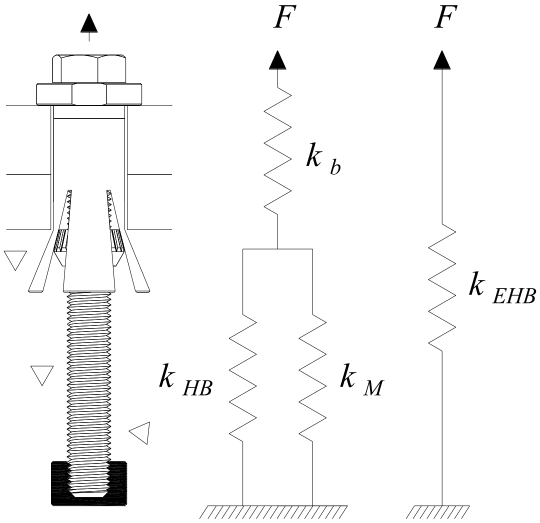


Fig. 10. Spring component model for EHB [3].

ability of the proposed analytical model. It was concluded that at the chosen prediction band level, the proposed component model predicts the experimental data with a good level of accuracy when considering different bolt batches, concrete strength, bolt grade, bolt diameter, and embedded depth.

Shamsudin [61] further developed the model presented in [3] to extend it to groups of EHBs using two regressions models: simple linear regression and multiple linear regression. The proposed model is based on deformation calculations at four different force intervals. Both models where validated against experimental and FE models displaying an error margin of 5%. It was concluded that the proposed equations show good level of accuracy when predicting the group component behaviour withing the ranges of validity of the analysis.

Table 4. EHB analytical models developed by different authors.

Ref	Model	Proposed equations	Variable definition
Bolt component			
[3]	Tetra-linear global force-displacement using Spring component model	$F_{EHB} = min(F_{HB} + F_M; F_b)$ $\delta_{EHB} = min(\delta_{HB}; \delta_M) + \delta_b$ $k_{EHB} = \left(\frac{1}{K_{HB} + k_M} + \frac{1}{k_b}\right)^{-1}$	Where: **HB, M, b**: sleeves, mechanical anchorage, and internal bolt shank components respective properties.
[61]	Tetra-linear global force-displacement using simple linear regression	$\delta_1 = \frac{0.15F_u}{c_{c,i,g}k_{i,g,80}}$, $\delta_2 = \frac{0.85F_u - 0.15F_u}{c_{c,i,g}k_{i,g,80}} + \delta_1$ $\delta_3 = \frac{0.90F_u - 0.85F_u}{c_{c,i,g}k_{i,g,80}} + \delta_2$ $\delta_4 = \frac{F_u - 0.90F_u}{0.02k_x^e} + \delta_3$	$\mathbf{k_{i,g,80}}$: stiffness for gauge g and concrete C80. $\mathbf{c_{c,i,g}}$: proposed coefficient for gauge distance g. $\mathbf{F_u}$: bolt ultimate strength. $\mathbf{k^e{}_x}$: bolt elastic stiffness.
	Tetra-linear global force-displacement using multiple linear regression	$\delta_1 = \frac{0.15F_u}{-232.7 + 1.9f_{cu,i} + 1.2G_i + 2.2ED_i}$ $\delta_2 = \frac{0.85F_u - 0.15F_u}{-203.2 + 1.3f_{cu,i} + 1.2G_i + 2.2ED_i} + \delta_1$ $\delta_3 = \frac{0.90F_u - 0.85F_5}{-219.4 + 0.5f_{cu,i} + 0.8G_i + 3.0ED_i} + \delta_2$ $\delta_4 = \frac{F_u - 0.90F_u}{0.02k_x^e} + \delta_3$	$\mathbf{f_{cu,i}}$: concrete strength $\mathbf{G_i}$: bolt gauge distance $\mathbf{ED_i}$: embedment depth $\mathbf{k^e{}_x}$: bolt elastic stiffness.

Table 4. EHB analytical models developed by different authors.

