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Bolted connections to tubular columns at ambient and elevated temperatures - A review

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Abstract. Tubular column members have been widely adopted in current construction due to its numerous advantages. However, the closed-section profile characteristics of tubular columns severely limit the connection possibilities. Welding type is acceptable but discouraged because of on-site issues. Blind-bolted connection is preferable because of its simplicity, economic benefit, and easy assembly. This paper presents a state-of-the-art review on bolted connections to tubular columns for bare steel tubes, including square and circular sections. Available studies on bolted connections at ambient and elevated temperatures are reviewed, but emphasis is given on the latter. Various methods of determining the connection performance through experimental, analytical, component based, and finite element approaches are examined. Future research areas are also identified.

Keywords: steel bolted connections; tubular columns; blind bolt; elevated temperature

1. Introduction

Tubular columns have been widely adopted in a steel structure because of their geometrical property. With a higher radius of gyration, tubular columns have higher compressive strength than an open section with increasing buckling resistance. Thus, compared with the use of standard open-section columns, the use of tubular columns results in a total steel-weight-usage reduction between 14% and 24% for seismic loads resisting moment frames (Kang *et al*. 2001). The closed-profile concept of the hollow section works similarly to formwork, and the cavity is often filled with concrete to increase the strength and the load carrying capacity of the column (Cheng and Chung 2003, Tizani *et al*. 2013b). Concrete addition also provides a new option for bolts to be effectively anchored into the column, thus increasing the tension resistance because of the bond between the bolt threads and concrete. In general, tubular columns in construction can be divided into bare steel tubes (BST) or concrete-filled tubes (CFT). Owing to the increased stiffness at the column due to the in-filled concrete, the rotational axis is shifted to the compression area of the beam, thus causing the connection to have high stiffness and moment capacity at the cost of low connection ductility (France *et al*. 1999c).

In connecting steel beams to tubular columns, welded connection is considered as one of the

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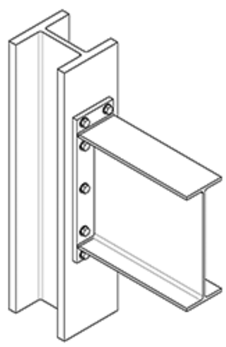
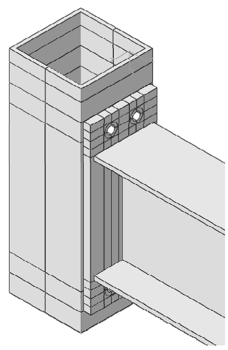
acceptable solutions with good connection performance (Beutel *et al*. 2001, Torabian *et al*. 2012, Qin *et al*. 2014). Welding may either involve direct connection on the tubular column face (Shin *et al*. 2004) or a through-beam method (Elremaily and Azizinamini 2001). However, connections that require on-site welding are not preferred because of the limit in allowance for welding in volatile gas work sites and worker's skill that governs the welding quality. Load bearing members are also not recommended to be welded directly on the column face to avoid failure at the welding points (Alostaz and Schneider 1996). Shen and Astaneh-Asl (1999) described the advantages of bolted connections to open-section steel columns over welded connections. The advantages are also applicable to tubular columns. Therefore, the practicality of total welded connections is reduced, and bolting method is preferred.

Although bolted connection has advantages over welded connection, a major drawback is identified with the use of tubular columns. As shown in Fig. 1 for bolted end-plate connections to both column types (Ghobarah *et al*. 1996, Adam and Hamburger 2010), tubular columns limit the available options for a bolted connection. Conventional bolted connections are not feasible because of the limited access to the nut, which severely hinders the tightening process and results in an incomplete connection. Modifications on the bolting connection type by changing the bolt type and mechanism are needed to solve this problem. A combination of both welding with standard bolts within a single connection has also been proposed. However, a large number of different assemblies are available and considerable researches have been conducted. The latest studies are highlighted in this paper. Regardless of the connection configuration, the load transfer mechanism should be understood for each configuration.

Structural steel has the risk of being exposed to high-temperature conditions, such as in the occurrence of a fire. The requirement of a performance-based design highlights the needs for evaluating the fire resistance of steel structures in terms of their structural and thermal responses given a set of loading and fire exposure conditions. Recent fire cases and full-scale fire tests show that joints may often be the weakest link in a structural frame in fire conditions. Extensive studies are available on structural members under fire, such as beams, columns, and connections for open section steel members, including studies conducted by Liu *et al*. (2002), Saedi Daryan and Yahyai (2009), Wang and Wang (2013), Mao *et al*. (2009) and Li *et al*. (2012). However, the number of studies conducted for steel connections in tubular column at elevated temperatures is relatively small.



(a)



(b)

Fig. 1 General end-plate connections to (a) Open section column (Adam and Hamburger 2010); (b) Tubular column

This paper highlights the latest studies conducted on bolted connections and the combination of bolted/welded connections to tubular columns at ambient and elevated temperatures. Emphasis is given to elevated temperature studies because the behavior of the connection components in tubular column is not understood well under fire condition. This article reviews the different methods of studies adopted in literature, including experimental testing, finite element (FE) modeling, component-based approach, and analytical methods. Suggestions on the areas to be explored on bolted connections to tubular columns are also highlighted.

