Simplified component model for curved T-stub connection to concrete-filled steel tube with blind bolts and extensions

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Abstract

This paper describes a simplified component model developed to predict the behaviour of a blind-bolted T-stub connection to a concrete-filled steel tube with or without anchorage extensions within the tube. The components of the connection are considered as springs with certain mechanical properties, such as stiffness and strength. They are assumed to follow a bilinear, trilinear, or non-linear force-displacement relationship. The behaviour of the connection can be predicted by assembling the stiffness of the various components. Comparison of the analytical result with existing experimental data shows good correlation. The proposed model can be easily modified to describe the response of the overall beam-to-column connection coupled with other types of assemblies. The proposed method will efficiently serve practicing engineers in designing appropriate frame connections with blind bolts in regions of low to medium seismicity.

Keywords: Blind-bolted connections, Spring, T-stub, Cog extensions, Concrete-filled steel tube

Introduction

Circular hollow sections (CHS) can be effectively used as columns in multi-storey building construction when combined with one-sided fastening techniques using blind bolts. With concrete filling, CHS provides smaller column footprints than other design solutions and enhances load carrying capacity under fire condition as the infilled concrete acts as a heat sink. A novel blind bolted connection has been developed at the University of Melbourne by adding cogged extensions to the conventional Ajax blind bolts. This type of connection can be used as moment resisting connections in composite steel frame building for regions of low to medium seismicity with great efficiency (Goldsworthy and Gardner 2005 & 2006). A typical blind bolted T-stub connection to the concrete-filled steel tube is shown in Figure 1.

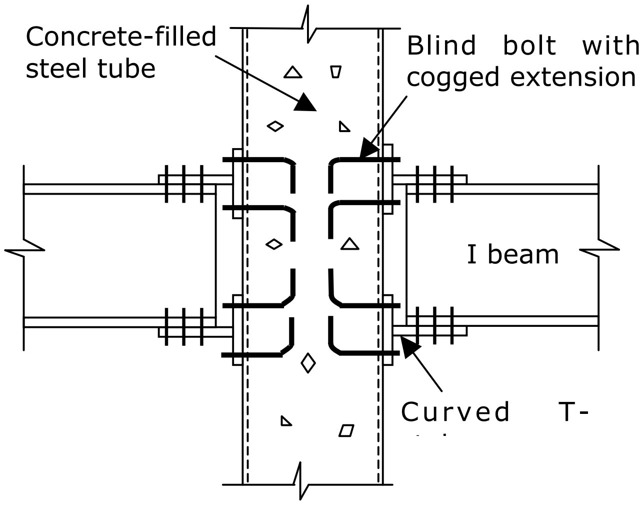

Figure 1: A typical blind-bolted T-stub connection

This paper illustrates a spring-stiffness component model developed to predict the behaviour of blind-bolted T-stub connection between steel beams and concrete-filled circular columns. In the model, the connection components are treated as spring with predefined characteristic such as stiffness and strength. By assembling the characteristics of individual components, the complex response of the joint can be predicted in a reasonably simple way.

Idealisation of blind-bolted T-stub connection

The principal of spring-stiffness (component) models is based on dividing the joint into its basic elements as springs with defined mechanical characteristics (i.e. strength and stiffness). Components of the joint are simulated by individual springs with known stiffnesses which are assumed to follow a predefined force-displacement relationship. For simplicity (see Figure 2), an equivalent single spring stiffness, K_t, is used to represent the stiffness of all components in the tension zone, whilst the compression zone is defined by a separate spring, K_c. The tension zone comprises blind bolt stiffness (K_b), curved endplate stiffness (K_p), cogged extension stiffness (K_x), and membrane stiffness of circular hollow section (K_m). An idealized representation of the T-stub connection joint is shown in Figure 3.

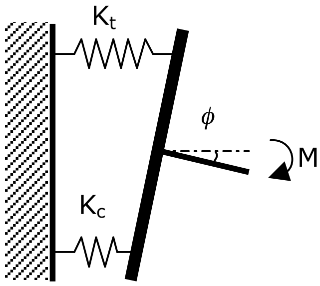

Figure 2: An overall spring model

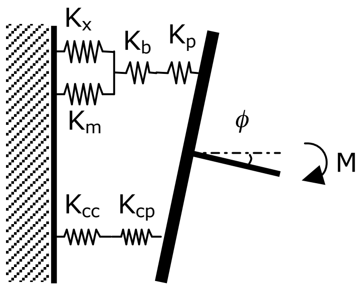

Figure 3: Various spring assembly

Simplified model of the T-stub onnection

Overall joint

The global rotational stiffness, S_j, of the joint can be determined for any given moment based on the assembled stiffness, K_t, of all components acting in the tension zone, and K_c in the compression zone. Therefore, the overall stiffness of the joint can be expressed as:

