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Bearing strength at bolt holes in connections with large end distance and bolt pitch

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ABSTRACT

The paper presents test results of one and two bolt connections with very large end distances that failed in bolt bearing, where very high bearing forces were recorded. The purpose of the tests was to investigate the behaviour of the plate in bearing that was not limited by shear, splitting, bolt or net cross-section failure, but with tearing of the material in front of the bolt. The tests showed that the bearing capacity increased insignificantly as the width of the plate increased. Numerical simulations show that bearing resistance is in cases of large end distances significantly influenced by friction forces. They develop because the bolt head and nut, together with the lap plates, constrain the increase of the plate thickness related to plastic deformation. The paper deals with the formation of the stress-strain field as well as the influence of the inner bolt determined by the numerical simulations. The resistances obtained from the tests agree very well with the bearing strength model presented recently by Može and Beg (2014). The coefficient of the bearing strength model that considers the influence of the inner bolt is calibrated on the basis of the presented test results as well as on high strength steel connections with several bolts. The presented bearing strength model was adopted in the final draft of the second generation of EN 1993-1-8.

1. Introduction

Bolting is a practical and simple way of connecting elements. However, sufficient clearance of the bolt holes simplifies the assembly of structural elements and severely reduces the fabrication costs. In practice, bolts are not perfectly aligned and, therefore, certain bolt holes have to elongate to achieve the distribution of the load between all bolts. Unlike some other materials, such as glass or FRP composites, steel has the ability to develop significant plastic strain that localizes around the bolt holes, enabling sufficient bolt hole elongations for load redistribution. The load is transmitted through the contact between the plate and the bolt shank by high bearing stress in the plates around the bolt holes and in the bolts. The bearing pressure causes high compressive stress in the vicinity of the bolt-plate contact. Initially small contact area and high compression stress lead to yielding of the plate material at low load, allowing hole elongation in the plate material. The plate resists the compressive stress by creating a tensile arc that forms in the plate material around the bolt and is anchored in the net cross-section. Fracture may occur in the apex of the arc due to high tension stress, in the shear planes or in the net cross-section. The formation of full bearing behaviour may be obstructed due to too short edge distance or bolt spacing p_2, leading to net cross-section or block tearing failure that are checked by other design rules. Engineering understanding of this relatively complex bearing behaviour is simple and presented by nominal or average bearing stress σ_b in the plate that is uniform over the projected area of the bolt. The design rules for bearing resistance at bolt holes that are presented in international standards (e.g. [1,2].) are also based on the principle of nominal bearing stress. These rules are based on several hundreds of test results that were mainly performed in the middle of the 20th century [3,4], when the effect of bearing pressure on the resistance of the connections was carefully studied. Research on high strength steel (HSS) plates up to grade S960 showed that local ductility of HSS plates also assures large hole elongations, enabling redistribution of forces between all bolts [5–15]. HSS connections are characterized by plate material that has similar strength as bolt material (e.g. plate S690, bolts 8.8), which makes it difficult to ensure the ductile response of the connection (strong plate, weak bolts). A good design practise is to ensure ductility by choosing bolts with shear resistance that is higher than bearing resistance. While EN 1993-1-8 does not provide the criterion for ductile response, this requirement, taking into account overstrength, is given in seismic design of connections EN 1998-1 [16]. Respecting the ductile criteria, the failure moves from the bolts to the plate. Moreover, it guarantees the force distribution between all bolts placed in misaligned holes. Bolts placed in misaligned holes come into bearing prior to other bolts in the joint. In order to transfer the load by shear and bearing of the bolts, the bolts and plates should have sufficient ductility to accommodate for the unequal forces [3]. Mild and high strength steel plates possess enough ductility to accommodate for force redistribution by allowing misaligned holes to elongate. HSS connections are usually

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used with bolts of higher strength. Since these bolts have less deformation capacity in shear, a critical bolt could be sheared prematurely. Henriques, et al. [17] analysed the ductility requirements for the design of the connections in bolt bearing caused by hole misalignment. They studied non-simultaneous transfer of forces between the bolts. This situation appears in misaligned bolt holes due to imperfections related to fabrication. They conclude that the most unfavourable position of misaligned holes, evaluated according to EN 1090-2 [18], may result in fracture of the bolt (s), prior to the distribution of the force between all bolts.

The bearing resistance at normal round holes was evaluated on the basis of maximum resistance [14], where the upper limit of average bearing stress of $2.5f_u$ was set to limit the hole elongation for large end distances. The background documentation to EC3 [4] does not provide the hole elongation limit, but Frank and Yura [19] demonstrated that any hole elongation greater than 6.35 mm would generally begin to develop when the bearing force is increased beyond $2.4\,f_u$. A definition of the bearing resistance was recently proposed by Može and Beg [11]. They based the definition on single bolt connections, on the assumption that the width of the plate (or edge distance e_2) has a minor effect on the bearing resistance, whereas the end distance e_1 is of major importance. In view of this assumption, the lower bound of the bearing resistance is defined as: A plate with edge distance e_2 exists for each given end distance e_1, where the maximum resistance of the net cross-section and the maximum bearing resistance (for given e_1) are reached simultaneously, as shown in Fig. 1(b). In case of end distances smaller than 2.5 d_0, the lower bound of the bearing resistance is usually represented by splitting failure. In case of shorter edge distance e_2, the net cross-section failure is relevant (Fig. 1(a)). In case of larger e_2, the bearing resistance increases compared to the lower bound of the bearing resistance (Fig. 1(c)). For end distances up to 1.5 d_0, Može and Beg [9,11] showed numerically and experimentally that the increase of the bearing resistance is not more than 20%. This paper shows that the increase of the bearing resistance is even smaller for end distances equal to and larger than 3 d_0.