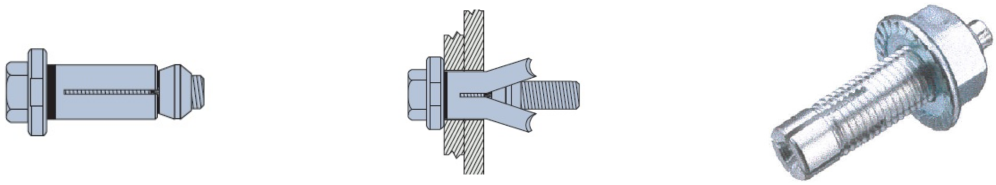
2. Blind bolt studies

In connections to tubular columns, the standard bolts in a bolted connection must be modified to hold the member in place. Modifications on the bolt type involve the use of blind bolts that require only one-sided tightening and access. This requirement raises the major concept of the capability to hold the bolt in place while forces are being transferred through these bolts. Currently available commercial brands (Tizani *et al*. 2013a) include the following: Hollo-Bolts (Lindapter International, UK), which provide one-sided bolt-tightening through expansion of the sleeve; flowdrill bolts (Flowdrill B.V., The Netherlands), which create nut imitating grooves on member; Molabolts (Advanced Bolting Solutions, UK); HuckBolts (Huck International, USA), which compress the sleeve; AJAX bolts (Ajax Engineered Fasteners, Australia), which have collapsible washers, which are shown in Fig. 2. To understand the behavior of modified bolted connections, various studies of blind bolts connection to tubular columns are investigated. The basic investigation for these bolts is on the tension and shear behavior because bolts are usually loaded in either forces in any connection.

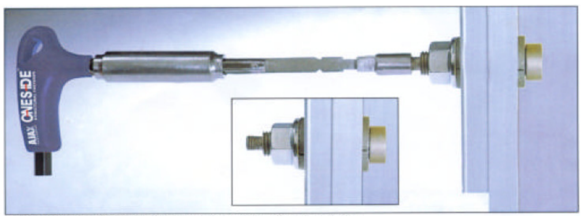
Studies on Hollo-Bolts have been conducted on shear behavior in both single and double shears (Liu *et al*. 2012b). Owing to the significantly larger holes required to fit Hollo-Bolts, the out-of-plane deformation is higher in Hollo-Bolts than in standard bolts (Elghazouli *et al*. 2009). The increased hole sizes also cause the initial stiffness of the connection to be lower than when a standard bolt is utilized. The pullout of the bolt from the column is a common failure because of the increased hole size. In summary, Hollo-Bolts deform by pullout through a large hole when subjected to tension loads.

In terms of mechanism, the flare component of Hollo-Bolts has been found to have relatively low contribution to the overall bolt behavior (Wang *et al*. 2010). Compared with standard bolts in T-stub, the tension behavior works in reverse. Thick members are advantageous to blind bolts, whereas thin members work well for standard bolts. Comparison among threaded long bolts, standard blind bolt, and extended blind bolt has also been conducted (Pitrakkos and Tizani 2013). In this study, the performance of extended blind bolt exceeds the performances of the other two variations under tensile tests.

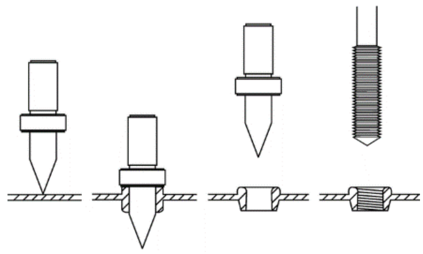
Tizani and Ridley-Ellis (2003) tested a Reverse Mechanism Hollo-Bolt (RMH) that was proposed by Barnett *et al*. (2000), as shown in Fig. 3. Connections made with standard Hollo-Bolts are lacking in clamping force and are generally not considered as moment-resisting connections. The testing setup included a T-stub connected to another T-stub, and axial tension was applied. The other setup involved a thick T-stub connected to a tubular column, and tension loads were applied. The bending of the T-stub was eliminated because of the thickness. The test results show that RMH has higher ductility than standard bolts and that its stiffness has comparable properties to standard bolts. Although this modified bolt has greater performance than Hollo-Bolts, this setup has not been used for other subsequent research.