$$\frac{1}{S_j} = \frac{1}{S_t} + \frac{1}{S_c} \quad (1)$$

$$\frac{1}{S_j} = \frac{1}{K_t \cdot z^2} + \frac{1}{K_c \cdot z^2} \quad (2)$$

where

S_j: global rotational stiffness of the beam-circular column joint
S_t: joint rotational stiffness in the tension zone
S_c: joint rotational stiffness in the compression zone
z: distance from the center of rotation to location of equivalent tension spring

Therefore, the rotation of the joint, at any given moment, M can be expressed as:

$$\phi = \frac{M}{S_j} \quad (3)$$

where

ϕ: rotation of the joint

Equivalent spring in the tension zone and compression zone

The overall stiffness of the components in the tension zone can be expressed as:

$$\frac{1}{K_t} = \frac{1}{K_p} + \frac{1}{K_b} + \frac{1}{K_x + K_m} \qquad (4)$$

In a similar way, the overall stiffness of the components in the compression zone can be expressed as:

$$\frac{1}{K_c} = \frac{1}{K_{cc}} + \frac{1}{K_{cp}} \qquad (5)$$

Behaviour of the connection components

In order to determine the overall stiffness and capacity of the connection, the response of the individual components must be defined.

Blind bolt behaviour

Snug tight condition

The blind bolts are considered to be subjected to direct tensile force in isolation. By applying the principles of Hooke's law, the elastic stiffness of the bolt can be expressed as:

$$K_b = \frac{A_s \cdot E_b}{L_b} \qquad (6)$$

where

A_s: blind bolt shaft area
E_b: modulus of elasticity of blind bolts
L_b: bolt elongation length

The bolt elongation can be obtained from the following relationship.

$$L_b = t_{ep} + t_{tb} + 2 \cdot t_w + t_{bh} \qquad (7)$$

where

t_{ep}: thickness of the curved endplate
t_{tb}: thickness of the tube wall
t_w: thickness of the split washer
t_{bh}: thickness of the blind bolt head

Pretension condition

Until the pretension in the blind bolts is overcome, they are assumed to be infinitely rigid. The stiffness of the preloaded bolts is assumed to be 1000Kb.

Curved endplate behaviour

When load is applied to the joint and the endplate is pulled away from the circular column face, it is assumed that the element is subject to pure bending. The endplate is considered to be a rigid fixed beam subject to a point load. The endplate is restrained against rotation at the horizontal lines of blind bolts. Figure 4 shows the idealisation of the endplate in the tension zone. From simple beam-deflection theory, the endplate stiffness in bending can be expressed as:

$$K_p = 24 EI_{ep} / m^3 \quad (8)$$

$$I_{ep} = \frac{\left(R^4 - r^4\right)}{4}\left(\frac{\pi\alpha}{180} + \sin\alpha\cos\alpha\right) - \frac{80\sin^2\alpha(R^3 - r^3)^2}{\pi\alpha(R^2 - r^2)} \quad (9)$$

where

R: radius of external surface of the curved endplate
r: radius of internal surface of the curved endplate
a: angle of endplate from side edge to its centreline
e: distance of bolt row to endplate top and bottom line
m: distance of bolt row to centre of the flange

The stiffness of the endplate is assumed to be elastic until the formation of plastic hinges.

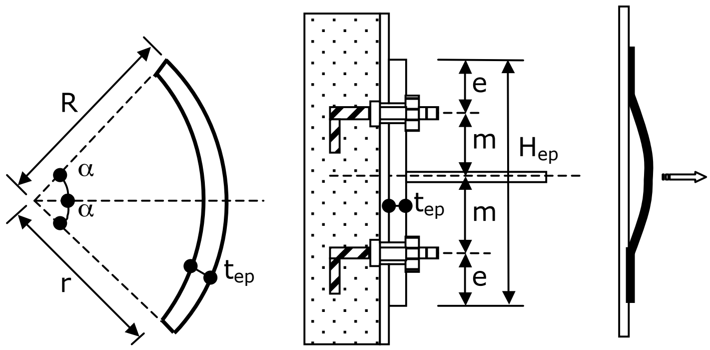

Figure 4: Curved endplate

Cogged extension behaviour

The cogged extensions attached to the blind bolt head provide substantial anchorage to prevent the blind bolts from pulling out, and they also provide considerable stiffness. The performance of cogged bars anchored in concrete filled steel tubes has been studied in great detail by experimental and numerical methods (Yao et al. 2004). The circular hollow section can provide sufficient confinement to the concrete core. As the straight lead-in length is short due to the restriction imposed by the size of the tube and the installation allowance for the blind bolts, its effect on the pullout behaviour is ignored. The pullout resistance of the cog itself can exceed the tensile yield strength of the anchored reinforcing bar. A modified Soroushian model (Soroushian 1988) is proposed to suit the conditions of concrete filled steel tubes instead of reinforced concrete beam-to-column joints.

