Experimental investigation of two-bolt connections for high strength steel members

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Abstract

This paper presents an experimental research on bearing-type bolted connections consisting of two bolts positioned perpendicular to the loading direction. A total of 24 connections in double shear fabricated from high strength steels with yield stresses of 677MPa and 825MPa are tested. Two failure modes as tearout failure and splitting failure are observed in experiments. The effect of end distance, edge distance, bolt spacing and steel grade on the failure mode and bearing behavior are discussed. For connection design with bolts positioned perpendicular to loading direction, it is further found that combination of edge distance and bolt spacing effectively determines the failure mode and ultimate load. The test results are compared with Eurocode3. An optimal combination of edge distance and bolt spacing as well as related design suggestion is thus recommended.

Keywords: High strength steel; two-bolt connection; tearout failure; splitting failure

1. Introduction

Bearing-type bolted connection is a widely used connection type in design of steel structures. The resistance of connection is provided by the bearing between bolt and plate. If bolt is designed sufficient to avoid shear failure, the resistance of connection is determined by the material strength of steel plate. High strength steel (HSS) with a nominal yield strength $\geqslant$ 460MPa [1] has improved material strength compared to normal strength steel. Thus, application of HSS into bearing-type bolted connection is a promising strategy, which will effectively increase the bearing resistance.

Experiment on single-bolt connection has been a popular method to test the bearing resistance of an individual bolt [2-4]. However, in multi-bolt connection, the applied load is carried by a group of bolts. Behavior of an individual bolt in multi-bolt connection will be affected by other bolts nearby, which is not considered in single-bolt connection. As a result, research on multi-bolt connection is necessary. The connection with two bolts positioned perpendicular to the loading direction is a basic form of multi-bolt connection. Study on this type of two-bolt connection can effectively test the bearing behavior of an individual bolt affected by another bolt positioned perpendicular to loading direction. Thus, the connection with two bolts positioned perpendicular to loading direction will be mainly discussed in this paper. This paper further provides an experimental analysis on 24 groups of connections with two bolts positioned perpendicular to loading direction. Two types of high strength steels with yield stress of 677MPa and 825MPa are used, which particularly supplements the data set for two-bolt connections made from high strength steels.

2. Experimental work

A total of 24 groups of two-bolt connections positioned perpendicular to loading direction are prepared for the research. Two high strength steels including Q550D and Q690D are used. The two HSS steels are produced by Wuyang Iron & Steel Co., Ltd. Based on GB/T 228-2002 [5], standard tensile tests are conducted at room temperature. The measured material properties are listed in Table 1, where f_y is yield strength, f_u is tensile strength, E is elasticity modulus, ε_u is the strain at tensile strength, Δ is the elongation

ratio at fracture. Fig. 1 presents the measured stress-strain relationship for each high strength steel.

The two-bolt connection is named as TH connection, which is abbreviation for "Two-bolt, Horizontally positioned". Five main geometric parameters are displayed in Fig. 2, including end distance e_1, edge distance e_2, bolt spacing p_2, bolt hole diameter d_0 and plate thickness t. All the TH specimens are cited in terms of TH-e_1/d_0-e_2/d_0-p_2/d_0-steel grade. The nominal and measured dimensions for each specimen are listed in Table 2. In Table 2, two different end distances e_1 as $1.2d_0$ (minimum requirement in Eurocode3) and $1.5d_0$ are adopted. Six combinations of edge distance e_2 and bolt spacing p_2 are prepared for each e_1, as is listed in Table 2.

Table 1 Measured material properties

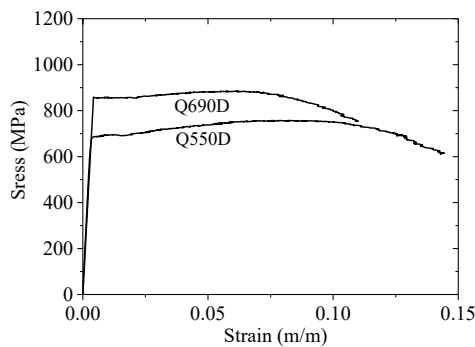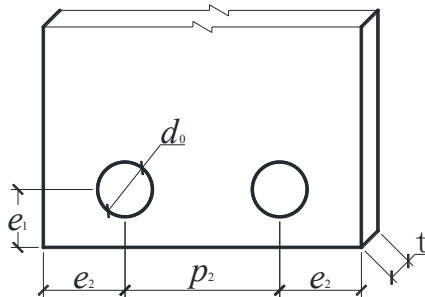| Steel Grade	f_y (MPa)	f_u (MPa)	f_y/f_u	E (GPa)	ε_u	Δ (%)
Q550D	677	757	0.894	205	0.0642	18.5
Q690D	825	859	0.960	203	0.0511	13.5