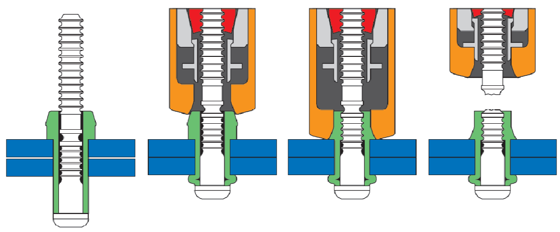
(a) Hollo-bolts (b) Molabolts



(c) AJAX-Bolts



(d) Flowdrill-bolts



(e) Huck-bolts: Blind Oversized Mechanical (BOM)

Fig. 2 Different blind-bolts available

The performance of HuckBolts is comparable with that of standard A325 bolt performance, whereas mechanically oversized bolts has low levels of resistance (Korol *et al*. 1993). The resistance factors of HuckBolts and A325 bolts are 0.65 and 0.75, respectively. This insignificant difference in resistance factor shows that HuckBolts have a comparative behavior with standard structural bolts (Tabsh and Mourad 1997). Other studies on connections by using flowdrill bolts (France *et al*. 1999a, c) have shown that flowdrill bolts are as capable as standard bolts. These studies have indicated that blind bolts are generally suitable for connections to tubular columns.

In terms of design for Hollo-Bolts and flowdrill bolts, the guidelines provided by the British Steel (1997) organization are applicable. In the guideline, shear and tension values for bolts are provided. The geometrical requirements to be used with these blind bolts are also shown. However,

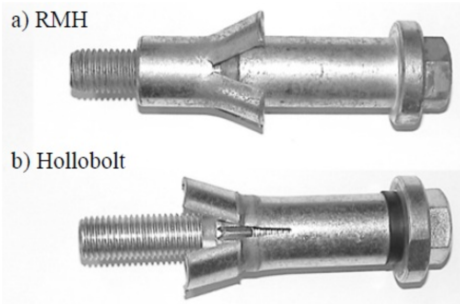


Fig. 3 Difference between RMH and Standard Hollo-Bolt (Tizani and Ridley-Ellis 2003)

no studies have compared these bolts in terms of their effectiveness, cost, load transfer mechanism and structural performance. A comparison of blind bolt types will be useful for design considerations and industrial applications.

3. Connection at ambient temperature

Extensive studies involving beam connections to tubular columns are available under ambient temperature conditions. In terms of loading, research with static loadings is focused in this paper because this is fundamental to the study on connections to tubular columns. Research works in the last decade on bolted connections to tubular columns with consideration to various adopted methods are highlighted in the following section.

3.1 Experimental studies

Experimental testing is the most accurate method for obtaining the actual connection behavior and forms the basis for further simulation and analytical works. Significant numbers of studies are available for end-plate connections by using blind bolts, including the work completed (Wang and Chen 2012, Wang *et al*. 2013). The proposed method by Maquoi *et al*. (1984) to weld threaded studs on to the column flange (Fig. 4) in order to act as the bolts for the incoming end-plate connections has been discussed in various studies (Korol *et al*. 1993, Barnett *et al*. 2001). It was recognized that each stud must be protected from damage during the erection and assembly stage. The small welded area of the bolt which is susceptible to failures due to the cantilever force acting on the bolt when the bolt clashes with other elements. Meanwhile, deformation of the column in the threaded stud connection is determined using the component method from EN1993-1-8 (2005) in a study conducted by Vandegans and Janss (1995).

Sufficient information on the behavior of end-plate connections is available, including connections to open-section columns. The major difference in these two connections is the column and bolt components, which are unique to the connection to tubular columns. Thus, other connection types, such as the top-seat angle connection, are currently being examined.

To observe the actual shear deformation from blind bolts, a series of connections by using angle connections is tested. The angle is subjected to shear load (Liu *et al*. 2012b). The resulting shear deformation is mostly contributed by the deformation of the angle section. Web angle connection configurations also have eccentricity because of the gap between the angle and column. Thick top

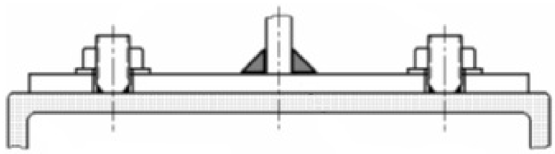


Fig. 4 Welded threaded studs

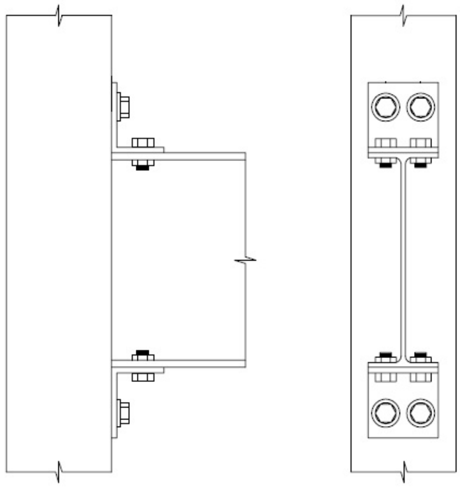


Fig. 5 Angle connections to tubular column (Elghazouli *et al*. 2009)

angle sections transfer shear forces onto the blind bolts. Connection ductility is increased with the use of blind bolts. For thin top angles, the deformation of the top angle section occurs; thus, prying force develops in the bolt. Therefore, bolts are not fully loaded in terms of shear force only but are also affected by tension forces developed from the prying action.

