Experimental Analyses on the Resistance of Tapped Blind Holes
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Abstract
Bolted connections are commonly used in steel construction. The load-bearing behavior of bolt fittings has extensively been studied in various research activities and the bearing capacity of bolted connections can be assessed well by standard regulations for practical applications. With regard to tensile loading, the nut does not have strong influence on resistances, since the failure occurs in the bolts due to higher material strengths of the nuts. In some applications, so-called “blind holes” are used to connect plated components. In a manner of speaking, the nut is replaced by the “outer” plate with a prefabricated hole and thread, in which the bolt can be screwed and tightened. In such connections, the limit load capacity cannot solely be assessed by the bolt resistance, since the threaded hole in the base material has strong influence on the structural behavior. In this context, the available screw-in depth of the blind hole is of fundamental importance. The German National Annex of EN 1993-1-8 provides information on a necessary depth in order to transfer the full tensile capacity of the bolt. However, some connections do not allow to fabricate such depths. In these cases, the capacity of the connection is unclear and not specified. In this paper, first experiments on corresponding connections with different screw-in depths are presented and compared to limit load capacities according to the standard.

Keywords
Experiments, Tapped Blind Holes, Connection, Bolt, Thread

1 Introduction
For common bolt fittings as shown in Figure 1a, the strength of the bolt and nut are to be adjusted to each other, i.e. the strength of the nut has to at least reach the class of the bolt (e.g. screw 10.9 and nut 10 or higher). In case of an overloading, the failure is therefore caused in the bolt and not in the form-fitting thread between bolt and nut. For that reason the bolt characterizes the maximum tensile load capacity of the connection. It cannot be increased by enlarging the length of the form-fitting thread.

However, in case of connections with tapped holes in conventional structural steels such as S235 or S355 (Figure 1b, c), the base material generally has a significantly lower strength than the bolt. In comparison to conventional bolt fittings, the load-bearing capacity may for this reason be limited by further failure modes in the area of the thread. In connection with metal forming (plastic deformation) and shearing of the thread, these modes are in general of comparatively benign and ductile load-bearing behaviour [1]. Nevertheless, the screw-in depth of the bolt into the base material is of fundamental importance with regard to the capacity.

The current regulations of Eurocode do not allow a calculation of the load-bearing capacity in this context. In the German National Annex of EN 1993-1-8 a required screw-in depth in the structural steel is merely defined, which guarantees the transmission of the full tension bolt resistance and thus has a significant influence on the thickness of the component with tapped hole. In practical use, this is very unfavorable when lower acting loads would allow a smaller screw-in depth and a reduction of the plate thickness from a static point of view. In this context, first experimental investigations have been performed at the University of Weimar with the aim of identifying the load bearing capacities of bolted connections with tapped holes in dependency of reduced screw-in depths. These tests and corresponding results are presented in the following and compared to results obtained by different calculation approaches, for instance according to EN 1993-1-8/NA.

Figure 1 Connections using bolts

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https://doi.org/10.1002/cepa.1273
2 Calculation approaches for necessary screw-in depths

2.1 Eurocode 3 [2]

EN 1993-1-8 [2] does not provide specific information regarding the tensile capacity of bolted connections with tapped holes. The corresponding German National Annex gives non-contradictory information (NCI) by the following equation in terms of a necessary minimum screwing depth m:

\[
m = \left(\frac{600}{f_{u,k}}\right) \times \left(0.3 + 0.4 \times \frac{f_{u,b,k}}{500}\right) \cdot d \tag{1}
\]

The value m represents a depth to be provided in order to assure the full tension capacity of the bolt. \(f_{u,k}\) and \(f_{u,b,k}\) are the tensile strengths (in N/mm²) of the structural steel (component with tapped hole) and the bolt (component with external thread), respectively, and d is the diameter of the external thread (bolt). The application of Equation (1) presupposes that \(f_{u,k} \leq f_{u,b,k}\). According to [3], the equation was derived from regulations of technical approvals of space framework nodes and it has already been included in the former German National Standard DIN 18800 [4]. An evaluation of Equation (1) for bolt strengths 8.8 and 10.9 in dependency of varying strengths of the structural steel with tapped hole is shown in Figure 2. The grey region of the diagram reflects the area, in which Equation (1) is not valid due to \(f_{u,k} > f_{u,b,k}\).

![Figure 2 Non-dimensional screw-in depths of bolts 8.8 and 10.9 depending on structural steel strength according to DIN EN 1993-1-8/NA](image)

It is well known that Equation (1) may lead to quite conservative and therefore uneconomic results with comparably high values of m, especially when smaller strengths of the base material in comparison to the bolts are considered. For that reason the NCI of the German National Annex refers to the Guideline VDI 2230 [5], which is supposed to provide a more precise calculation of screw-in depths.