Ref	Model	Proposed equations	Variable definition
		Column component	
	Tetra-linear global force-displacement using yield line theory and spring method	$k_{i,single} = \dfrac{E_s t_{eq}^3}{24\gamma_f (b-2t)^2(1-\nu^2)}$ $k_{i,double} = \dfrac{E_s t_{eq}^3}{12\gamma_f (b-2t)^2(1-\nu^2)}$	$\mathbf{E_s}$: SHS Young modulus. $\mathbf{t_{eq}}$**:** equivalent thickness. $\gamma_\mathbf{f}$: deflection coefficient. **b**: SHS width, **t**: thickness, & ν: Poison ratio.
[56]	Tetra-linear global force-displacement using yield line theory and spring method	$F_{p,single} = 2\pi M_p \left(1 + \dfrac{R_s + r}{R_s}\right) + 2M_p \left(\dfrac{2g - 2r}{R_s + r}\right)$ $F_{p,double} = 4\pi M_p \left(1 + \dfrac{R_s + r}{R_s}\right) + 4M_p \left(\dfrac{2g - 2r}{R_s + r}\right)$ $F_{p,comb} = 2\pi M_p \left(1 + \dfrac{R_s + r}{R_s}\right) + 2M_p \left(\dfrac{3p + 3g - 4r}{R_s + r}\right)$ $k_1 = \dfrac{0.75F_p}{\delta_1},\ k_2 = \dfrac{0.25F_p}{\delta_2 - \delta_1},\ k_3 = \dfrac{F_d - F_p}{\delta_3 - \delta_2},\ k_4 = \dfrac{F_u - F_d}{\delta_4 - \delta_3}$	$\mathbf{R_s}$: yielded area radius **r**: radius of bolt hole **g, p**: gauge & pitch $\mathbf{M_p}$: plastic moment of resistance for a unit length of SHS plate. $\mathbf{F_p}$: plastic strength. $\mathbf{F_d}$**:** lowest strength after plastic load. $\mathbf{F_u}$: ultimate column face strength. δ_i: column face displ.
		Combined component	
[62]	Tetra-linear global force-displacement using spring component method	$k_1 = 95t + 263,\ k_2 = \dfrac{0.8F_p}{\delta_2 - \delta_1},\ k_3 = \dfrac{F_d - F_p}{\delta_3 - \delta_2},\ k_4 = \dfrac{F_u - F_p}{\delta_4 - \delta_3}$ $\delta_1 = \dfrac{0.2F_p}{k_1},\ \delta_2 = \dfrac{F_p}{0.28k_1},\ \delta_3 = 8.7\delta_2,\ \delta_4 = \dfrac{F_u}{0.001k_1}$	**t**: column face thickness. $\mathbf{F_p}$: plastic load. $\mathbf{F_d}$**:** drop load. $\mathbf{F_u}$: ultimate load.

Mahmood [56] used the yield line theory to derive equations for the the column face plastic load ($\mathrm{F_p}$) and initial stiffness. It was assumed that $\mathrm{F_p}$ is equal to the resistance provided by the SHS plate and the anchorage action. The overall behaviour of the component is divided into four stages: initial, secondary, drop and membrane action. The proposed analytical models showed the ability to represent the component behaviour with acceptable level of accuracy when compared to experimental and numerical data.

Cabrera et al. [62] combined the analytical models proposed by Mahmood [56] for the column face in bending and Pitrakkos [3] for the bolts in tension in order to represent the global behaviour of the combined component. The proposed equations were validated using numerical results from FEA obtaining reasonable agreement within an error band of 15%.

4. Sensitivity Analysis

Sensitivity Analysis (SA) allows to study how the output of a model is affected by the input variation or uncertainty. In this way, SA has been used in different engineering models to determine which parameters are key in a model and rank them according to their importance. Different applications of SA can be found in [71].

As summarised in the previous section, different authors have studied the influence varying design parameters on the EHB connection response under different loading cases. In this section, the influence of varying the studied parameters is assessed by means of SA.

Two representative studies have been chosen in the present work to perform a SA: Mahmood [56] for the column component and Shamsudin [61] for the bolt component.

4.1. Scatter Plots

Scatterplots allow for the investigation of the behaviour of the models by visual inspection when the number of important components is low. Fig. 11 and Fig. 12 show the scatterplots obtained after performing data standardization to the connection variables and response for the column and bolt components, respectively. Eq. 1 was used to standardize the data.