Fig. 1 Stress-strain relationship of steel plates

Fig. 2 Geometric parameters in TH connection

The tests are carried out on a hydraulic servo-controlled machine with loading capacity of 2000kN. Experimental set-up is displayed in Fig. 3. High strength bolt M24 (bolt diameter d = 24mm) with grade 12.9 is used and designed with adequate shear resistance to avoid bolt shear failure in experiments. No pretension of bolt is considered and a 1.6mm gap is reserved, as is shown in Fig. 3. These two precautions ensures that load is primarily transferred by bearing. A 10kN load is applied and unloaded to make bolt shank bear on hole wall before formal loading. Then, the specimens are loaded at a prescribed rate of 1.5mm/min until final failure occurs. Two linearly variable displacement transducers (LVDTs) are positioned along both edges of the specimen to measure the bolt hole elongation and plate deformations in the force direction, as shown in Fig. 3.

Table 2 Geometrical dimensions (Unit: mm)

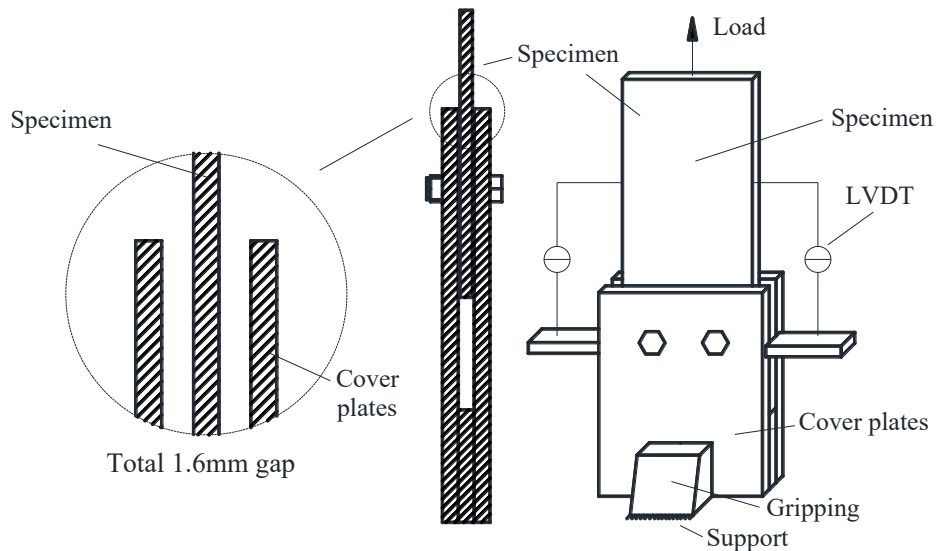| Specimen	Nominal dimensions				
	e_1/d_0	e_2/d_0	p_2/d_0	d_0	t
TH-12-12-24	1.20	1.20	2.40	26	10
TH-12-12-27	1.20	1.20	2.70	26	10
TH-12-12-30	1.20	1.20	3.00	26	10
TH-12-15-24	1.20	1.50	2.40	26	10
TH-12-15-27	1.20	1.50	2.70	26	10
TH-12-15-30	1.20	1.50	3.00	26	10
TH-15-15-30	1.50	1.50	3.00	26	10
TH-15-15-35	1.50	1.50	3.50	26	10
TH-15-15-40	1.50	1.50	4.00	26	10
TH-15-20-30	1.50	2.00	3.00	26	10
TH-15-20-35	1.50	2.00	3.50	26	10
TH-15-20-40	1.50	2.00	4.00	26	10

Fig. 3 Experimental set-up

3. Test results and observations

3.1. Failure mode

The comparison of failure modes of TH specimens for each high strength steel is shown in Fig. 4. Two profiles of failure modes associated with tearout and splitting failure are schematically shown in Fig. 5. The first three columns of each row in Fig. 4 show the experimental splitting failure and the second three columns display the tearout failure. In splitting failure, rotation of net cross-section exists, which is less significant in tearout failure. A comparison with the failue mode of single-bolt connection [2] is shown in Fig. 6. The single-bolt connections are made from the same steels in Table 1. With Fig. 4 to Fig. 6, the effect of the geometric parameters (e_1, e_2 and p_2) and mechanical properties of steel plate are observed as follows.