2.2 VDI 2230 [5]

The Guideline VDI 2230 [5] differentiates a failure of the internal thread (thread of tapped hole, screw-in depth \(m_{\text{ges,M}}\)) and the external thread (thread of bolt, screw-in depth \(m_{\text{ges,S}}\)), where the higher value of m is decisive:

\[
m_{\text{ges,M}} = \frac{R_m A_p P}{C_1 C_2 \tan(30°)/P (d_2-b_2) \tan(30°)} + 2 \cdot P \tag{2}
\]

\[
m_{\text{ges,S}} = \frac{R_m A_p P}{C_1 C_2 \tan(30°)/P (d_2-b_2) \tan(30°)} + 2 \cdot P \tag{3}
\]

In these equations, \(R_m\) is the tensile strength of the bolt (= \(R_m,M\)), \(A_p\) the tensile stress area, \(P\) the thread pitch and \(\tan(30°)\) as well as \(d_2\) the shear strengths of the tapped hole and the bolt material, respectively. As guide values, VDI indicates \(\tan(30°)/P = 0.8\) for structural steel and \(\tan(30°)/P = 0.62\) for bolts 10.9.

The diameters of the external thread \(d_2\) as well as the internal thread \(d_1\) and \(d_2\) of Equations (2) and (3) are exemplified in Figure 3, which shows denotations according to DIN ISO 965-1 [6]. The coefficients \(C_1\), \(C_2\) and \(C_3\) of the equations are defined in [5]. They are supposed to cover the expansion of the internal thread due to the force transmission and the decrease of capacity, where \(C_1\) covers influences of radial force components activated by the inclination of the thread geometry (also see section 3.1) and \(C_2\) as well as \(C_3\), respectively, those of elastic and plastic thread deformations. For tapped holes \(C_1 = 1.0\) is in general valid; \(C_2\) and \(C_3\) depend on the shear strengths of the materials and can be obtained by specifications in [5].

The first term of Equations (2) and (3), respectively, reflects an effective screw-in depth \(m_{\text{eff}}\) contributing to the force transmission within the thread. The term \(2 \cdot P\) accounts for the run-out with chamfer at the beginning of the bolt thread, not fully contributing in this context. The evaluation of Equations (2) and (3) for Bolts M12 and M20 of grades 8.8 and 10.9 depending on the strength of the base material is shown in Figure 4.

![Figure 3 Definition of thread notations according to [7]](image)

![Figure 4 Non-dimensional screw-in depths of bolts M12 (top) and M20 (bottom) grades 8.8 and 10.9 depending on structural steel strength according to VDI 2230](image)

Figure 5 compares the defined screw-in depths of DIN EN 1993-1-8/NA (see Figure 2) with the results of guideline VDI 2230 (see Fig-
ure 4). As can be seen, for the steel grades typically used in Structural Engineering (S235, S355, S460) the calculated screw-in depths of DIN EN 1993-1-8 are clearly larger. However, with an increase of $f_{u,k}$ the differences become smaller and at a certain strength of the base material, VDI is even more unfavourable than DIN EN 1993-1-8/NA. It is worth mentioning, that with the currently valid EN 1993-1 steel grades are limited up to strength of S460, however, EN 1993-1-12 in general opens the use up to S700 and therefore the application of Equation (1) as well.

2.3 Approach of Schwarz/Dose [9]

In comparison to guideline VDI 2230, Schwarz and Dose [9] do not determine different capacities regarding the internal and external thread. Instead, the failure in a combined shear plane is assumed, in which both, i.e. the internal and the external thread, have influence. The necessary screw-in depth of [9] is defined as follows:

$$m_{\text{min}} = \frac{R_m \cdot d_s}{\pi \cdot d \cdot \tan \tau_s \cdot (\tan \tau_s + \tan \tau_b)} \tag{4}$$

with

$$d_T = d_s + \left( \frac{1}{2} - \frac{\tan \tau_s}{\tan \tau_s + \tan \tau_b} \right) \cdot p \cdot \tan(30^\circ) \quad \{ \leq d \quad \geq D_s \} \tag{5}$$

The parameters of these equations are explained in the previous section in the context of VDI 2230. On the basis of the maximum distortion energy theorem (according to Huber, v. Mises, and Hencky), Schwarz and Dose suggest to refer to the following shear strength for the application in Equations (4) and (5):

$$\tau_B = R_m / \sqrt{3} \tag{6}$$

This formula is to be applied on the base material regarding $\tau_{BM}$ as well as the bolt strength $\tau_{BS}$.