$$P = \begin{cases} P_1(\delta/\delta_1)^{\lambda} & for\,\delta \le \delta_1 \\ P_1 & for\,\delta_1 < \delta \le \delta_2 \\ P_1 + (P_3 - P_1)\dfrac{\delta - \delta_2}{\delta_3 - \delta_2} \ge P_3 & for\,\delta > \delta_3 \end{cases} \quad (10)$$

where

$\delta_1 = 2.5mm$, $\delta_2 = 7.6mm$, $\delta_3 = 38.1mm$, $\lambda = 0.4$
$P_1 = 271(0.05d_b - 0.25)$, $P_3 = 147(0.05d_b - 0.25)$
d_b: diameter of the reinforcing bar

Thus, the stiffness of the cogged extension can be derived from the above force-displacement relationship.

$$K_x = \frac{P}{\delta} \tag{11}$$

Tube wall membrane behaviour

The bearing of the split-washer on the inside of the tube wall, together with the bearing of the concrete strut from the cogged bend, activates membrane action in the circular tube wall. The load can be shared between the anchorage of the cogged bar and the tube wall membrane action. Initially, the tension load is mainly carried by the cogged bars and the effect of membrane action is small. The membrane action comes into play as the load increases. The ratio of tension load taken by membrane action to the total tension load eventually builds up to 35% of the total load. The membrane action incurred in the tube wall is located at the band of the endplate and adjacent strips to both ends. The stiffness of membrane action in the tube wall can be estimated as:

$$K_m = \frac{1.35 E H_{ep} t_{tb}}{\pi (r + 0.5 t_{ep})} \tag{12}$$

where

E: modulus of elasticity of the steel
Hep: height of the end-plate as shown in Figure 4

Endplate bearing on the tube The stiffness of the T-stub in the compression zone can be estimated by idealising it as a curved plate subject to a uniform compressive force from the beam over the whole depth of the endplate. The stiffness of curved endplate and associated tube wall bearing on the concrete core can be expressed as:

$$K_{cp} = \frac{\pi E \alpha H_{ep} r}{180 (t_{ep} + t_{tb})} \tag{13}$$

Infilled concrete subject to compression The compression resistance from the concrete core is based on the assumption that the compression force applied is distributed across the depth of the endplate and the tube wall is assumed to act as a bearing plate on the concrete. The compression force from the endplate is dispersed to the centreline as shown in Figure 5. The stiffness of the concrete in the compression zone can be expressed as:

$$K_{cc} = \frac{\pi E_c \alpha (H_{ep} + 2 t_{tb})}{180} \tag{14}$$

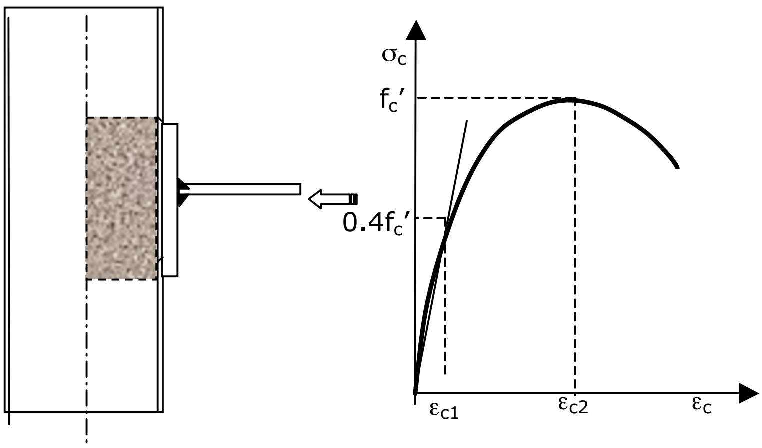

Figure 2: Infilled concrete subject to compression

T-stub tension test

A full scale T-stub connection representing an interior beam-to-column joint has been tested. The specimen consisted of a 323.9 x 6.0 mm circular hollow section of grade 350 with infilled concrete of 45 MPa characteristic compressive strength, two curved endplates (grade 300) of 20 mm thickness, and associated flared flanges (grade 250) of 16 mm thickness. The endplates were fastened to the tube with 16 mm diameter Ajax blind bolts, which had a minimum tensile strength of 800 MPa and yield strength of 640 MPa. Cogged extensions were provided to the head of the blind bolts by using N type reinforcing bars of grade 500 MPa. The specimen achieved a maximum tensile load of 690 kN while it failed due to the weld fracture at the middle bolt of the top T-stub. The load versus displacement is provided in Figure 6.