(1) End distance e_1: For specimens with $e_1=1.2d_0$ or $1.5d_0$, similar bolt hole elongation and shear fracture are observed, no matter what e_2 or p_2 are used. Compared to failure mode of single-bolt connection in Fig. 6, bolt hole elongation and profile of shear fracture display no significant difference.
(2) Edge distance e_2 (e_1/e_2): For specimens with $e_1=1.2d_0$ or $1.5d_0$, two types of e_1/e_2 are used. For e_1/e_2 around 1.0 (e.g., TH-12-12-24-550: $e_1=1.2d_0$ and $e_2=1.2d_0$), significant rotation of net cross section is observed. For e_1/e_2 around 0.8 (e.g., TH-12-12-24-550: $e_1=1.2d_0$

and $e_2=1.5d_0$), no significant rotation of net cross section is found. The similar rotation of net cross-section can also be found in single-bolt connection with $e_1=1.5d_0$ and $e_2=1.5d_0$, as is shown in Fig. 6, indicating the similarity of bearing behavior between TH connection and the single-bolt connection.
(3) Bolt spacing p_2: There are six values of p_2 increasing from $2.4d_0$ to $4.0d_0$ for each high strength steel. The value of $2.4d_0$ is the minimum value accepted in Eurocode3. Result in Fig. 4 indicates that effect of p_2 on bolt hole elongation or shear fracture is negligible when tearout or splitting failure occurs.
(4) Steel grade: The TH specimens with identical dimensions but different steel grades show similar failure modes.

3.2. Load-displacement curve and ultimate load

The load-displacement curves of TH specimens are displayed in Fig. 7. Two clusters of curves are observed. It can be found that specimens with $e_1=1.5d_0$ have obviously increased ultimate load as well as deformation capacity compared to specimens with $e_1=1.2d_0$. For specimens with the same e_1, smaller edge distance e_2 will cause slight reduction of ultimate strength but no significant reduction of deformation capacity, as is shown in Fig. 7. Effect of steel grade on the profile of load-displacement curve for TH specimens is negligible. Smooth descending stage is observed in each load-displacement curve, no matter what steel grade is used. Smooth descending stage is

observed in each load-displacement curve, no matter which steel grade is used.

| (1)TH-12-12-24-550 | (2)TH-12-12-27-550 | (3)TH-12-12-30-550 | (4)TH-12-15-24-550 | (5)TH-12-15-27-550 | (6)TH-12-15-30-550 |

| (7)TH-15-15-30-550 | (8)TH-15-15-35-550 | (9)TH-15-15-40-550 | (10)TH-15-20-30-550 | (11)TH-15-20-35-550 | (12)TH-15-20-40-550 |

| (13)TH-12-12-24-690 | (14)TH-12-12-27-690 | (15)TH-12-12-30-690 | (16)TH-12-15-24-690 | (17)TH-12-15-27-690 | (18)TH-12-15-30-690 |

| (19)TH-15-15-30-690 | (20)TH-15-15-35-690 | (21)TH-15-15-40-690 | (22)TH-15-20-30-690 | (23)TH-15-20-35-690 | (24)TH-15-20-40-690 |