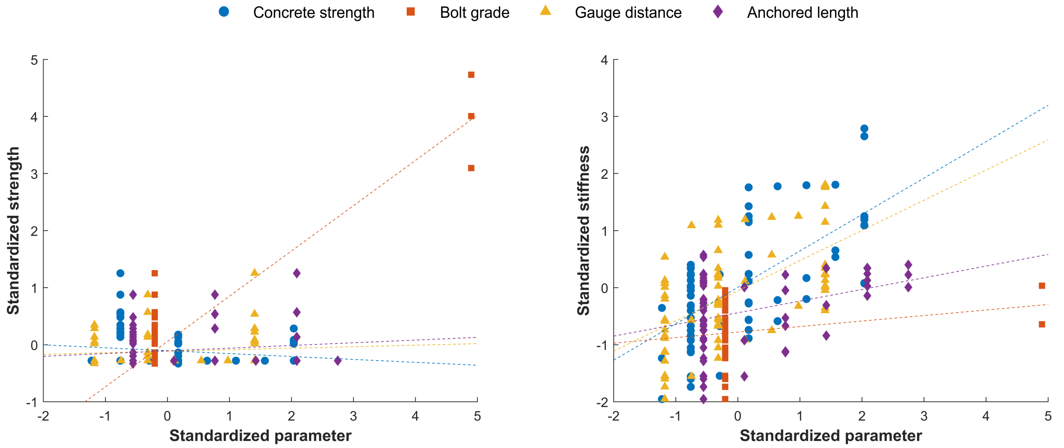
$$Z_i = \frac{x_i - \mu}{\sigma} \tag{1}$$

Where Z_i is the standardized value, x_i is the observed value, μ is the mean, and σ is the standard deviation of the sample.

The scatterplots for the bolt component in Fig. 11a show that the connection strength is only influenced by the bolt grade. This expected as the failure corresponds to bolt fracture and therefore the strength properties of the bolt define the connection strength, this is also in agreement with Pitrakkos [3]. On the other hand, Fig. 11b shows that all studied parameters have a positive correlation with the connection stiffness such that the parameter influence can be rank as: concrete strength > gauge distance > anchored length > bolt grade.

In the case of the column component, a linear relationship between component strength and concrete grade can be observed in Fig. 12a with this parameter being the most influential. In the case of gauge distance and anchored length, parabolic correlations are observed. On the other hand, the slenderness ratio has a negative correlation with the strength of the connection as the wall thicknesses is inversely proportional to the slenderness ratio, this parameter has the smallest influence on the component strength.

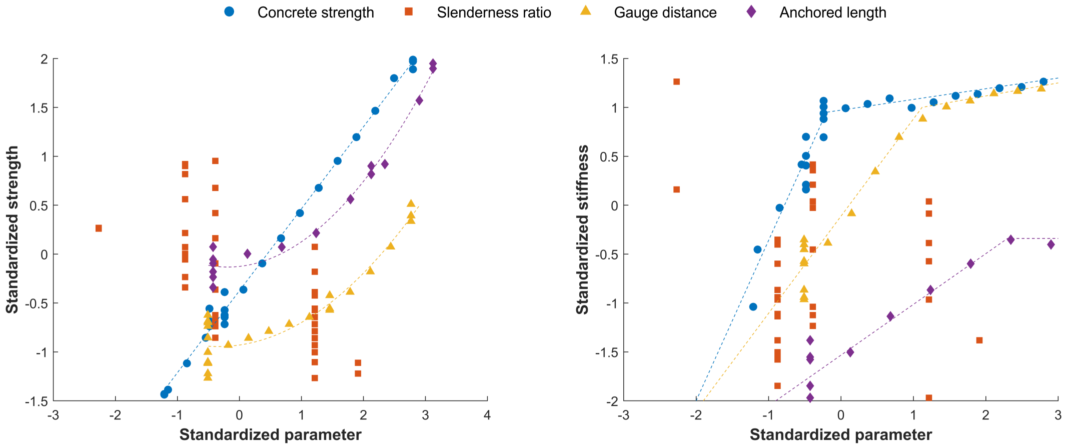
Fig. 12b shows gauge distance to have a bi-linear tendency which is in agreement



(a) Strength sensitivity analysis.

(b) Stiffness sensitivity analysis.

Fig. 11. Scatterplots of connection response versus design parameters from bolt component studies by Shamsudin [61].



(a) Strength sensitivity analysis.

(b) Stiffness sensitivity analysis.

Fig. 12. Scatterplots of connection response versus design parameters from column component studies by Mahmood [56].

Table 5. Parameter sensitivity measures calculated using EE method.

