2 BOLTS

Introduction

Connections are used to transfer the forces from one member to another. Although both welded and bolted connections can be used in steel structures, bolted connections are commonly used because of the ease of fabrication, buildability and ability to accommodate minor site adjustments. The different types of bolted connections include cover plates, end plates and cleats and in each of these connections the bolts are used to mechanically fasten the steel elements.

The performance of a bolted connection is complicated and both the stress distribution in the connection and the forces in the bolts are dependent on the stiffness of the bolts, and the connecting steel elements (end plates, cleats, etc.). Consequently, an exact theoretical analysis is not possible.

The design of a bolted connection is semi-empirical, namely based on past experience of good performance, custom and practice, but always validated with a statistical evaluation of test results. An example of a semi-empirical rule is given in Clause 3.6.1(5) of prEN1993-1-8: 2003 which states that the shear resistance of M12 and M14 bolts should be calculated by multiplying the expression for calculation the shear capacity by a factor 0,85 in cases where they are used in holes with 2 mm clearance. When they are used in 1 mm clearance holes, this reduction with the 0,85 factor is not necessary. For bolts M16 to M24, this reduction is also not necessary, when used in 2 mm clearance holes. This also holds for bolts M27 and larger, when used in 3 mm clearance holes.

Basic characteristics of bolts

The bolt grades shown in Table 2.1 are commonly used in steel connections. All of these bolt grades are generally used in connections subject to static forces and moments. For connections subject to fatigue friction grip connections with high strength bolts such as grades 8.8 and 10.9 are to be used because of their high fatigue strength and limited deformation characteristics. The basic mechanical properties for 4.6, 5.6, 6.8, 8.8, and 10.9 grade bolts are shown in Table 2.1.

Table 2.1 Basic mechanical properties of structural bolts

Bolt grade	**4.6**	**5.6**	**6.8**	**8.8**	**10.9**
f_{yb}, *MPa*	240	300	480	640	900
f_{ub}, *MPa*	400	500	600	800	1000
Material and treatment	low or medium carbon steel, fully or partially annealed			medium carbon alloy steel, quenched and tempered	

The weakest section of any bolt is its threaded portion. The strength of the bolt is usually computed by using the "tensile stress area" (also called the "resistant area") defined by the average diameter of the core of the shank d_n and the "average" diameter, d_m, as pictured in Figure 2.1.

$$d_{res} = \frac{d_n + d_m}{2} \, . \tag{2.1}$$

Bolt sizes are defined in terms of their nominal diameter, length under the head and thread length.

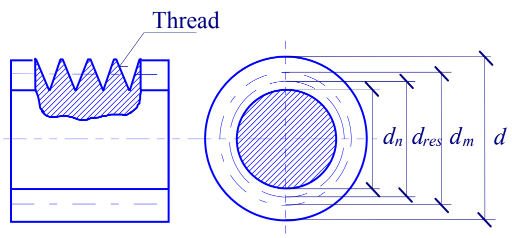


Figure 2.1 Cross-section of the bolt and the resistant area [Ballio, Mazzolani, 1983]

Bolt performance in the connection

The ultimate strength of bolted connections is evaluated assuming simplifications on the redistribution of internal forces as suggested by experimental evidence. Considering the load transfer across the joint, bolts may behave as either:

1) bearing-type bolts. This means that the plates joined are restricted from moving primarily by the bolt shank;
2) pre-loaded friction-grip connection made with high-strength bolts. This means that the plates are clamped together by the tension induced in the bolts by tightening them; or
3) bolts in tension.

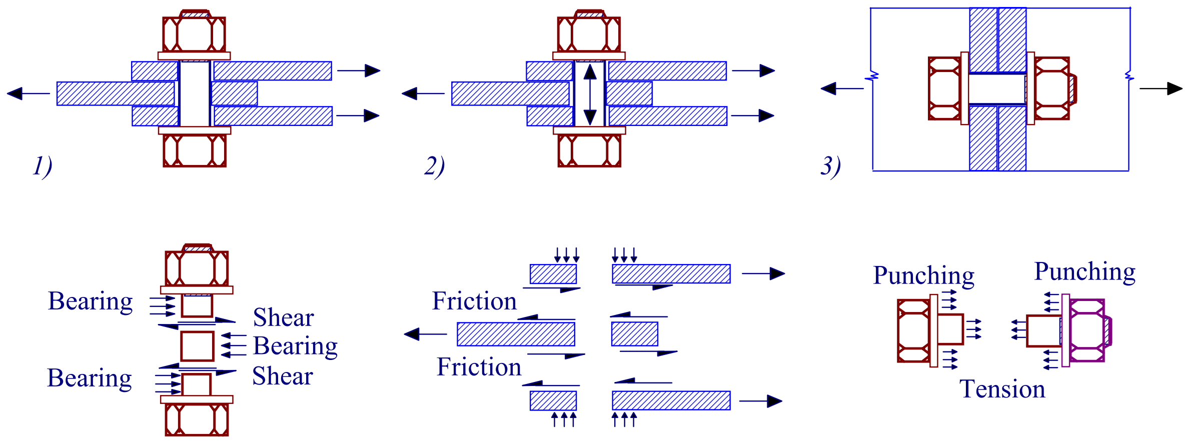


Figure 2.2 Force components in the bearing bolts and pre-loaded bolts, according to [Trahair et al, 2001]