Elghazouli *et al*. (2009) investigated a series of connections by using angle connections depicted in Fig. 5. A total of 10 specimens were tested under monotonic loadings. Variations in the tests included angle thickness, tubular column thickness, beam size, and changes in blind-bolt grade. For angle connections, the bolt gauge distance and the stiffness of the angle contributed to the resistance of the connection. In cases where the angle is sufficiently stiff, the bolts will be affected by the grade and size. From the tests, three deformation patterns were observed with bolted angle connections, namely, bending of angle, pulling out of the blind bolt, and column flange pullout. As one of the critical components, the column thickness governed the connection behavior. The connection width should be similar to the column width to avoid any local deformation on the column face.

By using AJAX bolts, standard bolts, and plates, Lee *et al*. (2010c) proposed a series of moment connections consisting of extended T-stub to BST tubular columns (Fig. 6). The column and T-stub components were studied by connecting a T-stub to the column and subjected to axial loading. The column had a punching failure in tension, and crushing failure is observed in compression. The full connection was tested after the components were studied. Connection to the column sides was also proposed by using channels and plates (Lee *et al*. 2010b). Further moment connection proposals were made (Lee *et al*. 2011a, b), The concept was to move away

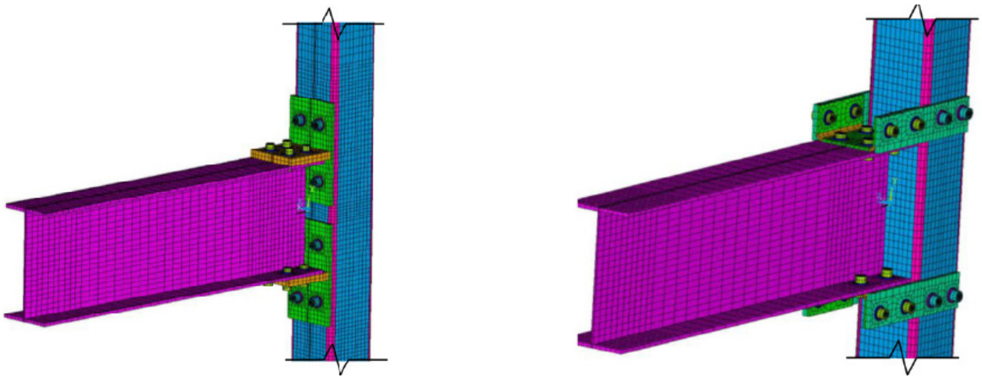


Fig. 6 Extended T-stub and channel connection to tubular column (a) Lee *et al*. 2010c, (b) Lee *et al*. 2010b)

from the flexible face of the column and utilize the entire column section to resist the applied loadings. The extended T-stub and channel was concluded to be five times stiffer than the connection in the previous study. The connection was considered as rigid to EN1993-1-8 (2005) standards. However, the proposed connections were relatively complicated and required multiple fabrication works for only a single joint. Fabrication simplicity is often preferred to reduce construction time.

To avoid utilizing blind bolts, several connections are proposed, which emphasized on the usage of standard bolts with welding of specific parts of the connection. This method combines the use of standard bolts and connectivity to tubular columns. According to another test conducted at elevated temperatures (Ding and Wang 2007), a reverse channel connection (Fig. 7) displays advantageous behavior. Compared with direct column connections, including end plate and fin-plate connections, reverse channel connection was adopted by Málaga-Chuquitaype and Elgazhouli (2010a) for further studies at ambient temperatures. A series of tests under monotonic loadings was conducted for top-seat angle connections with reverse channel. The effects of angle thickness, column thickness, and reverse channel thickness were studied. Similar to previous studies using angle connections, the affecting parameter included gauge distance, angle thickness, reverse channel thickness, and provision of web angles. Without the use of blind bolts, bolt pullout failure did not occur in this study. In thin-walled members, column flange pullout usually occurs in members when using bolted connection.

Reverse channel connections with end-plate connections are tested under monotonic loading to determine the moment-rotation behavior (Wang and Xue 2013). Several specimens are fabricated. The end-plate thickness, reverse channel dimensions and thickness, column width, and the type of end-plate connection were studied. The main outcome is the deformation and failure of the reverse channel, and a column width that is similar to connected member length results in minimal column deformations. The critical point for this connection type is commonly at the heel of the reverse channel. When a thin end plate is used, bolt pullout failure may occur at the reverse channel web.

By using a concept similar to beam splicing, Bagheri Sabbagh *et al*. (2013) proposed new connections wherein the beam was bolted to an external diaphragm and a web fin plate. Among the three connections proposed, the connection shown in Fig. 8 was selected for further experimental testing. By substituting a fin plate for a T-section, Al-Rodan (2004) proposed a connection with

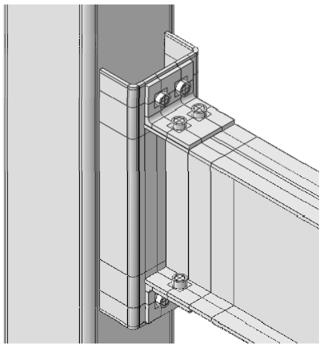


Fig. 7 Reverse channel connection

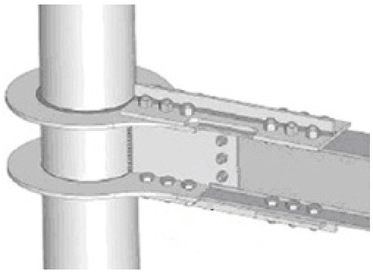


Fig. 8 Connection to CHS with diaphragm. (Bagheri Sabbagh *et al*. 2013)

better performance than the fin-plate connection. The welds increased the moment of inertia and the flange bending capacity.

