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Behavior of single bolt bearing on high strength steel plate

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ABSTRACT

This paper presents an experimental program investigating the behavior of high strength steel connections consisting of one bolt in double shear. A total of 24 bolted connections fabricated from three grades of high strength steel with the nominal yield strengths of 550 MPa, 690 MPa and 890 MPa were tested. The effects of end distance, edge distance and steel grade on the bolt bearing behavior were evaluated. The bolt hole elongation due to bolt bearing on high strength steel plate was measured and its implication on the plate bearing resistance was discussed. The test results were compared with Eurocode 3 and AISC 360-10 predictions and it was found that Eurocode 3 could be used conservatively to predict the bolt bearing resistance on high strength steel with nominal yield strength up to 890 MPa whereas AISC 360-10 method tends to overestimate the bearing resistance of the bolted connection. A regression analysis was performed based on the test data and those from the literature so that a more general method was proposed to predict the bolt bearing resistance on normal strength and high strength steel plate. Splitting failure was observed as a transitional failure mode between tearout failure and net cross-section failure. Splitting failure showed a lower resistance than the bolted connection with tear-out failure, therefore, a reduction factor was proposed to improve the prediction. The upper and lower boundaries of end distance to edge distance ratio for splitting failure were theoretically derived and experimentally verified.

1. Introduction

High strength steels (HSS) with nominal yield strength ≥ 460 MPa has been increasingly used in high-rise buildings, bridges and long span spatial structures [1]. The highest steel grade specified in Eurocode 3 [2,3] and AISC 360-10 [4] is S700 (700 MPa) and A514 (690 MPa), respectively. The China code for the design of steel structures GB 50017-2003 [5] limits the steel grade up to Q420 (420 MPa). Compared with normal strength steel, HSSs are attractive alternatives due to the expected smaller cross-sectional size and self-weight with the same design resistance. Nevertheless, the ductility is expected to decrease with the increase of steel strength. Generally, the elongation of HSS at fracture is lower than that of normal strength steel. In bearing-type bolted connections, bearing resistance is developed accompanied with significant plastic deformation around the bolt hole due to high stresses and stress concentration. The favorable ductility of normal strength steel ensures a fully developed bearing resistance. The ductility requirement of steel is implicitly included in the design specifications. Although the use of HSSs with the nominal yield strength up to 700 MPa are allowed in AISC 360-10 [4] and Eurocode3 [6], the adopted bearing resistance formulae are based on the experimental investigation of normal strength steel [7,8]. Moreover, the excessive bolt hole elongation should be limited when the deformation of the bolt hole is a design consideration. Since the ductility and plastic deformation capacity decrease with the increasing of steel grade, it is necessary to check whether the current design formulae are still applicable for HSSs.

The investigations on bearing type bolted connection made of HSS were carried out by several researchers. Kim and Yura [7] conducted an experimental study on the bearing resistance of one-bolt and two-bolt lap connections. Two different grades of steel with ultimate-to-yield strength ratio of 1.13 and 1.61 were used. They found that ultimate-to-yield strength ratio > 1.13 do not affect the strength at 6.35 mm displacement and reconfirmed that the bearing resistance is proportional to the ultimate stress of the material. Aalberg and Larsen [8,9] performed a similar experimental study with the specimens made of three different grades of steel with the ultimate strength of 539 MPa (S355), 870 MPa (Weldox700) and 1440 MPa (Weldox1100). The edge distance was set constant as $2.0d_0$ and the end distance (e_1) was up to $2.2d_0$, where d_0 is bolt hole diameter. Compared with S355 steel, the displacement at ultimate load for Weldox700 and Weldox1100 showed a reduction of < 30%. Puthli and Fleischer [10] conducted a series of

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tests on 25 two-bolt connections using 17.5 mm thick plates. Two bolts were positioned perpendicular to the direction of loading. HSS S460 was adopted in their tests. The minimum bolt spacing ($1.8d_0$-$3.0d_0$) and edge distance ($0.9d_0$-$1.5d_0$) were evaluated while end distance was set as $1.2d_0$. They found that the reduction of the design bearing resistance prescribed in Eurocode3 for edge distance not < $1.2d_0$ or bolt spacing not < $2.4d_0$ are not necessary. The minimum end distance and bolt spacing may be reduced to $0.9d_0$ and $1.8d_0$ with the proposed reduction factor of 3/4. Recently, Moze and Beg [11,12] performed a comprehensive investigation of the effect of geometric parameters on bearing resistance. Experimental research of 38 tension splices with one and two bolts made from S690 steel and 19 single-bolt connections made from S235 were conducted. The end distance of the tested specimen is from $1.2d_0$ to $3.0d_0$ while the edge distance (e_2) is up to $2.0d_0$. The splitting failure mode was observed and the transition boundary between splitting failure and net cross-section failure was derived. However, the transition boundary between tearout failure and splitting failure are not mentioned. Moreover, different from the hole elongation of 6.35 mm accepted in AISC 360-10 [4] and the limit of 12.7 mm suggested by Rex and Easterling [13], they proposed a new method to control the excessive hole elongation base on the threshold value of $d_0/6$.