Internal forces (shear, bearing, and tension) may be transferred by bearing bolts and by friction between plates clamped together in the case of a preloaded friction grip joint. These forces are shown in Figure 2.2 for bearing bolts and preloaded bolts, respectively. Furthermore, there are many types of connections where bolts are exposed to combined shear and tension.

Bearing type bolts

Bolts predominantly loaded by static loads should be "snug-tight" (spanner-tight). The tightness is attained by a person using an ordinary spanner. The clamping is sufficient to produce a small friction force between the connected parts and is enough to transfer a small load with no slip. Increasing the applied load overcomes this friction and permanent slip occurs due to clearance between bolt and hole. The slipping stops when the shank of the bolt comes into contact with the plate. When further load is applied, there is an elastic response until plastic deformation starts either in the shank of the bolt or in the connected plate. The plastic deformation may start simultaneously in the bolt and in the plate. The connection will eventually fail in one of following modes:

- Shear of the bolt
- Bearing failure
- Block tearing

The design values for shear resistance and bearing resistance are given in Table 3.4 and for the block tearing the method is given in Clause 3.10.2 of prEN1993-1-8: 2003. The resistance for block tearing is actually based on two possible failure mechanisms: either shear yielding combined with tension rupture or shear rupture combined with tension yielding, according to [Aalberg, Larsen, 2000]. The failure type depends on the dimensions of the connection and the relative strength of the bolt materials and that of the connected parts.

Slip-resistant connections

In the case of reversible loads, high-strength bolts need to be tightened to, at least, 70% of their ultimate tensile strength [Nair et al, 1974]. By using this method, the load is transferred across the joint by friction between the connected parts rather than by shear of the fasteners [Kitipornchai et al, 1994]. Three categories of bolted connections B, C and E. These are specified in Clause 3.4.1 of prEN1993-1-8: 2003. Their resistance is a function of the slip factor (slip coefficient) of the faying surfaces, μ, and the clamping force, $F_{p.C}$, provided by the high-strength bolts. Clause 3.5 of prEN1993-1-8: 2003 gives a number of classes of friction surfaces where μ varies from *0,2* to *0,5*. However, other surface conditions may be used provide the coefficient of friction is obtained by testing. A hardened washer has to be used under the element which is rotated during the tightening for 8.8 bolts (under the bolt head or the nut whichever is to be rotated) and under both the bolt head and the nut in the case of 10.9 bolts, see Clause 8.5(4) [ENV 1090-1].

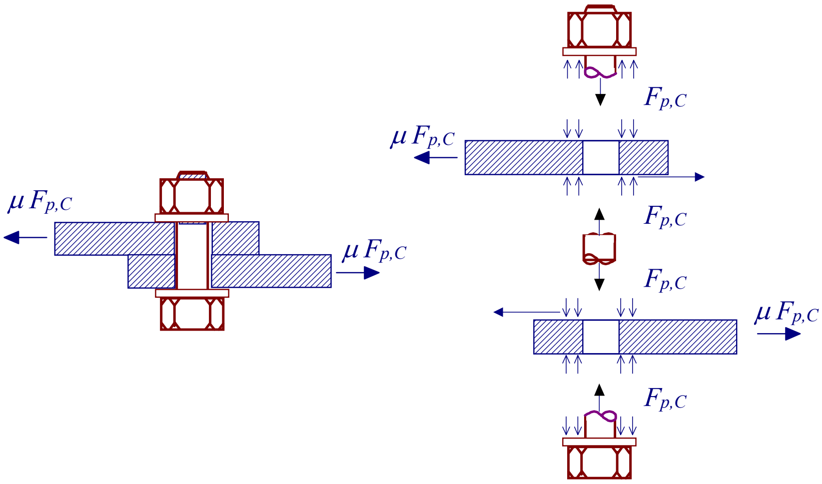


Figure 2.3 High-strength bolt in a friction type connection, according to [Kuzmanovic, Willems, 1983]

The tensile force introduced into a high-strength bolt during installation may be controlled using one of the following methods:

1) Torque control method using a torque wrench (based on controlling the applied torque)
2) Turn-of-the-nut method (a certain angle of rotation is applied beyond the “snug-tight” condition which depends on a total thickness of all packs and washers)
3) Direct-tension indicator method
4) Combined method (combination of the first two methods)

Q&A 2.1 Loss of bolt pre-load

Recent tests in France have indicated that considerable reductions in bolt pre-load of between 25% to 45% can occur over a 2 to 3 month period when standard protective paint coatings are used. How is this effect incorporated in the design of connection with pre-loaded bolts?