Yao *et al*. (2008) used double T-sections bolted to circular hollow section(CHS) and square hollow section (SHS) columns at the top and bottom flanges of the beam. At the column, modified AJAX bolts with an additional perpendicular end were used, and the connection was shown to resist seismic loads. By realizing the issue with the welding of beams, Wu *et al*. (2005) proposed a connection wherein the bolts were connected through the depth of the CFT SHS column. Compared with other tests, the connection did not fail with an angular drift of 7%, whereas others reached up to 5%. The effect of the column width to thickness ratio was highlighted as the major contributing component to the dissipation of energy from the cyclic loads.

A similar concept has been explored in a series of connections involving CHS (Sheet *et al*. 2013). A comparison between CHS and SHS shows that the connections perform similarly and that a minimal difference exists between the two profiles. Another connection with through beams without welding and bolting is also proposed. An angular drift of 5% is achieved with the proposed through connection. Although a through component may seem a viable option, a through bolt raises the issue of fabricator accuracy and construction viability. Bolts can be inserted on one side and installed first; however, installing the other side will be difficult because of the exisitng stud from the bolts, thereby resulting in smaller clear distance for the beam. A probable scenario would be that the columns on the next gridline have to be pulled apart. If both beams will be installed together, multiple lifting equipment must be employed and the question of costs need to be further considered.

For tubular beams connected to tubular columns, Satish Kumar and Prasada Rao (2006) proposed a connection involving a welded channel to the tubular column and bolted to the tubular beam. Considering the closed section of the tubular beam, square gaps were cut to the side of the beam, thereby enabling access to the bolting of the beam. With the large gap, the failure mode would occur near the thinner side of the cutout at the beam. However, the tested connection showed sufficient ductility and was suitable for seismic designed steel structures.

3.2 Component-based method

The component-based method has been widely adopted to model the beam-to-column connection response. Different components have to be considered depending on the connection type, and the constitutive laws for each component are determined. A component method for connections to open-section columns is available and well established. The main difference for the tubular columns connection is the blind-bolt component and the behavior of the thin-wall tubular column flange. Other components can be assumed to behave according to the outline provided by EN 1993-1-8 (2005).

For connections using blind bolts, the behavior of the blind bolt is currently characterized through the linearization of force–deformation data from experimental tests conducted previously (Wang *et al*. 2010). In terms of the component method, this study focuses on the initial stiffness and resistance of the connection. The angle section behavior plays a significant role; therefore, Madas (1993) and Lin and Sugimoto (2004) compared the behavior proposed in EN 1993-1-8 (2005) to obtain accurate behavior. For end-plate connections, three failure modes have been proposed wherein effective gauge distances are altered accordingly for angle connections. The proposed dimensions are based on the stiffness of the angle section in tension zone. Wang *et al*. (2010) proposed Hollo-Bolt stiffness for the deformation of the flaring sleeve, including parameters for the area of the flaring sleeve, thickness of the shell element, meridional length, flaring sleeve angle coordinate, and angle coefficient. This proposed stiffness was combined with the bolt stiffness outlined in EN 1993-1-8 (2005) for the final stiffness.

In terms of the behavior for the column, Málaga-Chuquitaype and Elghazouli (2010b) proposed the stiffness of the tubular column face subjected to tension forces, which involved the column face width and column thickness. The resistance of a tubular column in tension was determined from the least resistance of the punching resistance and yielding (which depends on the number of bolts in tension, bolt hole diameter, bolt spacing and plastic moment capacity of the column face). Considering that the moment capacity of the column face would involve the column thickness and width, these parameters were not explicitly specified for the resistance of the column in tension. Other parameters for angle connections have been documented in previous studies, including the prying action. New dimensions are proposed for flexible angles wherein prying may occur. Bolt slippage is also considered. Slippage occurs when the acting forces overcome the friction between the two surfaces. The major components that influence the connection behavior are the column face flexibility and the Hollo-Bolt grade.

Other studies are based on individual component, and the summary of the interaction stiffness between bolts and columns is improved from the works of Jaspart (Jaspart *et al*. 2004) because of the separation of each bolt row as a component instead of the treatment of the tension zone as a whole (Park and Wang 2012). The contribution of the sidewall because of deformation has also been considered. However, it is assumed to be applicable to flowdrill bolts because of the verification with the test results in the study by France (France *et al*. 1999a, b, c). The behavior of flowdrill bolts and that of the more commonly used Hollo-Bolt are significantly different because of the mechanism and fastening method of each system.