Parameter	**Strength**			**Stiffness**		
	μ^*	μ	σ	μ^*	μ	σ
Bolt Component						
Concrete strength	0.006	-0.006	0.025	0.786	0.786	0.762
Bolt grade	0.737	0.737	0.087	0.063	0.050	0.049
Gauge distance	0.014	0.014	0.039	0.680	0.680	0.415
Anchored length	0.012	-0.012	0.041	0.359	0.359	0.265
Column Component						
Concrete strength	0.797	0.797	0.456	1.147	0.071	1.634
Slenderness ratio	0.352	-0.352	0.112	0.545	-0.441	0.342
Gauge distance	0.471	0.471	0.268	0.596	0.596	0.531
Anchored length	0.468	0.468	0.339	0.523	0.523	0.086

with the literature which states that the initial stiffness is improved by an insignificant amount when large bolt gauges are used. Similar trends are observed for concrete strength and anchored length. The parameter influence on the component stiffness is classified as: concrete strength > gauge distance > slenderness ratio > anchored length.

4.2. Elementary Effects Method

Different SA measures have been developed to provide the information provided by scatterplots in a condensed format. The Elementary Effect (EE) is a SA method introduced by Morris in 1991 [72] and used to identify the most important model parameters when a relatively small number of sample points is available.

This method uses two sensitivity measures to identify the input factors to have more effects on the output of the system: the mean μ and the standard deviation σ of a finite distribution F_i. Consider a model Y with k normalized independent inputs $X_i, i = 1, ..., k$, hence varying in a k-dimensional unit cube across p selected levels. Therefore, the input spaced is discretized into a p-level grid Ω. For a given point X in this grid, the elementary effect of the ith input factor is given as:

$$EE_i = \frac{Y(X_1, X_2, ..., X_{i-1}, X_{i+\Delta}, ...X_k) - Y(X_1, X_2, ..., X_k)}{\Delta} \tag{2}$$

Where Δ is a value in $\{1/(p-1), ..., 1-1/(p-1)\}$, $X = (X_1, X_2, ...X_k)$ is any selected value in Ω such that the transformed point $(X + e_i\Delta)$ is still in Ω for each index $i = 1, ..., k$, and e_i is a vector of zeros but with a unit as its ith component.

The distribution of elementary effects associated with the ith input value is obtained by randomly sampling different X from Ω, denoted by F_i, i.e. $EE_i \sim F_i$. The mean μ estimates the overall influence of the input factor to the system response, while the standard deviation σ assesses the interaction effects with the other parameters as well as the nonlinear relation between the input [71].

The sign of the elementary effect might vary between different evaluation points, and therefore the value of the mean can lead to erroneous conclusions. To overcome this limitation, Campolongo et al. [73] proposed using μ^* which is the mean of the distribution of the absolute values of the elementary effects, denoted as G_i, i.e. $EE_i \sim G_i$. For the purpose of completeness, all sensitivity measures are calculated in this study.

The sensitivity indices for the studied standardized parameters are given in Table 5. The mean of the elementary effect absolute value μ^* allows to rank the parameters according to their influence in the strength and stiffness response of the system. For the bolt component, the most influential parameter in the component strength is the bolt grade. This result is expected as the failure mode of these components is bolt fracture, which is determined by the bolt ultimate strength. The following parameters are gauge distance and anchored length, which have similar sensitivity measures, and finally the concrete strength. The μ^* value for the bolt grade is significantly larger than the other three studied parameters concluding that the latest have low to insignificant influence in the system response. In the case of the stiffness response, the concrete strength and gauge distance are the most influential with similar values of μ^*, followed by the anchored length and the least influential parameter is the gauge distance.

In the case of the column component, the parameters are ranked as: concrete strength $>$ gauge distance $>$ anchored length $>$ slenderness ratio for the component strength, and concrete strength $>$ gauge distance $>$ slenderness ratio $>$ anchored length for the component stiffness.

The EE method also identifies the nonlinear relationship between the studied parameters and the connection response. Large σ values, like the one obtained between concrete strength and connection stiffness for the column component, reflect the bi-linear behaviour observed in the scatterplots discussed in the previous section.

The classification obtained with scatterplots and EE method shows similar results increasing the reliability of the study.