Standard protection paint coatings should not be used with slip-resistant connections as they reduce the coefficient of friction between the contact surfaces. This, in turn, will significantly reduce the capacity of the connection. However, special friction paints can be used.

Q&A 2.2 Bearing of slip resistant connections

Why are Category C slip resistant connections checked for bearing at the ultimate load, see Clause 3.4.1(4), when slip is not allowed in the connection at the ultimate limit state?

In this type of connection there is a possibility that some of the bolts may bear against the connection plates as a result of the set-up during erection (i.e. the bolts are not in the centre of the bolt holes but are in contact with the plate at the edge of the bolt hole). Therefore, to ensure complete safety, the bolts are also checked for bearing failure at the ultimate load.

Q&A 2.3 Shear resistance of pre-loaded bolts carrying a tension force

According to Clause 3.9.2 the pre-loading force $F_{p.Cd}$ is not reduced by the whole tension force F_t applied externally when tension and shear for friction bolts are combined. What is the reason for this?

Preloading the bolt deform both the plates and the bolt. This behaviour may be simplified as shown in Figure 2.4 [Fisher, Struik, 1987]. The elongation of the bolt δ_b is adequate to bolt preload F_p and the plate shortening δ_p. By applying an external tensile force F_t, the total bolt force will be F_b under an elongation of $\delta_{b,ext}$, see [Kulak et al, 1974].

The external tensile force will be partially absorbed as new, additional forces in the bolt ΔF_b, and partially absorbed by a reduction in the force that the joint originally exerted on the bolt ΔF_j. The increase of bolt force is ΔF_b and the decrease of clamping force is ΔF_p with the deformation of joint $\delta_{p,ext}$. The dashed line shows the influence of plate bending flexibility under prying. By applying the tensile force to the joint a part of the preloaded force remains, due to the deformation of the plates see Figure 2.4. The stiffness ratio between the tensile bolt and the compression plates (of about *1* to *4*) results in a contact force remaining between the plates, at least equal to

$$F_c = F_p - 0{,}8\, F_t\,, \tag{2.2}$$

when the force F_t is applied under the usual conditions. The validity of the *0,8* factor is based on an assumed cylinder in compression with a fixed area, whereas finite element studies indicate a barrel of compression such that the factor should be a function of the thickness, and possibly of the bolt grade, steel grade and number of plies.

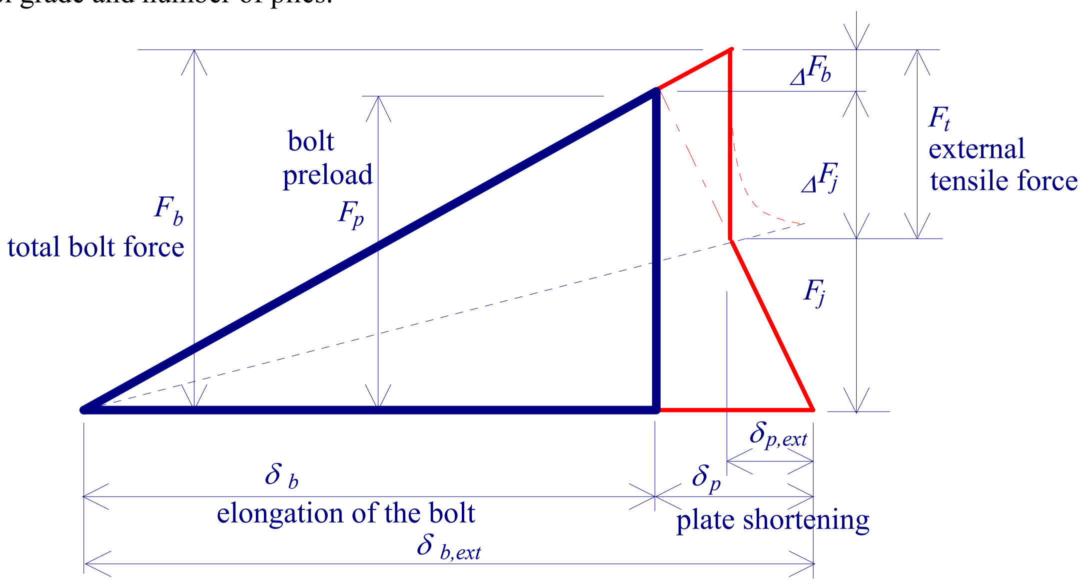


Figure 2.4 Diagram of internal forces in joint with preloaded bolt loaded by tensile forces, according to [Bickford, 1995]

Q&A 2.4 Maximum bolt end and edge distances

What is the background to the maximum spacing p_1 and p_2 of *14 t* or *200 mm* given in Table 3.3, prEN1993-1-8?