Liu *et al*. (2012a) suggested new component characteristics for column faces in tension/compression and angles in the tension/compression of Hollo-Bolted and combined channel/angle connection. The resistance of the channel in the tension and stiffness of the column was obtained from previous studies (Wang and Guo 2012). Bolt stiffness and resistance in tension were set according to EN 1993-1-8 (2005), including three modes of failures. In terms of the compression area for the channel, the angle and channel were combined as a unit. Two yielding mechanisms were considered, and the occurrence of either mechanism depended on the angle stiffness. They were applicable to both angle connections directly connected to the tubular column or to the channel. However, the model can obtain accurate predictions only up to the yield capacity and initial stiffness of the connection.

3.3 Analytical method

The analytical method focuses on the derivation of rotational stiffness and moment resistance of a joint on the basis of the basic concepts of structural analysis. The derivation can also be used in the component method. Several well-known analytical models are available for connection in open-column section, as reviewed by Diaz *et al*. (2011), but are still limited for connections in tubular column. The total deformation of a connection to a blind-bolted end-plate tubular column is attributed to the deformation of the end plate and the column (Ghobarah, Mourad *et al*. 1996).

Park and Wang (2012) derived an analytical equation for predicting initial stiffness in bolted end-plate connections to RHS columns. The main assumption was that the infinite stiffness in the compression zone and tension zone deflection was calculated between bolts. Wang *et al*. (2010) proposed a new theoretical model for the initial stiffness of a blind-bolted connection on the basis of the bolted T-stub of EN 1993-1-8 (2005) and the analytical model of a conical shell for Hollo-Bolts. The model was successfully validated with experimental and FE models.

In contrast to other investigations that focus on the behavior of end-plate connections, Jones and Wang (2010) developed a method to determine the load displacement for a fin-plate connection to tubular columns. The maximum displacement and yield point can be determined depending on the ratio of the column thickness and width of the column connected side. Three failure mechanisms were defined, including membrane action only or a combination of membrane action and yield line. Further studies on the behavior of the tubular column under shear and bending loads have resulted in a simplified method to determine the capacity of the column when connected with a fin plate (Jones and Wang 2011) incorporating the yield line mechanism.

3.4 FE method

The FE method is the closest simulation to the actual behavior if proper settings are used. The basic T-stub component for joint analysis is developed for the parametric study of blind bolts (Elghazouli *et al*. 2009). On the basis of the test results, end-plate connections are modeled and different parameters are explored, including steel strength, concrete strength, bolt diameter, and end-plate thickness and width (Wang and Spencer Jr. 2013). Connection behavior is affected by the end-plate thickness and type. Liu *et al*. (2012a) modeled and analyzed the full geometry of Hollo-Bolts for comparison with actual test results. Similarly, Tizani *et al*. (2013b) modeled the entire bolt with SOLID95 elements by using ANSYS, including the extension at the back of the bolt regarded as a single component.

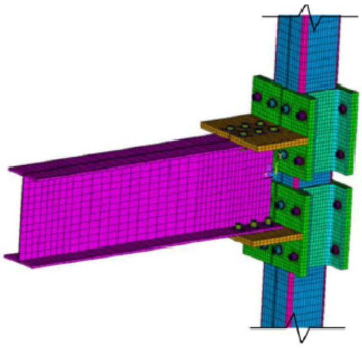


Fig. 9 FEM model of channel with T-stub connection (Lee *et al*. 2011b)

By using the shell element for the main members and connector elements for bolts, Bagheri Sabbagh *et al*. (2013) developed a connection model by using ABAQUS. The connection was further selected for experimental testing by using the results from the model. Comparison between the FE model and experimental test results by Lee *et al*. (2010b) shows that the results match closely with the proposed FE model by using ANSYS. To accommodate snug tight bolts, 50 kN pretension is used in the model. The results from experimental testing (Lee *et al*. 2011b) are used to validate the model of the proposed connection (Fig. 9).

Coupled with the experimental test results, Lee *et al*. (2010a) showed that the connection to the sides of the tubular column is a concept that can be explored. Although no comparison was conducted with the connection to the column flange, deformation limits were set to 1% and 3% of the column width for serviceability and ultimate states, respectively. Assuming that the tension loads were uniform, each bolt resisted an approximately 100 kN shear force at the maximum deformation. When loaded at 175 kN, the deformation between the column and plate was 0.5 mm. With this minor deflection, this concept can be used for moment-resisting connections to tubular columns.

Following the experimental test results of an earlier study on reverse channel connection (Wang and Xue 2013), FE model is proposed and validated in ABAQUS (AlHendi and Celikag 2015). Element C3D8R is used but no pretension is applied to the bolts. The validated model is used for further parametric studies to determine the parameters that affect connection behavior. A comparison is made with the moment-rotation behavior of the connections. Mesh sensitivity, friction effect, and load speed are explored prior to the actual study. The reverse channel is the critical component that affects the connection behavior with specific parameters such as the thickness, width ratio, and channel height. In terms of bolting, the use of large bolts and small gauge distances improves the connection behavior. To reduce the effects on the column face deformation, the channel height is recommended to have a ratio higher than 0.72.