Fig. 4 Failure mode of TH connection

Tearout failure   Splitting failure

Fig. 5 Typical failure modes

(a) $e_1=1.5d_0$, $e_2=3.0d_0$, Q550D

(b) $e_1=1.5d_0$, $e_2=3.0d_0$, Q690D

(d) $e_1=1.5d_0$, $e_2=1.5d_0$, Q550D

(e) $e_1=1.5d_0$, $e_2=1.5d_0$, Q690D

Fig. 6 Failure mode of single-bolt connection
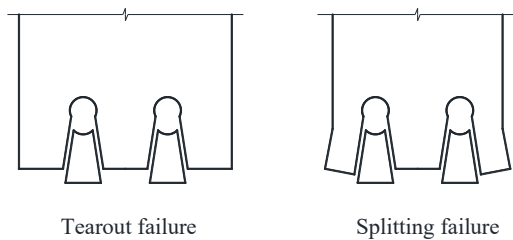
The measured ultimate load F_u, corresponding deformation D_u and the normalized ultimate load ($F_u/f_u dt$, d is the diameter of bolt shank) for each TH specimen are summarized in Table 3. For specimens with the same end distance e_1, similar values of D_u are observed no matter what combination of e_2 and p_2 is used. For different high strength steels, similarity of the normalized ultimate load is found for each TH specimen. Comparison with result of single-bolt connection is also conducted in Table 3. The ultimate load of single-bolt connection ($F_{uSingle}$) in Table 3 is experimental result 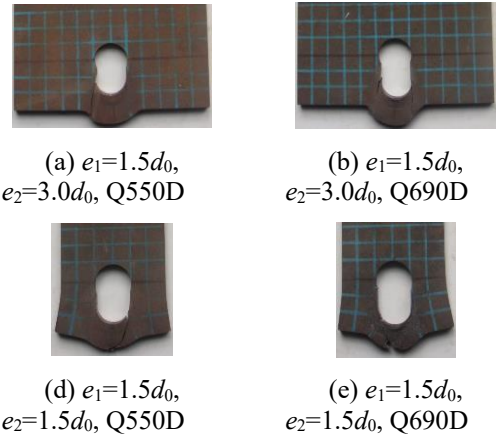from [2], which is also conducted by the authors of this paper. It can be found that both F_u of TH connection is close to sum of two single-bolt connections with the same e_1, while D_u shows similarity between the two types of connections. The observation in Table 3 indicates that an individual bolt in TH connection has the similar bearing behavior compared to single-bolt connection with the same e_1.
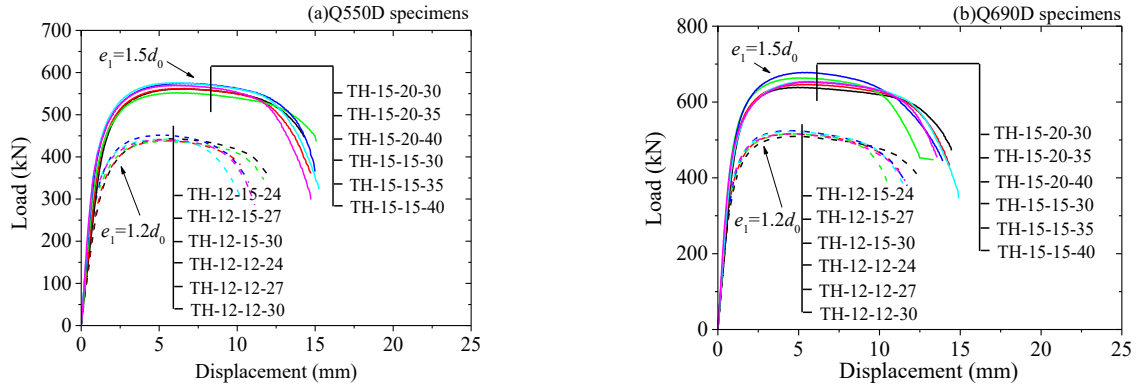
Fig. 7 Load-displacement curves

Table 3 Ultimate load of TH connection and comparison with single-bolt

Specimen	F_u (kN)	F_u/f_udt	D_u (mm)	$F_u/(2*F_{uSingle})$	$D_u/(D_{uSingle})$
TH-12-12-24-550	443	2.44	5.25	0.98	1.04
TH-12-12-27-550	439	2.41	5.26	0.97	1.04
TH-12-12-30-550	438	2.41	5.37	0.97	1.07
TH-12-15-24-550	452	2.49	5.31	1.00	1.05
TH-12-15-27-550	442	2.43	5.29	0.98	1.05
TH-12-15-30-550	441	2.43	5.11	0.97	1.01
TH-15-15-30-550	561	3.09	6.66	0.96	0.96
TH-15-15-35-550	562	3.09	6.64	0.96	0.96
TH-15-15-40-550	552	3.04	6.38	0.95	0.92
TH-15-20-30-550	575	3.16	6.63	0.98	0.95
TH-15-20-35-550	576	3.17	6.44	0.99	0.93
TH-15-20-40-550	570	3.14	6.34	0.98	0.91
TH-12-12-24-690	511	2.43	4.55	1.03	1.01
TH-12-12-27-690	516	2.45	4.57	1.04	1.01
TH-12-12-30-690	516	2.45	4.64	1.04	1.03
TH-12-15-24-690	525	2.49	4.60	1.05	1.02
TH-12-15-27-690	523	2.49	4.46	1.05	0.99
TH-12-15-30-690	516	2.45	4.61	1.04	1.02
TH-15-15-30-690	639	3.04	5.50	0.96	1.02
TH-15-15-35-690	646	3.07	5.52	0.97	1.03
TH-15-15-40-690	663	3.15	5.63	1.00	1.05
TH-15-20-30-690	678	3.22	5.41	1.02	1.01
TH-15-20-35-690	654	3.11	5.38	0.99	1.00
TH-15-20-40-690	654	3.11	5.55	0.98	1.03