The limits for p_1 and p_2 are given independent of the weather or other corrosive influences on the joint. Appearance of the structural element local buckling and behaviour of a long joint have to be taken into account. Local buckling resistance between the fasteners should be calculated according to EN 1993-1-8, see requirements in Table 3.3 note 2. If the joint is made very long the strains in the base material will lead to an uneven distribution of forces. This effect is taken into account by the rules in 3.8 where the shear resistance may be reduced depend on the joint length.

Note that there are no maximum limits specified for the edge distances e_1 and e_2 for a joint not exposed to corrosive influences.

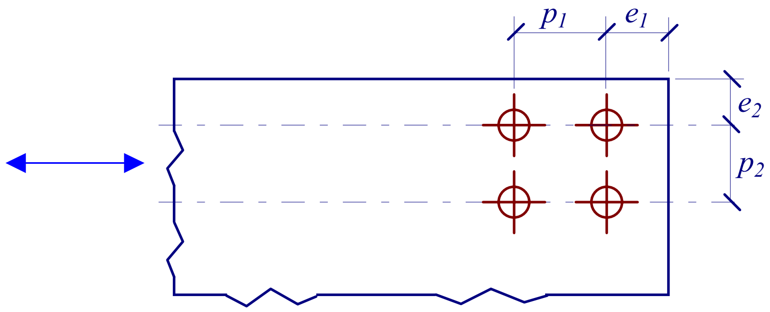


Figure 2.5 Symbols for spacing of fasteners

Q&A 2.5 Deformation criteria for bolt bearing resistance

Bearing design is more concerned with avoiding excessive hole deformations than with avoiding actual failure of the connection. Comparison of the design formula for bearing with tests confirms this point. Could you give the background to the deformation criteria that has been adopted in the derivation of the formula?

The traditional background of most codes indicates the resistance $F_{exp;1,5}$ is limited to a deformation of *1,5 mm*, see [Owens at al, 1999]. The resistance for the structural members obtained from the tests to failure $F_{exp;fy/fum}$ is evaluated by reducing the resistance from structural material strength f_{um} to the characteristic yield strength f_y, see [Bijlaard et al, 1989] and [Bijlaard et al, 1988]. The procedure is used in form $F_{exp;fy/fum} = 0,9\, F_{exp;ult}\, f_y \,/\, f_{um}$ if a brittle rupture occurs [Snijder et al, 1988a]. The conventional (elastic) limit of resistance $F_{exp;conv}$ defines the resistance as the intersection of a straight line with the initial stiffness and of a straight line having the slope equal to stiffness divided by ten, which is drawn as a tangent to the non-linear part of the curve, see Figure 2.6, test [Piraprez, 2000]. The conventional resistance depends more on the joint stiffness than on the failure type. Annex D of prEN 1990: 2001 was used for cover plate tests with slotted holes to validate the model of resistance, see [Wald et al, 2002b].

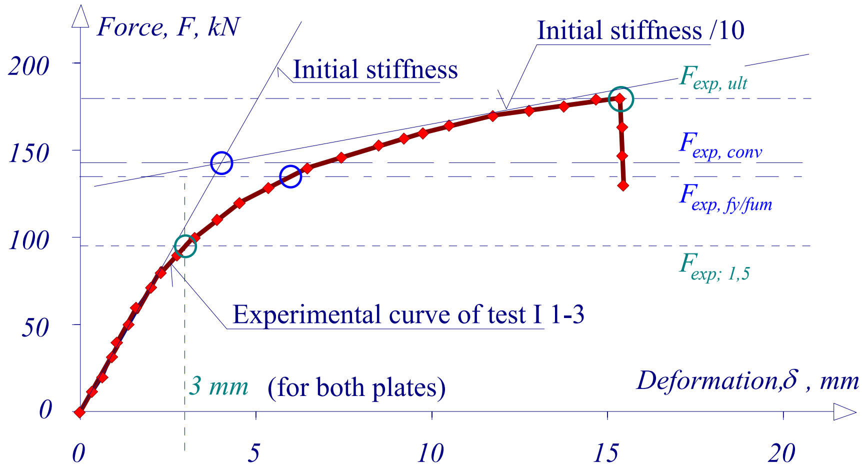


Figure 2.6 Limits of the resistance of joint; deflection limit $F_{exp;1,5}$; ultimate limit $F_{exp;ult}$; conventional limit $F_{exp;conv}$; reduced limit by steel yield ratio $F_{exp;fy/fum}$, [Piraprez, 2000]

Q&A 2.6 End and edge bolt distances

prEN 1993-1-8: 2003 does not contain edge/end distant rules when the edges and row of fasteners are neither in the direction of the force nor perpendicular to the force, see Figure 2.7. How should these distances be determined?