5. Conclusions

A modified blind bolt, termed the Extended Hollo-Bolt (EHB), provides a convenient and reliable means of connecting to steel hollow sections. The EHB has shown to have superior performance in terms of moment and strength resistance, and initial stiffness when compared to the commercially available Hollo-Bolt (HB), showing potential to be used in moment-resisting connections. Studies available in the literature regarding this type of fastener have been reviewed here. It is found that there are areas which have not been addressed yet and therefore there is insufficient knowledge at present for the safe design of moment-resisting connections using the EHB. Other findings and recommendations from this research include:

- From the EHB joint tension zone review, it is found that the bolts in tension and column face in bending components are not fully characterized yet. These components are required in order to extend the component method from EC3 for this type of blind bolted connection. From the range of studies found in the literature assessing the joint zones independently, it is found that special attention has been paid to the bolts in tension component. A wide range of design parameters such as: bolt diameter and grade, anchored length, concrete grade and type, and gauge and pitch distance have been assessed. Additionally, the connection has been subjected to different loading procedures: monotonic tensile pull-out, quasi-static cyclic and thermal. On the other hand, for the column face in bending component, studies addressing the behaviour of the connection when varying the tube thickness, anchored length, gauge distance, concrete strength and grade are found only under monotonic tensile pull-out. In the case of combined failure mode, only numerical and analytical models are presented with no experimental tests performed. It is concluded that further studies are required in the combined failure mode in order to fully characterize the connection behaviour.

- The whole connection (beam and column) has been experimentally and numerically studied under quasi-static cyclic loading for different tube thickness, concrete strength, pitch distance, endplate type and thickness, bold grade and diameter, and beam section. The moment-rotation behaviour of the connection shows semi-rigid and rigid behaviour as well as adequate performance for seismic applications. Additionally, the moment-rotation behaviour of the connections has been addressed when a rigid column is used. However, the whole connection behaviour has not been fully characterized when all components can deform and therefore further studies are required..

- A review of the available analytical studies performed by different authors shows that the spring component method is widely adopted for the components in the tension zone of the EHB connection. All models describing the global force-displacement behaviour of the connection adopt tetra-linear models and present equations for the stiffness and/or displacement for the four linear sections of the graph. Analytical models for whole connections are not found in the literature.

- Sensibility Analysis (SA) was performed using two representative studies of the column and bolt components of the tension zone of the EHB connection. Scatterplots and the Elementary Effect (EE) method were used to rank the importance of the model parameters with respect to their effect on the connection response to tensile loading. Both methods yielded similar results. The concrete grade shows to be the most influential parameter in terms of stiffness of the bolt component, and both strength and stiffness of the column component. In the case of the bolt component, the bolt grade has shown to have the highest effect on the component strength. All parameters considered in the SA have shown to influence in the connection response, either in terms of strength and/or stiffness, and therefore, it is recommended to continue considering them in future studies.

- The considered parameters produce different effects in each independent component, i.e., bolts in tension and column face in bending. Therefore, further parameter studies are recommended to be performed for combined failure mode, and beam and column connections in order the identify the most influential parameters for the whole joint.

Funding

This research received funding from the University of Nottingham and materials from Lindapter International.

Acknowledgments

The authors wish to acknowledge TATA Steel, Lindapter International, and the University of Nottingham HPC, for supporting this research.

References

[1] T. C. Barnett, The Behaviour of a Blind Bolt for Moment Resisting Connections in Hollow Steel Sections, Ph.D. thesis, University of Nottingham, 2001.

[2] Z.-Y. Wang, Q.-Y. Wang, Yield and ultimate strengths determination of a blind bolted endplate connection to square hollow section column, Engineering Structures 111 (2016) 345 – 369.

[3] T. Pitrakkos, The Tensile Stiffness of a Novel Anchored Blind-bolt Component for Moment-resisting Connections to Concrete-filled Hollow Sections, Ph.D. thesis, University of Nottingham, 2012.

[4] Y. Oktavianus, H. Chang, H. Goldsworthy, E. Gad, Component model for pull-out behaviour of headed anchored blind bolt within concrete filled circular hollow section, Engineering Structures 148 (2017) 210 – 224.

[5] S. A. Mahin, Lessons from damage to steel buildings during the northridge earthquake, Engineering Structures 20 (1998) 261 – 270.

[6] M. Nakashima, K. Inoue, M. Tada, Classification of damage to steel buildings observed in the 1995 hyogoken-nanbu earthquake, Engineering Structures 20 (1998) 271 – 281. Innovations in Stability Concepts and Methods for Seismic Design in Structural Steel.

[7] Federal Emergency Management Agency (FEMA-351), Recommended Seismic Evaluation and Upgrade Criteria for Existing Welded Steel Moment-frame Buildings, volume Chapter 2, SAC Joint Venture, 2000.