3 Experimental Investigations

3.1 Test Specimen and Setup

The load capacities of bolts with tapped holes were determined experimentally in limited test series. Bolts of strength 10.9 with thread diameters M12 and M20 as well as base materials S235 and S355 were analysed. For each combination of bolt-diameter and base material, three different screw-in depths were tested, where for each configuration five experiments were performed to provide a certain statistical representation. The screw-in lengths to be tested were defined after gaining results of a first series using 0.5 · m according to Equation (1), aiming that at least two screw-in depths of a certain combination of bolt diameter and base material are prone to a thread failure mechanism and not a bolt rupture.

The base plates of structural steel S235 and S355 were fabricated from same charges to minimize the spread of parameters and improve statistical significance of experiments. The stress-strain-relationship was analysed with tensile tests. Results are presented in Figures 7 and 8 as well as Table 1. The parameters $\mu(f)$ in Table 1 represent the mean values of yield strength $f_y$ and tensile strength $f_u$, respectively, and $s(f)$ the corresponding standard deviations. As can be seen, the material parameters of the applied steel grade S235 are strongly exceeding nominal values of EN 1993. Regarding the tensile strength, both materials, i.e. S235 and S355, are basically equal.
addition allows a more specific statement of the loading capacities in relation to the material strengths and the applied screw-in depths. The thickness of the base plate was chosen in accordance to the necessary screw-in depth of DIN-EN 1993-1-8/NA (representing the required screw-in depth to reach bolt rupture).

The setup of the experiments using a servo-hydraulic 1000 kN (tension) testing machine at the laboratory in Weimar is shown in Figure 9. The specimens are mounted in the machine using a specific device, which has been designed and fabricated especially for these experiments [10]. It is shown in the Figure 9a and helps to easily assemble the specimens in the testing machine as shown in Figure 9b.

In addition to the capacity of tapped holes, the tension strength of the bolts themselves was preliminarily tested using the setup and the machine, respectively, shown in Figure 9 as well. For that purpose the bolts were not screwed into the base plate but fixed using nuts, see Figure 10. Five bolts M12 and five bolts M20 were tested. The results are summarized in Table 2 and evaluated regarding the tensile material strengths \( f_{u,b} \), the mean values \( \mu(f_{u,b}) \) and the standard deviations \( s(f_{u,b}) \).

With the transmission of the tension bolt force into the base plate, radial force components due the inclination of the thread flank are caused next to the force components in longitudinal direction of the bolt axis. Theoretically, the radial forces lead to a widening of the internal thread of the tapped hole going along with a reduced shearing area in the thread region and a reduced capacity. However, these influences are in general negligible due to the structural detailing provided in practical applications using tapped holes. For the experiments, the geometric dimensions (length and width \( s \)) of the base plate were therefore chosen to provide ratios \( s / d \geq 1.9 \), since according to VDI 2230 this minimizes the expansion of the thread (\( C_1 = 1.0 \)). With regard to the limited number of test specimens, this in addition allows a more specific statement of the loading capacities in relation to the material strengths and the applied screw-in depths. The thickness of the base plate was chosen in accordance to the necessary screw-in depth of DIN-EN 1993-1-8/NA (representing the required screw-in depth to reach bolt rupture).
In case of bolt rupture, oblique/diagonal fractures are sometimes observed as shown in Figure 13, particularly when screw-in depths decrease. It is noteworthy mentioning that in these cases the rupture commonly occurs before reaching the full tension capacity of the bolts, determined by the experiments of Figure 10, see Table 2 as well. Additional bending or shear stress in the bolt shank, which is induced by an unsymmetrical force transmission in the thread area at certain screw-in depths due to the thread pitch, could be an explanation of the effect. However, the circumstances have not been clarified yet and are supposed to be focused in further research.

Table 3 gives an overview on the different test series using bolts M12, 10.9 and M20, 10.9 and base materials S235 and S355 and the considered screw-in depths m_{eff}. It compiles the mean value of the maximum force \( \mu(F_{\text{max}}) \) for each configuration (of the 5 tests using the same configuration in each series) and the standard deviation \( s(F_{\text{max}}) \) going along with the test results. In addition, Table 3 specifies the number of experiments with a failure of the thread (T) and a rupture of the bolt (B).

| Bolt | Steel | Screw-in depth m_{eff} | \( \mu(F_{\text{max}}) \) | \( s(F_{\text{max}}) \) | N | T/B |
|------|-------|------------------------|----------------|----------------|---|-----|
| M12, 10.9 | S235 | 4.40 (20%) | 36.15 | 2.50 | 5/0 |
| 7.70 (35%) | 69.82 | 1.74 | 5/0 |
| 11.0 (50%) | 92.94 | 0.73 | 0/5 |
| S355 | 5.65 (35%) | 46.40 | 1.09 | 5/0 |
| 8.10 (50%) | 73.46 | 2.56 | 5/0 |
| 10.50 (65%) | 91.64 | 1.44 | 4/1 |
| M20, 10.9 | S235 | 7.30 (20%) | 100.3 | 3.26 | 5/0 |
| 12.80 (35%) | 196.0 | 6.56 | 5/0 |
| 18.35 (50%) | 256.0 | 1.34 | 4/1 |
| S355 | 9.40 (35%) | 130.7 | 5.44 | 5/0 |
| 13.50 (50%) | 198.5 | 5.94 | 5/0 |
| 17.50 (65%) | 255.3 | 1.62 | 1/4 |