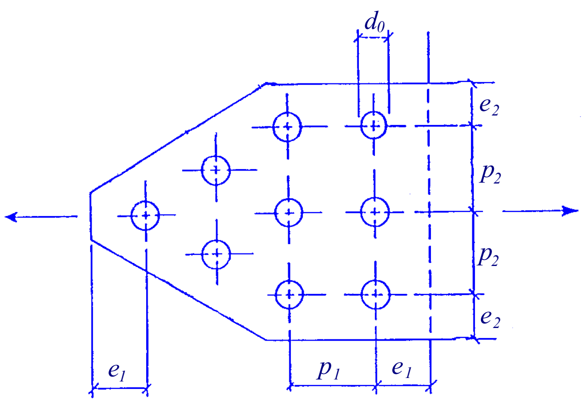


Figure 2.7 End and edge bolt distances

The edge distances e_1 and e_2 and the distances between rows of fasteners p_1 and p_2 may be determined using the semi-axis in the ellipse with the plate edge as tangent, and the semi-axis in the ellipse with its centre in one hole and through the other hole, respectively. This is illustrated in Figure 2.8.

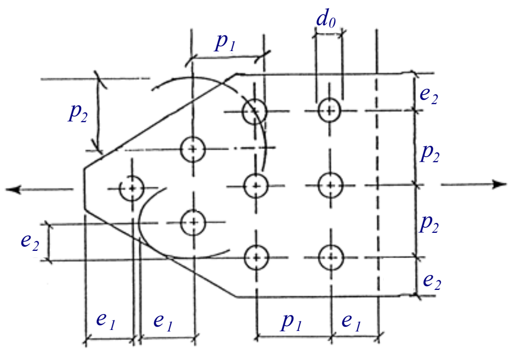


Figure 2.8 Distances to the end and edge

Q&A 2.7 Bearing resistance of bolt group

Can the bearing resistance for individual bolts be added together or not? Some clarification is needed. See Figure 2.9 and example below:

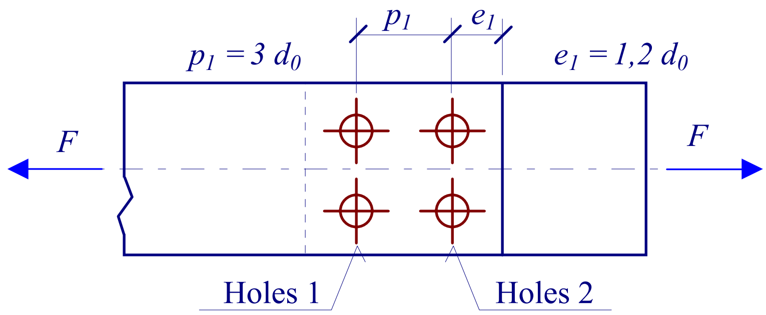


Figure 2.9 Non-symmetrical connection

For the holes 2:

$$\alpha = \frac{e_1}{3\,d_0} = \frac{1{,}2\,d_0}{3\,d_0} = 0{,}4$$

For the holes 1:

$$\alpha = \frac{p_1}{3\,d_0} - 0{,}25 = \frac{3\,d_0}{3\,d_0} - 0{,}25 = 1 - 0{,}25 = 0{,}75\,.$$

Method 1

The total bearing resistance is based on direct summarising

$$F_{b.Rd} = \left(\sum \alpha\right)\frac{2{,}5\,d\,t\,f_u}{\gamma_{Mb}} = \left(2 \cdot 0{,}4 + \underline{\mathbf{2 \cdot 0{,}75}}\right)\cdot\frac{2{,}5\,d\,t\,f_u}{\gamma_{Mb}} = 2{,}3 \cdot \frac{2{,}5\,d\,t\,f_u}{\gamma_{Mb}}\,.$$

Method 2

The total bearing resistance is based on smallest of the individual resistances

$$F_{b.Rd} = \left(\sum \alpha\right)\frac{2{,}5\,d\,t\,f_u}{\gamma_{Mb}} = \left(2 \cdot 0{,}4 + \underline{\mathbf{2 \cdot 0{,}40}}\right)\cdot\frac{2{,}5\,d\,t\,f_u}{\gamma_{Mb}} = 1{,}6 \cdot \frac{2{,}5\,d\,t\,f_u}{\gamma_{Mb}}\,.$$

If method 1 is used then the deformation in holes 2 can be high at the serviceability limit state if all loads are permanent loads.