Validation of the simplified model

Initial stiffness and secant stiffness

Two load cases were modelled at tension loads of 160 KN and 600 KN to obtain the initial stiffness and secant stiffness respectively. The stiffness of the various components is listed in Table 1. The comparison between the experimental result and analytical result for the tension load versus outwards displacement is shown in Figure 6. The proposed model predicts closely the initial stiffness and secant stiffness of the blind-bolted T-stub connection. However, the model is unavoidably approximate because the behaviour of blind-bolted T-stubs is highly nonlinear, which is due to mechanical and geometrical nonlinearity and to complex contact phenomena. Nevertheless, the application of the simplified component model provides satisfactory results.

Table 1: Spring stiffness for various components

	K_b (kN/mm)	K_p (kN/mm)	K_x (kN/mm)	K_m (kN/mm)	K_t (kN/mm)	K_{cc} (kN/mm)	K_{cp} (kN/mm)	K_c (kN/mm)	S_j (kNm/rad)
160kN	913000	13653	411.3	913.7	1206	8252	276948	8013	94341
600kN	913	13653	139	913.7	472	8252	276948	8013	40117

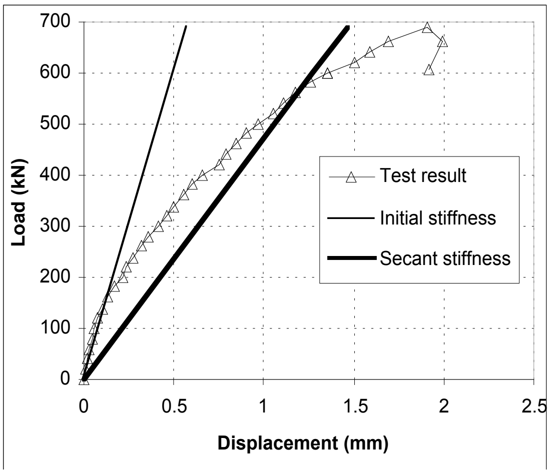

Figure 6: T-stub connection test

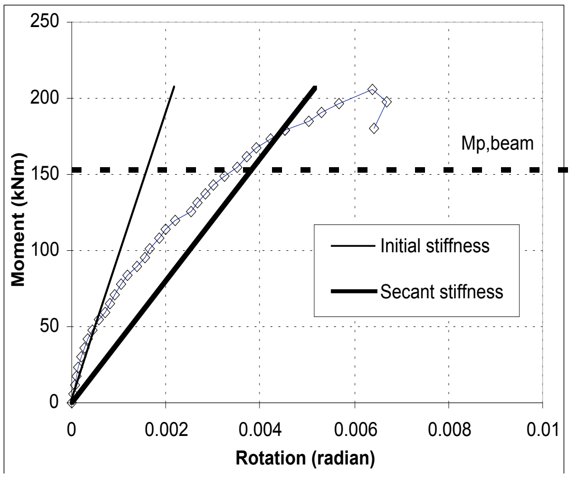

Figure 7: Moment-rotation curve

Moment-rotation curve

Behaviour of a beam-to-column connection can be conveniently represented by a moment-rotation curve (CEN 2005). A moment-rotation relationship has been determined for a concrete-filled circular column with diameter of 323.9 mm and a thickness of 6 mm connected to a steel universal beam of 310UB 40.4kg/m through the double split T connection shown in Figure 7. This represents a moment-resisting connection in a low-rise frame with a beam span of approximately 6 m. The design is based on capacity design principles so that the beam will reach its plastic moment capacity whilst the connection remains strong and stiff.

Conclusions

A simplified spring-stiffness model was presented for modelling the response of a curved T-stub connection with blind bolts and extensions. Joints were modelled by assembling the contributions of individual components. Separation of the joint into its main components allowed different force-displacement response models to be incorporated. The main parameters describing stiffness and capacity of the components were examined. The predicted behaviour of the joint was compared with the observation from the experimental test. There was good agreement between the analytical and the experimental results. The proposed component method can be employed to predict the behaviour of this type of blind-bolted T-stub connection while maintaining a relative ease of practical application.

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