In terms of yield line deformation, the reverse channel connection is further examined by using the ABAQUS FE software (Jafarian and Wang 2015). Analytical formulas from previous study are then applied to determine the yield load, ultimate resistance, and deflection. The yield pattern of the reverse channel depends on the position of the bolts. The ultimate resistance is governed by the membrane action of the reverse channel, punching shear of the plate, and bolt failure. A comparison with the test behavior indicates that the proposed method can predict connection stiffness with reasonable accuracy, but the post yield remains significantly stiffer than the actual behavior.

4. Connection at elevated temperature

This paper explores future research on tubular column connections at elevated temperatures. Recent studies in this area covering experimental and FE methods are reviewed in the following.

4.1 Experimental studies

Under high temperatures, steel material stiffness and strength degrade because of material degradation from external heat. The degradation of strength and stiffness is given in EN 1993-1-2 (2005). Testing at elevated temperature conditions is expensive because of the additional cost of providing a furnace. Several limitations are also presented, including the time factor. Owing to the high heat generated, specialized data measurement equipment that is able to withstand and continue working under elevated temperature conditions is required.

Several connection types are studied under the effect of elevated temperatures, including T-stub, fin-plate, extended end plate, and reverse channel connections to CFT columns (Ding and Wang 2007). Strain data are not measured because of the high cost of thermal strain gauges and their low performance at high temperatures. However, displacements and temperatures are measured by protecting the transducer with hollow ceramic tubes to minimize the effect of temperature on the transducers. Among the various connections tested, the reverse channel connection is considered one of the preferred connections because of its excellent ductility and performance under catenary action.

Eight tests have been conducted at ambient temperatures and at 550°C for fin-plate and reverse channel connections to CFT columns (Huang *et al*. 2013). The parameters studied include the difference between the SHS and CHS as the column member, and the effects of temperature and the types of channel used on both the CHS and SHS section columns. Compared with other tests at elevated temperatures, video processing is used to measure the deformation of specimens. The connections are governed by either bolt head punching through the channel thickness at ambient temperature or by the tensile fracture of the bolts. The use of ductility as the basis is more effective than designing the connection to a higher strength for higher survivability in fire conditions.

Considering that the reverse channel critically governs the behavior of the connection type, the influence of different types of reverse channel is researched (Lopes *et al*. 2013). Standard channels and built-up sections and channels cut from hollow sections are tested in both compression and tension loads. Behavior at both ambient and elevated temperatures is compared together with the proposed stiffness of the reverse channels. At ambient temperature, failure by bolt pullout occurs, as well as shear failure near the sides of the channels. The constant thickness of the channel results in the continuous deformation found in channels cut from hollow sections, whereas the deformation stops at the sides of the channel for the built-up and standard channel sections. Deformations at elevated temperatures are observed to be an exaggerated form of the same deformation at ambient temperatures. The exaggeration is caused by the degradation of the steel material under heat. The use of channels cut from hollow sections is recommended because of the increased stiffness.

A similar method is applied, and connection parameters are studied at elevated temperature conditions (Jafarian and Wang 2014). Variations include the channel thickness, channel width, leg length, and bolt row. Only ambient, 550°C, and 750°C temperatures are selected to test the effect of these parameters on the behavior of the reverse channel. The reverse channel is welded onto a thick plate at the top and bottom and subjected to tension load. The joint may increase in ductility at elevated temperatures, whereas the membrane action governs the behavior of the reverse channel. Behavior arising after the yield lines formed on the reverse channel has not been studied.

Wang and Davies (2003) studied the SHS as the column component in fire together with the connecting beam assembly. Two beams with end plates were bolted to a single column. Loads were applied axially on the column and on both beams, either balanced or unbalance loads. Anisothermal temperature condition was used. The governing factor in the buckling of the SHS column was the column-to-plate thicknesss ratio. A value of 30.7 instead of 38 (as provided by EN 1994-1-1 (2004)) is proposed. Local buckling may occur near the beams when loads are balanced; otherwise, local buckling occurs on the column length. This phenomenon provides an outline to the column to be used when SHS is designed for fire conditions to avoid local buckling deformation.

Although the test of the entire connections provide understanding on the connection behavior and interaction between connection members, investigating on individual components is necessary to provide a basis for the component method (López-Colina *et al*. 2010, 2011). Experimental tests were conducted wherein 20 mm plates were used to apply compressive loads onto a BST column side and at different temperatures up to 642°C. SHS100, SHS120, and SHS140 were the sizes selected for the tubular column.

4.2 FE studies

Following the test results in an earlier study (Ding and Wang 2007), a FE model is developed in ABAQUS and verified (Elsawaf *et al*. 2011) for reverse channel connections to CFT columns, both SHS and CHS (Fig. 9). Several sensitivity studies have been conducted, including those on mesh size, material mechanical property, contact parameters, effect of lateral restraint, and energy dissipation factor. Although lateral restraint has not been elucidated, the location is placed on the plate where loads are transferred to the beam; therefore, horizontal displacement restraint is assumed on the four-point edges of the plate. Temperature distribution is based on the actual measured value, and the behavior of the developed model is in good accuracy in comparison with test results.