It is good engineering practice to create a symmetrical connection to avoid an unnecessary plastic redistribution of internal forces. The summation of the resistances of the individual bolts is not a safety but a serviceability issue. If there is a need to limit the deformations then a separate serviceability limit state check should be carried out. Reccommendations are given in Clause 3.7, prEN 1993-1-8, on how to calculate the resistance of a group of bolts. For unsymmetrical connections strain hardening of the plates may be taken into account by ensuring $F_{v,Rd} \geq 1{,}2\,F_{b,Rd}$.

Q&A 2.8 Bearing resistance in slotted holes

Note 1 to Table 3.4 prEN 1993-1-8 states that the reduction in bearing resistance for the case of slotted holes is 60% of that used for a normal size clearance hole when the force is perpendicular to the long direction of the slot. Is there any experimental evidence available to support this?

Nominal clearances for bolts in slotted holes are given in ENV 1090-1, Clause 8. The reduction factor for resistance applied in prEN 1993-1-8 is based on the latest experiments [Wald et al, 2002a,b], [Piraprez, 2000], [Tizani, 1999]. A lower design resistance is required primarily because of the lower stiffness.

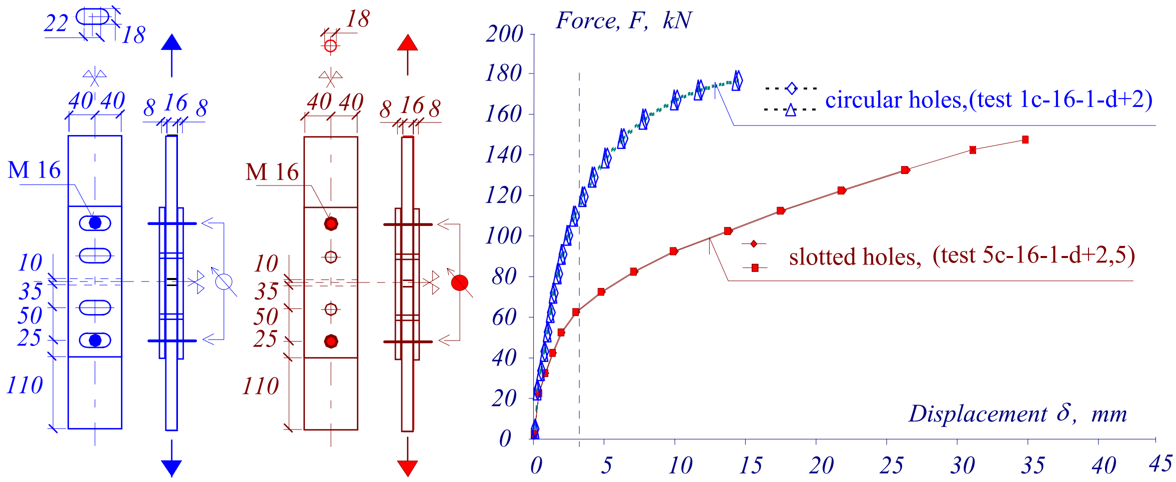
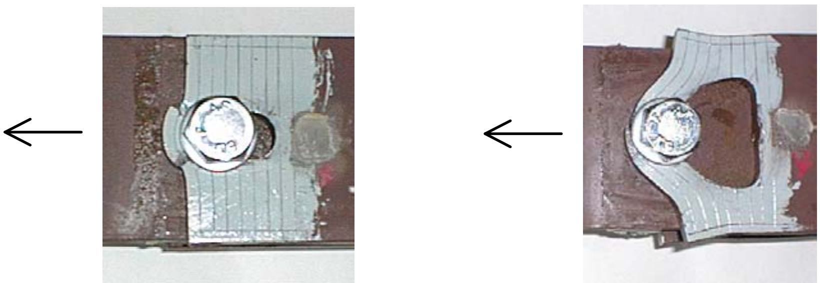


Figure 2.10 Comparison of typical force - displacement diagrams of test with slotted holes to circular holes, [Wald et al, 2002a]

It is clear from Figure 2.10 that bolted connection with slotted holes perpendicular to the applied forces exhibit lower stiffness and higher deformation capacity compare to connections with circular holes.



a) bearing failure in shear *b) bearing failure in bending*

Figure 2.11 Bearing failure of the slotted plate [Wald et al, 2002b]

The bearing resistance is predicted using the following simple model

$$F_{b.Rd} = \beta_R \, \frac{2{,}5 \;\alpha\; f_u \, d \; t}{\gamma_{Mb}}, \tag{2.3}$$

where α is the smallest of

$$\frac{e_1}{3\,d_o} \quad ; \quad \frac{p_1}{3\,d_o} - \frac{1}{4} \quad ; \quad \frac{f_{ub}}{f_u} \quad or \quad 1{,}0\,. \tag{2.4}$$

The reduction factor β_R due to the slot was established using a standard procedure for determining the partial safety factors from the test results, see [Wald et al, 2002b]. Influence of the slot length in the plate failure is shown in Figure 2.12 where the results of 70 tests are shown.