[8] Blind Bolt Company Ltd, Blind bolt uk, https://www.blindbolt.co.uk/, 2012. Accessed: 13th of February 2020.

[9] Arconic Fastening Systems and Rings, Huck bom brochure, https://www.arconic.com/, 2017. Accessed: 14th of February 2020.

[10] Advanced Bolting Solutions, Design resistance of molabolt peg anchors, http://molabolt.co.uk/, 2016. Accessed: 14th of February 2020.

[11] Flowdrill Ltd, Flowdrill brochure, https://www.flowdrill.com/, 2020. Accessed: 14th of February 2020.

[12] Ajax Engineered Fasteners, Oneside brochure b-n012 data sheet, 2002.

[13] Lindapter, Hollo-bolt product brochure, uk, 2019.

[14] W. Tizani, A. Al-Mughairi, J. Owen, T. Pitrakkos, Rotational stiffness of a blind-bolted connection to concrete-filled tubes using modified hollo-bolt, Journal of Constructional Steel Research 80 (2013) 317 – 331.

[15] Y. Kurobane, J. Packer, J. Wardenier, N. Yeomans, Design Guide for Structural Hollow Section Column Connections, volume 9 of *Construction with hollow steel*

sections, Comite international pour le developpement et letude de la construction tubulaire, 2004.

[16] L.-H. Han, W. Li, R. Bjorhovde, Developments and advanced applications of concrete-filled steel tubular (cfst) structures: Members, Journal of Constructional Steel Research 100 (2014) 211 – 228.

[17] N. Abd Rahman, Fatigue behaviour and reliability of Extended Hollobolt to concrete filled hollow section., Ph.D. thesis, University of Nottingham, 2012.

[18] J. France, J. B. Davison, P. Kirby, Moment-capacity and iffness of endplate connections to concrete-filled tubular columns with flowdrilled connectors, Journal of Constructional Steel Research 50 (1999) 35 – 48.

[19] L. C. Neves, L. S. da Silva, P. C. da S. Vellasco, Experimental behaviour of end plate i-beam to concrete-filled rectangular hollow section column joints, in: Advances in Steel Structures (ICASS '02), pp. 253 – 260.

[20] H. Yao, H. Goldsworthy, E. Gad, Experimental and numerical investigation of the tensile behavior of blind-bolted t-stub connections to concrete-filled circular columns, Journal of Structural Engineering 134 (2008) 198–208.

[21] W. Tizani, D. J. Ridley-Elis, The performance of a new blind-bolt for moment-resisting connections., in: Tubular structures X: proceedings of the 10th international symposium on tubular structures, pp. 395–400.

[22] Y. Oktavianus, H. M. Goldsworthy, E. Gad, Group behavior of double-headed anchored blind bolts within concrete-filled circular hollow sections under cyclic loading, Journal of Structural Engineering 143 (2017) 04017140.

[23] Y. Zhang, M. Liu, Q. Ma, Z. Liu, P. Wang, C. Ma, L. Sun, Yield line patterns of t-stubs connected by thread-fixed one-side bolts under tension, Journal of Constructional Steel Research 166 (2020) 105932 1–17.

[24] P. Wang, L. Sun, B. Zhang, X. Yang, F. Liu, Z. Han, Experimental studies on t-stub to hollow section column connection bolted by t-head square-neck one-side bolts under tension, Journal of Constructional Steel Research 178 (2021) 106493.

[25] H. Loh, B. Uy, M. Bradford, The effects of partial shear connection in composite flush end plate joints part i — experimental study, Journal of Constructional Steel Research 62 (2006) 378–390.

[26] H. Loh, B. Uy, M. Bradford, The effects of partial shear connection in composite flush end plate joints part ii—analytical study and design appraisal, Journal of Constructional Steel Research 62 (2006) 391–412.

[27] Y. Liu, C. Málaga-Chuquitaype, A. Elghazouli, Response and component characterisation of semi-rigid connections to tubular columns under axial loads, Engineering Structures 41 (2012) 510–532.

[28] A. Ataei, M. A. Bradford, H. R. Valipour, Experimental study of flush end plate beam-to-cfst column composite joints with deconstructable bolted shear connectors, Engineering Structures 99 (2015) 616–630.

[29] A. Ataei, M. A. Bradford, Numerical study of deconstructable flush end plate composite joints to concrete-filled steel tubular columns, Structures 8 (2016) 130–143.