4. Comparison with design code

According to current Eurocode3 [6], the bearing resistance for an individual fastener is designated as Eq. (1-5). For group of fasteners, if bolt shear failure does not happen, bearing resistance of the whole connection is sum of each bolt.

$$F_{b,Rd} = \alpha_b k_1 f_u dt \le 2.5 f_u dt \qquad (1)$$

For edge bolts

$$\alpha_b = \min(\frac{e_1}{3d_0}; \frac{f_{ub}}{f_u}; 1) \qquad (2)$$

$$k_1 = \min(2.8\frac{e_2}{d_0} - 1.7; 2.5) \qquad (3)$$

For inner bolts

$$\alpha_b = \min(\frac{p_1}{3d_0} - \frac{1}{4}; \frac{f_{ub}}{f_u}; 1) \qquad (4)$$

$$k_1 = \min(1.4\frac{p_2}{d_0} - 1.7; 2.5) \qquad (5)$$

Where, f_{ub} is the ultimate tensile strength of bolt

The formula of bearing resistance in current Eurocode3 can be divided into two parts [6]. The first part is $\alpha_b k_1 f_u dt$, which considers the condition of tearout failure. The second part is $2.5 f_u dt$, which considers the limit on bolt hole elongation. Prediction of Eurocode3 for specimens in tearout failure from this paper is displayed in Fig. 8. Two clusters of data are observed in Fig. 8. The first cluster of data has the relative difference around 20% and the second around 40%. Feature of the first data cluster is $e_2 \geq 1.5d_0$ and $p_2 \geq 3.0d_0$, while feature of the second data cluster is the opposite. The 45% relative difference is due to the parameter k_1 in Eq. (3). If $e_2 < 1.5d_0$ or $p_2 < 3.0d_0$, the parameter k_1 is smaller than 2.5, which incorporates a reduction into the bearing resistance. However, it can be found in Fig. 8 that prediction of Eurocode3 is already conservative without the reduction. As a result, the parameter k_1 is recommended to be 2.5 for all the values of edge distance e_2. Furthermore, the bearing resistance in Eurocode3 aims for tearout failure and limit on bolt hole elongation. Thus, a geometry check or the optimal geometry as $2e_2/p_2 = 1$ is suggested in order to exclude the possible mixed failure.
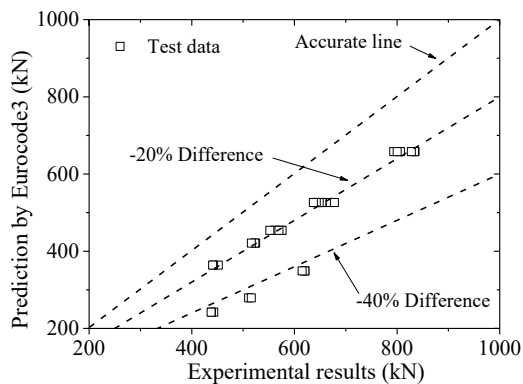

Fig. 8 Prediction of Eurocode3 for TH connection

5. Conclusions

An experimental and numerical study on two-bolt connections perpendicular to loading direction made from two grades of high strength steel (Q550D and Q690D) are conducted. Two failure modes as tearout failure and splitting failure are observed in the experiments. Parameter end distance e_1 has significant effect on the ultimate load and deformation capacity. Significant rotation of net cross-section and slight reduction of ultimate load are observed in specimens with e_1/e_2 around 1.0. In addition, bolt spacing p_2 and steel grade has negligible effect on the failure mode. Comparison with current Eurocode3 is conducted by this paper. The reduction of bearing resistance considered in the parameter k_1 is found unnecessary, since the designed resistance is already conservative without the reduction. A geometry check is recommended in order to exclude the possible mixed failure.

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