Next to Table 3, Figures 14 and 15 show the capacities of the experimental tests for the different screw-in depths. Comparable to Table 3, the displayed results also give information, whether a failure of the thread or a fracture of the bolt was decisive when reaching the limit state. As comparison to the experimental results of the tapped holes, the solutions regarding the required screw-in depths \( m \) of standard DIN EN 1993-1-8/NA, guideline VDI 2230 and the calculation approach of Schwarz/Dose are presented as well. In order to have better comparison with these approximations, the screw-in depths \( m_{\text{eff}} \) of the experiments are increased by the term “2 \cdot P” (compare Equations 2 and 3) to cover the run-out of the thread at the bolt ends:

\[
m = m_{\text{eff}} + 2 \cdot P
\]  

The values of the three approximations are determined based on Equations (1) to (6) for two different cases. In the first case, nominal material strengths of EN 1993-1-1 were considered. In the second case, \( m \) was determined using the existent material strengths of the base material and the bolts determined experimentally, see Figure 7 and Tables 1 and 2. As can be seen, DIN EN 1993-1-8/NA seems to overestimate the required screw-in depth \( m \). On the other hand, guideline VDI 2230 tends to underestimation \( m \) leading to a rather unsafe approximation of capacity. Based on the results of these pre-
liminary experiments, an unrestricted application of VDI 2230 cannot be recommended. The calculation according to Schwarz and Dose in general results in more appropriate approximations and it seems to be the most promising of the three approaches.

However, as mentioned previously, a correlation of screw-in depth to connection capacity is not provided by any of the analytical approaches so far. In order to derive a corresponding reliable and universally valid calculation approach, additional experimental investigations are obligatory and to be executed at the University of Weimar. In addition, numerical investigations addressed in the next section are supposed to support the research and to provide a wide and reliable data basis.

4 Numerical Approach

The structural behaviour of the tapped holes has been modelled by means of Finite Element Methods (FEM) taking the non-linear material behaviour into account – basis information can for instance be found in [11]. Figure 16 shows a very simplified two-dimensional model corresponding to the experimental investigations of a bolt M20, structural base material S235 and screw-in depths \( m_{\text{eff}} \) of 12.80 mm (left) as well as 18.35 mm (right). Regarding the material strengths, values of Tables 1 and 2 are considered. The simplified model (ANSYS Workbench) contains contact conditions between bolt and base material in the threaded area, however, it is of course not able to cover the pitch of the thread properly. To capture associated influences, more extensive three-dimensional models, which are not presented within this paper, are necessary. Here, the simplified numerical model is supposed to give general information on the qualitative behaviour of the connection. As can been seen, for smaller value of \( m_{\text{eff}} \) in Figure 15a the failure of the thread determines the capacity, while for the higher \( m_{\text{eff}} \) in Figure 15b a fracture of the bolt is decisive. This tendency corresponds to the experimental findings, where for \( m_{\text{eff}} = 18.35 \) mm first specimens with bolt ruptures were observed. Even though a very simplified numerical model is regarded, which has certain advantages in interpreting results, the calculated resistances of 221.9 kN (113 % of experimental resistance) and 273.1 kN (107 % of experimental resistance) already predict the experimental resistance quite well.

5 Conclusions and Outlook

In this paper, experimental research of connections with tapped holes is presented. Different screw-in depth in the base material of S235 and S355 using bolts M12 and M20 of strengths 10.9 are analysed regarding the connection capacities and the failure modes. The
experimental results are compared to three different approximations regarding the required screw-in depths, which are the standard DIN EN 1993/NA, the guideline VDI 2230, and the calculation approach of Schwarz and Dose. The experiments show that DIN EN 1993/NA seems to overestimate the required screw-in depths while VDI 2230 appears to underestimate the values, leading to an unsafe design. Considering the three approximations, the calculation approach of Schwarz and Dose tends to correspond to the experimental results best. However, to be able to formulate universally valid conclusions, further experimental and numerical investigations are required. For this reason, the research is to be continued at the University of Weimar. The aim is to derive a calculation formula, which allows to determine the resistance of a tapped hole connection depending on the screw-in depth for different grades of base material.

Acknowledgement

The experimental device and the test specimens were designed in cooperation with RSB Rudolstädter Systembau GmbH (www.rsb-stahlbau.de). RSB fabricated and financed the manufacturing of the components. The support is gratefully acknowledged.

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