The paper gives the test results of one and two bolt connections with very large end distances that failed in bolt bearing. The influence of the inner bolt is presented graphically and through the results of the numerical analysis. Contrary to the slip-resistance connections, where the bolt preload induces the friction forces, the friction forces develop also in bearing type connections, because the bolt head and nut, together with the lap plates, constrain the out-of-plane deformation of the plate. The numerical simulations show the effect of the developed friction forces as well as the effect of the lap plates that alter the strain-stress field.

2. Tests of single bolt connections

The objective of the tests was to measure the behaviour of plates in bolt bearing, where the bolt is placed far away from the edges. The test program included 10 single bolt connections (series W1), as well as 19 connections with two bolts, positioned in the loading direction (series W2). The connection geometries are given in Table 1. The symbols in Table 1 are defined in Fig. 2. The single bolt connections are presented by three sets. The first set, W101 to W104, includes the specimens with constant end distance of $e_1 = 3\,d_0$ and edge distance e_2 increasing from 2.43 d_0 to 5 d_0. The second set, W108 to W110, has a constant end distance of $e_1 = 5\,d_0$ and edge distance e_2 increasing from 3.36 d_0 to 7.47 d_0. The third set, W105 to W107, provides the results for end distances between 3 d_0 to 5 d_0 in combination with large edge distances. The objective of test series W2 (2 bolts) was to obtain the influence of the inner bolt on the bearing behaviour. Three sets and four additional specimens covering the intermediate geometries present series W2. Sets W201 to W205, W208 to W213 and W216 to W219 have constant pitch p_1 of 2.2 d_0, 3.0 d_0 and 4.0 d_0, respectively. Generally, the end distance is varied from 1.5 d_0 to 5.0 d_0.

The specimens were fabricated from a single 10 mm thick steel plate, where the rolling direction coincided with the direction of the force. The material parameters in the longitudinal and transverse direction were measured by standard tensile tests on two test coupons for each direction. The average material characteristics for both directions were: yield stress $f_y = 342$ MPa ($f_{y,\min} = 334$ MPa; $f_{y,\max} = 348$ MPa), tensile strength $f_u = 447$ MPa ($f_{u,min} = 445$ MPa; $f_{u,max} = 448$ MPa). The tensile strength was reached at a uniform strain of 16.3%, whereas the fracture was observed at engineering strain equalling 44%. The cross-sections were at fracture reduced by 65% of the initial area (on average).

The connections were designed as lap connections with non-preloaded bolts loaded in double shear. The bolts placed in standard size holes were tightened just to achieve firm contact between the plates. The experimental results showed that the initial slip occurred at force varying from 0 to 30 kN. Therefore, the load was transferred primarily by bearing and not by initial friction. Bolts M27 12.9 and the lap plates were designed with sufficient overstrength, thus the failure was always observed in the main plate. The lap plates ($t = 12$ mm) were stiffened by an additional 12 mm plate to minimize their bearing

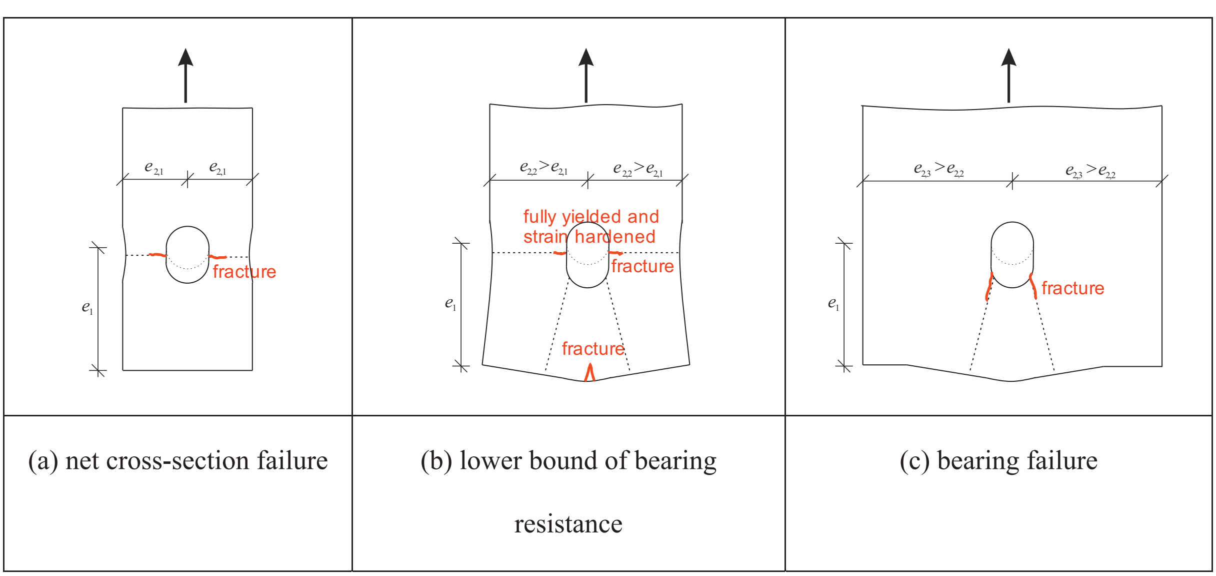

Fig. 1. Definition of the lower bound of the bearing resistance.