In the previous researches, the investigation of HSS with steel grade higher than S690 or equal is limited. The effect of steel grade on the bolt bearing behavior needs to be revealed by the comparison among different HSSs. In addition to the boundary between splitting failure and net cross-section failure, the boundary with tearout failure should be investigated, theoretically and experimentally. As a different failure mode, it is necessary to check whether bearing resistance formula is applicable for the specimens in splitting failure or whether modification is needed to improve the prediction. To address these concerns, a total of 22 single bolt splices fabricated from three different grades of HSS with the yield strength of 677 MPa, 825 MPa and 1022 MPa are tested in this paper. Five end distances from $1.0d_0$ to $2.5d_0$ and four edge distances from $0.8d_0$ to $3.0d_0$ were adopted. Based on the test results, a new bearing resistance formula is proposed and compared with those given in the current design codes. The effect of end distance, edge distance and steel grade on the bearing resistance and the deformation around bolt hole are discussed.

2. Experimental program

2.1. Material properties of steel plates

Three different grades of quenched and tempered HSS plates, Q550D, Q690D, Q890D with a nominal thickness of 10 mm were used in the test, which are produced by Wuyang Iron & Steel Co., Ltd. According to the technical delivery conditions steel in the Chinese code high strength structural steel plates in the quenched and tempered condition GB/T 16270-2009 [14], these three grades of HSS are equivalent to S550Q, S690Q and S890Q in EN 10025-6 [15]. Four tensile coupon tests were carried out for each steel plate to determine the stress-strain characteristics of the steel plate in accordance with GB/T 228-2002 [16]. The measured material properties are summarized in Table 1, in which f_y is the yield strength, f_u is the tensile strength, E is the elasticity modulus, ε_u is the strain at tensile strength, Δ is the elongation ratio at fracture. Fig. 1 shows the typical stress-strain relationship of HSSs.

Table 1
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
Q890D	1022	1064	0.960	203	0.0590	14.5

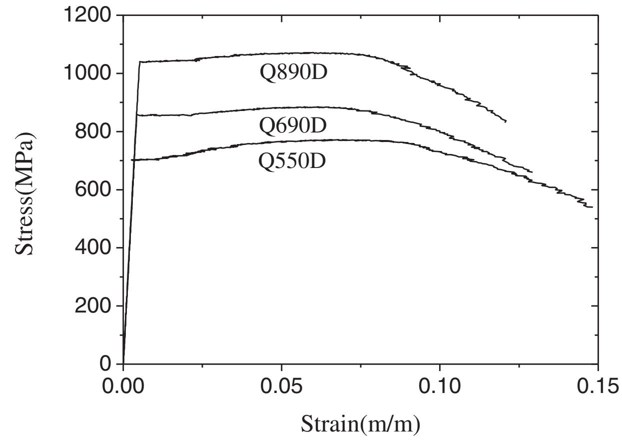

Fig. 1. Stress-strain relationship of high strength steel plates.

2.2. Geometric parameters

Single-bolt connections in double shear were investigated in the tests. Eight specimens for each HSS and in total of 24 specimens of HSS with various end distance and edge distance were prepared. Wire-electrode cutting was adopted to reduce the effect of heat on material properties. The specimens are named in terms of SD-e_1/d_0-e_2/d_0-steel grade, where SD represents single bolt in double shear and e_1, e_2 and d_0 are defined in Fig. 2. The end distance e_1 is varied from $1.0d_0$ to $2.5d_0$, including the end distance e_1 lower than the $1.5d_0$ limit specified in GB 50017-2003 [5] and the $1.2d_0$ limit according to Eurocode3 [6]. The edge distance e_2 of $0.8d_0$, $1.0d_0$, $1.5d_0$ and $3.0d_0$ are evaluated in the test. Nominal dimensions and measured dimensions are summarized in Table 2, where t is the plate thickness and A_{net} is the area of the net section.

2.3. Test set up

The tests were carried out on a hydraulic servo-controlled machine with the loading capacity of 1000kN. Grade 12.9 M24 bolts (without washers) were used to connect the test specimens to the support with enough shear resistance to avoid bolt shear failure, as shown in Fig. 3. No pretension of the bolt was applied so that load was transferred primarily by bearing not by friction. A 10 kN load was applied and unloaded before actual loading to make bolt shank bear on hole wall. Then, the specimens are loaded at a prescribed displacement rate of 1.5 mm/min until failure of specimens. Two linearly variable displacement transducers (LVDTs) were 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. The applied load was recorded

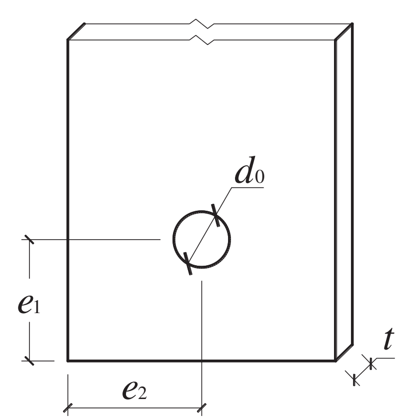

Fig. 2. Dimensions of test specimen.