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A complete study of bearing stress in single bolt connections

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ABSTRACT

The paper presents experiments on connections with one and two bolts made of mild steel grade S235. The results are compared with the tests on connections made of high strength steel. The test results are substantiated with numerical parametric analysis. The effect of bolt bearing is thoroughly analysed. The bearing strength at bolt holes according to standard EN 1993-1-8 is critically evaluated and a modified design check is proposed. The modified check is conceptually the same as the current one, but it is simpler, less conservative and it is in better correlation to the test results. The block shear strength and net cross-section strength are also discussed and modifications to the EN 1993 design rules are given.

1. Introduction

In bearing-type joints the connected plates are in contact with the bolt shank and the load is transmitted by shear on the bolts and high bearing stress in the plates around the bolt holes. This stress situation occurs also in friction-type joints when the frictional resistance is exceeded and major slip between the connected elements occurs. The paper focuses on the bearing stresses in single bolt connections. Such connections with bolt in bearing present a basic connection component of a multi-bolt connection. The presented topic was extensively studied in the second half of the previous century [1–3]. Application of high strength steels opened new issues in the topic [4–9]. Moreover, detailed numerical simulations also made possible to investigate stress–strain state that is very difficult to measure [8].

Failures of single bolt connection with bolt loaded in shear are commonly known. The failure occurs if the applied load exceeds the bearing strength of the material, or the shear capacity of the bolt, or the tensile capacity of the net cross-section. The net cross-section failure is very well defined. There are several different failure types that are understood as failure mode in bearing. The failure modes are dependent on the geometrical factors of the plate in bearing and material parameters. Researchers also report on curling failure [10] that decreases the bearing strength. Such failure type has been recorded in lap plates, where the plate edges tend to bend outward.

A bearing stress in the material is developed due to the contact pressure. Initially, the contact area is very small, causing stress concentrations and yielding of the material at very low loads. Yielding allows embedment of the bolt on a larger contact area. Such behaviour is interpreted as nominally elastic behaviour, as stress concentrations are eliminated by yielding of the material occurring at early load stage.

2. Test setup and programme

The test programme included 13 single bolt connections as well as 6 connections with two bolts, positioned perpendicular to the loading direction. The connection geometries are given in Table 1. The symbols from Table 1 are defined in Fig. 1. The main and lap plates of the connections were fabricated from a steel plate with the following material characteristics: yield stress $f_y = 313$ MPa and tensile strength $f_u = 425$ MPa. The tensile strength was reached at uniform strain of 16%, the standard tensile test coupon fractured at 37%. The cross-section was at fracture reduced to 73% of the initial size. The connections were designed as lap connections with bolts loaded in double shear. The bolts placed in standard size holes were tightened just to achieve firm contact between plates. The bolt preloading did not allow significant friction force development. Therefore, the load was transferred primarily by bearing and not by friction. The lap plates were wider and had the same thickness as the main plate. The bolts and the lap plates were designed to remain elastic, thus the failure was always observed in the main plate. The main plate on one side of the connection and the lap plates on the other side were clamped to the testing machine. A relative displacement between the main plate and the lap plate was measured on both sides of the connections by inductive displacement transducer (LVDT—Fig. 2). The tests were carried out at a prescribed displacement rate of 1.5 mm/min on a testing machine with the capacity of 1 MN.

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Table 1
Connection geometries.

Connection name	No. of bolts	Bolt	d_0 [mm]	e_1/d_0	e_2/d_0	p_2/d_0	b [mm]	t [mm]	l_m [mm]	l_c [mm]
M101	1	M24	26	1.23	1.23		64	12	120	149
M102	1	M24	26	1.5	1.23		64	12	132	154
M103	1	M24	26	2	1.23		64	12	142	149
M104	1	M24	26	1	1.5		78	12	120	156
M105	1	M24	26	1.23	1.5		78	12	119	148
M106	1	M24	26	1.5	1.5		78	12	130	152
M107	1	M24	26	2	1.5		78	12	141	150
M108	1	M24	26	2.5	1.5		78	12	151	146
M109	1	M16	18	1	1.5		54	12	81	119
M110	1	M16	18	1.22	1.5		54	12	92	123
M111	1	M16	18	1.5	1.5		54	12	92	121
M112	1	M16	18	2	1.5		54	12	112	118
M113	1	M16	18	2.5	1.5		54	12	112	121
M201	2	M20	22	1.5	2.41	2.41	159	12	131	153
M202	2	M20	22	2.5	2.41	2.41	159	12	146	152
M203	2	M20	22	1.5	1.23	3.68	134	12	162	200
M204	2	M20	22	2.5	1.23	3.68	134	12	161	165
M205	2	M20	22	1.5	1.5	3	132	12	159	181
M206	2	M20	22	2.5	1.5	3	132	12	139	160

3. Test results and comparison to high strength steel connections

In this chapter, the test results on mild steel (MS) connections will be given and compared to the results of the connections made of high strength steel (HSS) S690. The HSS connections had 10 mm thick S690 plate and M27 bolt in standard size holes. The average actual yield and tensile strengths were $f_y = 847$ MPa and $f_u = 885$ MPa, respectively. The test configuration was basically the same as described here. Further information on the high strength steel connections is given in [7,11].