A hybrid end-plate connection is proposed to increase the temperature resistance of the connection because of the increase in the connection ductility. Following the model verifications, parametric studies are conducted to determine the parameters that affect the connection before failure (Elsawaf and Wang 2012). The parameters studied include the effects of reverse channel web thickness, effect of fire protection, bolt grade, and the application of fire resistant materials on

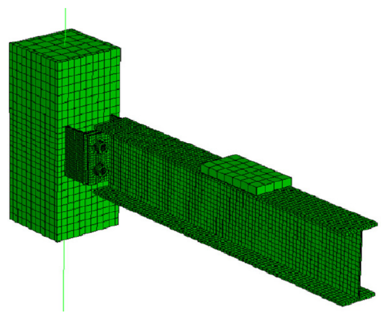


Fig. 10 FEM model for reverse channel connection

the connection components. In addition to the study on the connection component, investigation on the effect toward connection survivability has also been connected. Loads on the column and the increase in material plastic strains lead to high survival temperature for the connections. However, the focus of this study is limited only to the reverse channel connection configuration.

A series of factors based on the current external temperatures is proposed for the different components in fin plate, end plate, and reverse channel connections (Ding and Wang 2009). The proposed regions for each of the connection types and expected temperatures of these components are provided. The result of this proposal is an accurate model and simulation. However, temperatures in a joint are commonly assumed to be uniform for the simplicity of the analysis. A high temperature will result in a design with an increased safety factor.

Coupled with the experimental test results, the FE model is developed to simulate the behavior of the column component, including stiffness and resistance (López-Colina *et al*. 2010, 2011). The stiffness method is based on a four-point method from the plate edge, and the equilibrium of moments and buckling coefficient has been considered in this approach for the stiffness. For the resistance, the EN 1993-1-8 (2005) guideline for resistance of column web is modified to adapt to hollow section members. By combining both studies, an analytical method that is able to predict the behavior of the compression component of the hollow section column is proposed (López-Colina *et al*. 2014). Moment rotation curves show good agreement with the test results from the component studies. Meanwhile, for a full joint validation, the proposed method is validated with available ambient and elevated temperature test results.

By using the tests results from Huang *et al*. (2013), Lopes *et al*. (2013), and Jafarian *et al*. (2014), Heistermann *et al*. (2013) verified the models for the reverse channel component and connections. The temperature at the connection models was applied as a predefined field and was uniform across the applied area. Reverse channel component in tension and compression was modeled with acceptable accuracy. Connection stiffness was also proposed.

Post-fire condition of the connection has also been examined in the literature (Elsawaf and Wang 2013). Tensile forces caused by restrained shrinkage may be sufficiently large to cause tensile failure in the connection components. The proposed FE model is validated against the results of the study by Ding and Wang (2007). No experimental tests have been conducted on the cooling stage of the connection after exposure to fire. Similar conclusions have been drawn for the reverse channel connection, that is, to increase the web thickness of the channel. Limiting the design temperature to 50°C of the beam maximum will increase survivability during the cooling stage. Further studies confirm that the connection may fail during the cooling stage (Song and Han 2014).

5. Future research areas

This literature study identifies several research areas for future works:

(i) The effect of blind bolt geometry needs to be further investigated to improve the behavior because this geometry may affect the failure mode of the blind bolts and shift the load transfer mechanism.
(ii) Standard connections, such as end-plate and fin-plate connections, have been studied extensively. Limited studies have been found on angle connection.
(iii) Reverse channel connections provided good performance in terms of capacity and ductility at ambient and elevated temperatures. Considerable scrutiny has been conducted over the

behavior of the components and the variation of parameters affecting the performance. More simplified connections with equivalent or better performance are needed.
(iv) The connections in tubular column should be studied under realistic fire situations, particularly with loading and boundary conditions simulating the actual behavior as part of a structure.
(v) In addition to study of the entire connection, basic tests are needed on the constituent component level. These tests are necessary to provide a wider validation of the analytical, numerical, and component-based methods.
(vi) Ductility is a parameter of paramount importance on the performance and design of connections under fire situations. Therefore, further experimental information on the deformation capacity of connections at the individual component and overall joint levels is required.

6. Conclusions

This paper reviews the current studies on bolted connections to tubular columns. The limited access for bolting process has led to the use of blind bolts to replicate bolted connections to tubular columns. Investigations have shown that blind bolts can function in a similar way to a standard structural bolt that is commonly used in connections to open-section columns. Limited studies have been found on tubular column connections at elevated temperatures compared with those at ambient temperatures. Different methods of obtaining the connection performance on the basis of experimental, analytical, component, and FE approaches are reviewed. Experimental and FE models are expensive methods in terms of cost and computational effort. The component-based method has great potential, but the volume of work published in this method remains limited, particularly at elevated temperatures. More simplified connection types that can provide better performance at ambient and elevated temperatures are needed.

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