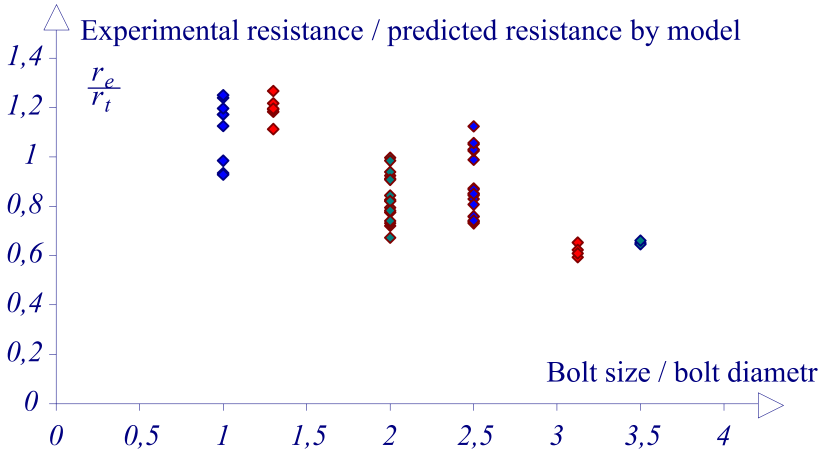


Figure 2.12 Experimental results versus resistance prediction by the design model for evaluation of β_R

Q&A 2.9 Design method for fitted bolts

Could you provide a design method for fitted bolts? Give clarification and guidance covering the following: tolerance on the hole diameters, bearing resistance, and assembly. Any limitations assumed on the presence of threads in the bearing areas and shear plane.

Usually the tolerances are h12/H13 [EN ISO 898-1] which leads to a clearance of approximately *0,3 mm*. Bearing resistance can be taken as the same as that for bolts in clearance holes. Assembly of the joint follows the normal procedure if the holes are prepared in the work shop. An alternative is to do the final reaming of the holes on site in connection with the assembly. Threads are not allowed in the bearing area.

Q&A 2.10 Combined shear and tension

According to Clause 6.5.5(5)of prEN 1993-1-8, a bolt loaded by a tension force equal to the design tension resistance $F_{t.Rd}$ can still take a shear force of $F_{v.Sd} = 0,286\, F_{v.Rd}$. What is the technical background to this formula? A more logical approach is given by the following formula

$$\frac{F_{v,Sd}}{F_{v,Rd}} + \frac{F_{t,Sd}}{F_{t,Rd}} \leq 1\,. \qquad (2.5)$$

Experimental observations have shown that bolts subjected to full shear have a significant tension capacity. The tensile resistance is limited by fracture of the threaded part of the bolt but the interaction between shear and tension is assumed to take place in the shank. An alternative interaction formula is one based on the terms squared with the tensile resistance of the bolt shank in the denominator as it is found in [Owens, Cheal, 1989]. According to Figure 2.13, variation in the ratio of shear strength to tension strength is *0,63-0,68* if the shear plane cuts the threaded portion and *0,75-0,89* if the shear plane is in the bolt shank.

If the shear plane cuts the bolt shank then the following two failure modes may occur:

- combine shear and tension on the shear plane, or alternatively
- the bolt fails primarily in tension in the threaded portion.

It is observed in experiments that the shear strength of the bolts increases with the increase in the grip length. This can be explained by the greater bending that develops in a long bolt as compared to a short grip bolt. The interaction equation used in prEN 1993-1-8: 2003 is given below.

$$\frac{F_{v,Sd}}{F_{v,Rd}} + \frac{F_{t,Sd}}{1{,}4\,F_{t,Rd}} \leq 1 \tag{2.6}$$