[30] X. Li, Y. Xiao, Y. Wu, Seismic behavior of exterior connections with steel beams bolted to cft columns, Journal of Constructional Steel Research 65 (2009) 1438–1446.

[31] J.-F. Wang, L.-H. Han, B. Uy, Hysteretic behaviour of flush end plate joints to concrete-filled steel tubular columns, Journal of Constructional Steel Research 65 (2009) 1644 – 1663.

[32] J. Wang, L. Zhang, B. Spencer, Seismic response of extended end plate joints to concrete-filled steel tubular columns, Engineering Structures 49 (2013) 876–892.

[33] J. Wang, J. Wang, H. Wang, Seismic behavior of blind bolted cfst frames with semi-rigid connections, Structures 9 (2017) 91–104. Advances in Steel-Concrete Composite Structures.

[34] R. Waqas, B. Uy, H.-T. Thai, Experimental and numerical behaviour of blind bolted flush endplate composite connections, Journal of Constructional Steel Research 153 (2019) 179–195.

[35] Ajax Fasteners Innovations, Joint design usin oneside structural fastener, 2005.

[36] A. Gardner, H. Goldsworthy, Moment-resisting connections for composite frames, in: Mechanics of structures and materials conference. Balkema, Rotterdam, pp. 309–314.

[37] A. Gardner, H. Goldsworthy, Experimental investigation of the stiffness of critical components in a moment-resisting composite connection, Journal of Constructional Steel Research 61 (2005) 709 – 726.

[38] H. Yao, H. Goldsworthy, E. Gad, S. Fernando, Experimental study on modified blind bolts anchored in concrete-filled steel tubular columns, in: Australian Earthquake Engineering Society Conference, Barossa Valley, Australia, pp. 1–9.

[39] Y. Oktavianus, H. Goldsworthy, E. Gad, Behaviour of headed anchor blind bolts embedded in concrete filled circular hollow section column, in: Australian Earthquake Engineering Society Conference, Lorne, Vic, Australia, pp. 1–9.

[40] Y. Oktavianus, H. Yao, H. Goldsworthy, E. Gad, Pull-out behaviour of blind bolts from concrete-filled tubes, Structures & Buildings 168 (2015) 747 – 759.

[41] H. Agheshlui, H. Goldsworthy, E. Gad, S. Fernando, Tensile behaviour of anchored blind bolts in concrete filled square hollow sections, Materials and Structures 49 (2016) 1511–1525.

[42] T. Pokharel, H. M. Goldsworthy, E. F. Gad, Tensile behavior of groups of double-headed anchored blind bolts within concrete-filled square hollow sections under cyclic loading, Journal of Structural Engineering 147 (2021) 04020349.

[43] M. Liu, X. Zhu, P. Wang, W. Tuoya, S. Hu, Tension strength and design method for thread-fixed one-side bolted t-stub, Engineering Structures 150 (2017) 918 – 933.

[44] X. Zhu, P. Wang, M. Liu, W. Tuoya, S. Hu, Behaviors of one-side bolted t-stub through thread holes under tension strengthened with backing plate, Journal of Constructional Steel Research 134 (2017) 53 – 65.

[45] T. Wulan, P. Wang, Y. Li, Y. You, F. Tang, Numerical investigation on strength and failure modes of thread-fixed one-side bolted t-stubs under tension, Engineering Structures 169 (2018) 15 – 36.

[46] P. Wang, T. Wulan, M. Liu, H. Qu, Y. You, Shear behavior of lap connection using one-side bolts, Engineering Structures 186 (2019) 64 – 85.

[47] T. Wulan, Q. Ma, Z. Liu, M. Liu, J. Song, J. Cai, P. Wang, Experimental study on t-stubs connected by thread-fixed one-side bolts under cyclic load, Journal of Constructional Steel Research 169 (2020) 106050.

[48] P. Wang, L. Sun, M. Liu, B. Zhang, X. Hu, J. Yu, Experimental studies on thread-fixed one-side bolted connection of beam to hollow square steel tube under static bending moment, Engineering Structures 214 (2020) 110655.

[49] L. Sun, M. Liu, Y. Liu, P. Wang, H. Zhao, J. Sun, Y. Shang, Studies on t-shaped one-side bolted connection to hollow section column under bending, Journal of Constructional Steel Research 175 (2020) 106359.

[50] European Committee for Standardisation (CEN), Design of steel structures, Part 1-8: Design of joints, Eurocode 3, 2005. EN 1993-1-8.