The fractured test specimens are presented in Figs. 3–5, while thee failure types, maximum resistance and the displacement at maximum resistance are given in Table 2. Failure, commonly referred to as shear failure, occurs when the end distance is relatively small, i.e. up to 1.5 d_0. The material in front of the bolt yields and is pushed out from the plate in a bending manner, creating two shear planes (Fig. 4—left column). The connection fails when the material capacity in the shear planes is exceeded, or when the tensile stress in the perpendicular direction on the free edge is exceeded.

The failure presented in the middle column of Fig. 4 is referred to as splitting failure, as the material in front of the bolt tends to split the plate in two parts. The plate edges bend outwards. The bending may occur only if a part of the net cross-section yields (see Fig. 6), allowing rotation in the net cross-section. Although this failure is considered as a bearing failure mode, it is often controlled by the net cross-section check. The HSS plate fractured on the free edge due to transverse tension stress, while the MS plate allowed high plastic deformations of the free edge and fractured in the shear plate. This observation is also depicted in Fig. 6, where the equivalent plastic strain is plotted on the MS and the HSS plate at the same hole elongation. The plastic strains are generally also more localized at the HSS plate than at the MS plate (see Fig. 6 and also Fig. 4). The finite element model used to obtain the results presented in Fig. 6 is presented in Section 4.

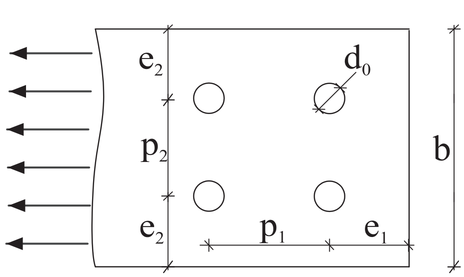

Fig. 1. Definition of distances.

If the end distance is sufficiently large to prevent shear and splitting failure, the plate material piles in front of the bolt, eventually leading to bolt shear failure or net cross-section failure (Fig. 4—right column). The net cross section fracture is also associated with different structural behaviour. If the gross-to-net cross-section ratio is lower than the ultimate-to-yield strength ratio, then the gross area yields, resulting in a ductile response of the structural element. If the net cross-section strength is similar to the bearing strength of the plate, plastic strain in front of the bolt and in the cross section allow large hole elongations (M112 in Fig. 5). If the net-to-gross area ratio is small, the plastic strain is limited to the net cross-section (B101 in Fig. 5). The bearing strength of the plate is in this case much larger than net cross-section strength. Such failure may lead to non-ductile structural response.

Figs. 7 to 9 present the response curves for single bolt connections made of MS and HSS [7]. The horizontal axis presents displacement u measured by LVDT, divided by bolt hole diameter d (normalized displacement), while the vertical axes presents force F, divided by the product of actual tensile strength of plate material f_u, plate thickness t and bolt diameter d (normalized force). In Fig. 7 the relative position of the bolt hole from the edges is similar for both connections, while Figs. 8 and 9 present the normalized response curves of the main plates that failed due to bearing pressure for all tested connections. There is almost no difference in the maximum bearing stress of the HSS and the MS connections (Figs. 7 to 9). The significant difference goes on

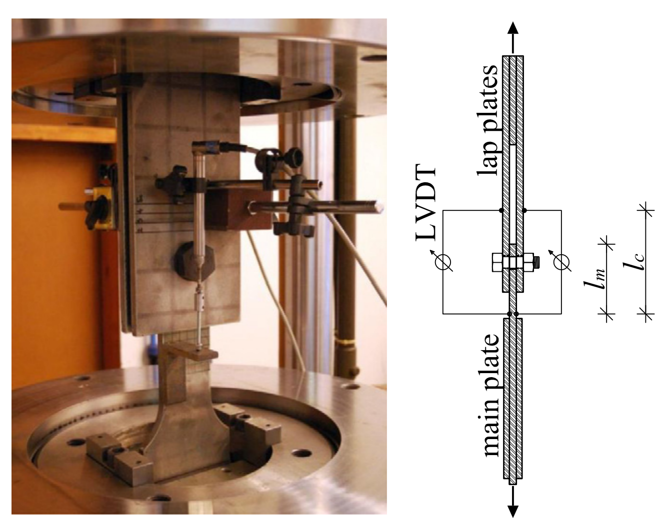

Fig. 2. Connection M101 being tested (left) and illustration of LVDT position (right).