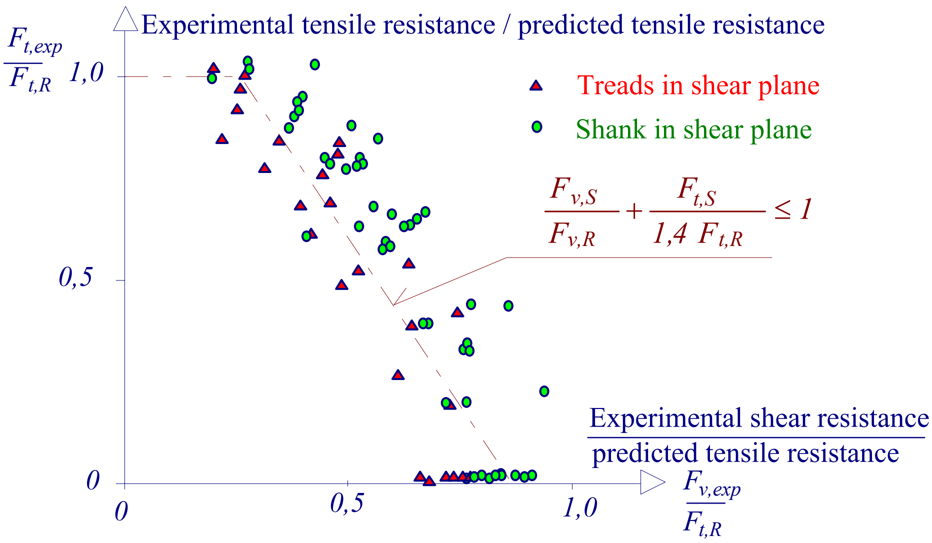


Figure 2.13 Interaction curves according to [Owens, Cheal, 1989] with requirements given in standard prEN1993-1-8

Q&A 2.11 Resistance of connections using high-strength steel

Is it possible to design connection in high-strength steel, with nominal yield strengths of 640 MPa using requirements given in prEN1993-1-8: 2003?

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prEN 1993-1-8: 2003 has been validated for steel grades up to S460 and therefore the method given in the standard should not be used for higher grade steels.

An experimental study performed on double shear plane bolted connection was presented in [Kouhi, Kortesmaa, 1990]. Plates were tested nominally yield strength of *640 MPa* and ultimate strength of *700 MPa*. Bolts made of 10.9 grade were used and the following failure modes were obtained in the tests: bearing resistance, block shear failure and the net section failure on 18 tests, 6, test and 6 tests, respectively.

Test results are compared with the design models given in prEN1993-1-8: 2003 and all the results are found to be on a safe side, see Figure 2.14.

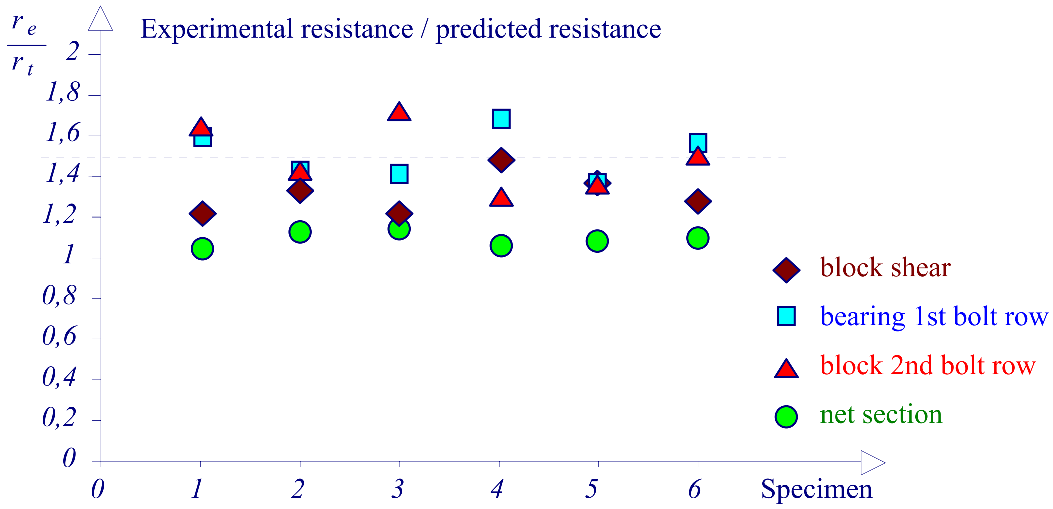

Figure 2.14 Resistance of the bolted connection of tests studied in [Kouhi, Kortesmaa, 1990].

Note:

- Formulae for bearing resistance and net section resistance used in the original paper give same results as prEN1993-1-8: 2003.
- Formula for block shear resistance in prEN1993-1-8: 2003 is conservative compared to the original publication.
- Bearing resistance of the whole connection calculated by summarizing the bearing resistance of each individual bolt is shown in Figure 2.14. The deformations measured in the tests at the ultimate limit state were similar to the magnitude of the bolt diameter. Bearing resistance obtained using the lowest individual bolt resistance are on the safe side.
- Two test groups were performed to study bearing resistance. One group of six specimens had one row of bolts and the second group had two rows of bolts, indicated in Figure 2.14 as bearing-1r and bearing-2r, respectively.
- Plates with thickness of *3 mm*, *4 mm*, *6 mm* and *8 mm* were used in the tests. Measured yield strengths in range from *604 MPa* to *660 MPa* for plate thickness *6 mm* and *4 mm* respectively. The ultimate strength was in the range *711 MPa* to *759 MPa* for plate thicknesses *6 mm* and *4 mm*, respectively. The measured properties were obtained as the mean values of three specimens.