[51] J.-F. Wang, L.-H. Han, B. Uy, Behaviour of flush end plate joints to concrete-filled steel tubular columns, Journal of Constructional Steel Research 65 (2009) 925 – 939.

[52] Federal Emergency Management Agency (FEMA-350), Recommended seismic design moment-frame buildings, SAC Joint Venture, 2000.

[53] T. Barnett, W. Tizani, D. Nethercot, The practice of blind bolting connections to structural hollow sections: A review, Steel and Composite Structures 1 (2001) 1–16.

[54] S. Ellison, W. Tizani, Behaviour of blind bolted connections to concrete filled hollow sections, Structural Engineering 82 (2004) 16–17.

[55] T. Pitrakkos, W. Tizani, Z. Wang, Pull-out behaviour of anchored blind-bolt: a component based approach, Proceedings of the International Conference on Computing in Civil and Building Engineering (ICCCBE), pp. 509 1–7.

[56] M. Mahmood, Column Face Bending of Anchored Blind Bolted Connections to Concrete Filled Tubular Sections, Ph.D. thesis, University of Nottingham, 2015.

[57] J. Ribeiro, A. Santiago, C. Rigueiro, L. S. da Silva, Analytical model for the response of t-stub joint component under impact loading, Journal of Constructional Steel Research 106 (2015) 23 – 34.

[58] I. O. for Standardization, Mechanical properties of fasteners made of carbon steel and alloy steel — Part 1: Bolts, screws and studs with specified property classes — Coarse thread and fine pitch thread, Standard, ISO, 2009.

[59] A. M. Pascual, M. L. Romero, W. Tizani, Thermal behaviour of blind-bolted connections to hollow and concrete-filled steel tubular columns, Journal of Constructional Steel Research 107 (2015) 137 – 149.

[60] A. M. Pascual, M. L. Romero, W. Tizani, Fire performance of blind-bolted connections to concrete filled tubular columns in tension, Engineering Structures 96 (2015) 111 – 125.

[61] M. F. Shamsudin, Group Behaviour of Extended HolloBolts (EHBs) in Tension, Ph.D. thesis, University of Nottingham, 2019.

[62] M. Cabrera, W. Tizani, M. Mahmood, M. F. Shamsudin, Analysis of extended hollo-bolt connections: Combined failure in tension, Journal of Constructional Steel Research 165 (2020) 105766 1–14.

[63] P. P. Debnath, T.-M. Chan, Tensile behaviour of headed anchored hollo-bolts in concrete filled hollow steel tube connections, Engineering Structures 234 (2021) 111982.

[64] T. Pitrakkos, W. Tizani, Experimental behaviour of a novel anchored blind-bolt in tension, Engineering Structures 49 (2013) 905 – 919.

[65] Steel Construction Institute (SCI) and British Constructional Steelwork Association (BCSA), Joints in steel construction: Moment-resisting joints to Eurocode 3, Steel Construction Institute, 2013.

[66] T. Pitrakkos, W. Tizani, M. Cabrera, N. Faqe Salh, Blind bolts with headed anchors under combined tension and shear, Journal of Constructional Steel Research 179 (2021) 106546.

[67] Z. Wang, Hysteretic response of an innovative blind bolted endplate connection to concrete filled tubular columns, Ph.D. thesis, University of Nottingham, 2012.

[68] W. Tizani, Z. Y. Wang, I. Hajirasouliha, Hysteretic performance of a new blind bolted connection to concrete filled columns under cyclic loading: An experimental investigation, Engineering Structures 46 (2013) 535 – 546.

[69] Y. Wang, Z. Wang, J. Pan, P. Wang, Nonlinear finite element analysis of anchored blind-bolted joints to concrete-filled steel tubular columns, International Journal of Performability Engineering 15 (2019) 676–687.

[70] Y. Wang, Z. Wang, J. Pan, P. Wang, J. Qin, S. Chen, Cyclic behavior of anchored blind-bolted extended end-plate joints to cfst columns, Applied Sciences 10 (2020).

[71] A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. G. M. Saisana, S. Tarantola, Global sensitivity analysis, The primer. John Wiley & Sons, 2009.

[72] M. Morris, Factorial sampling plans for preliminary computational experiments, Technometrics 33 (1991) 161–174.

[73] F. Campolongo, J. Cariboni, A. Saltelli, An effective screening design for sensitivity analysis of large models, Environmental Modelling & Software 22 (2007) 1509 – 1518.