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Influence of Strain-hardening on the Load-carrying Behaviour of Bearing Type Bolted Connections

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Abstract

The investigations presented in this conference paper focus on the hole bearing resistance of symmetric single-bolt connections, taking into account the distinct hardening behaviour of various steel grades and quantifying its impact on the resulting load-carrying behaviour. They synthesize the findings of a larger study that was published in full in previous publications by the authors. The main focus of the study was put on the limitation of the hole bearing deformations by defining a corresponding “resistance”, which is thus a quantity with the background of an implicit deformation limitation.

Experimental investigations were carried out on four different steel grades, each with eight different geometries, in order to investigate the influence of this hardening behaviour on the hole bearing deformations. The paper presents a new approach to define the point on the load-deformation curve between acceptable and excessive deformations. Based on the results of the hole bearing tests in combination with the new approach to define the transition point between acceptable and excessive deformations, an adapted resistance model is presented. In this model, the hardening behaviour of the steel is taken into account, whereby here specifically the ratio \( f_y/f_t \) of tensile strength to yield strength influences the load-bearing behaviour.

The proposed adaptation of the hole bearing verification which takes the \( f_y/f_t \) ratio into account facilitates the optimal use of material and can thus save resources. The format of the hole bearing verification remains almost unchanged, which should simplify its applicability in practice.

Keywords
Steel hardening, bearing type connections, experimental investigations, finite element simulation

1 Introduction

Due to increased demands on the life-cycle environmental costs of construction elements, for which the initial deployment of material remains the dominant factor, the most efficient use of material has recently regained much more significance.

A more material-efficient deployment of steel is possible if customized characteristics are used for the appropriate application. This is nowadays possible, because of recent technological advances in the steel industry, with which structural steels with modified properties can be produced and adapted to the specific requirements of the customer. With the focus on strength properties, it is possible to produce steels with high ultimate-to-yield strength ratios \( f_y/f_t \), (e.g. \( f_y/f_t > 1.50 \)), which are significantly above common values for conventional structural steels, while at the same time maintaining high ductility.

This results in a pronounced hardening behaviour, which can have positive effects in various applications. One such application is in bolted connections, where either the net cross-section weakened by the presence of the bolt hole or the hole bearing resistance becomes decisive in design. In non-prestressed bolted connections, which are very common in building construction and other structures that are primarily loaded by static loads, the majority of the load is transferred through bearing action between the bolt shank and the hole wall. The build-up of the hole bearing resistance is associated with increasing deformations (elongations) of the bolt hole. With the applied load approaching the ultimate bearing resistance, the elongation of the bolt hole becomes considerably large, which can affect the overall performance of the structure.

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Thus, the limitation of the hole bearing resistance is intended to prevent these excessive deformations and is therefore a strength that is implicitly governed by deformations and by the hardening behaviour of the steel.

Several studies have been conducted in the nearer and more distant past on the load-carrying behaviour of bearing-type bolted connections and their deformability and ultimate strength. In a study that provided the basis for comparison for much subsequent research work, Frank and Yuro [1] conducted a large experimental campaign and, crucially, defined the point where excessive deformations occur at a deformation of 6.35 mm (0.25 in.). At this point, approximately 80% of the ultimate bearing resistance was achieved, whereas an additional deformation of 19 mm was typically required to achieve the ultimate resistance. This limitation of the bolt hole elongations forms the basis of the bearing limit state in the current AISC 360 code [2]. Associated with this elongation, a characteristic resistance of 2.4-\( f_y \cdot d \cdot t \) was proposed. Where \( f_y \) is the material tensile strength, \( d \) is the bolt shank diameter and \( t \) is the plate thickness.

Another definition of such a transition point was provided by Snijder et al. [3]. In this paper, it was found that an average, notional ultimate bearing stress of 3.4\( f_y \) occurs before a significant drop in the stiffness of the joint becomes observable. This forms the basis for the upper limit of the bearing strength of 2.5\( f_y \cdot d \cdot t \) in the currently valid version of the protocol of Eurocode 3 dedicated to connections, EN 1993-1-8 [4]. Referring to the verification at tensile strength level and assuming that \( f_y \) is 1.5\( f_y \) according to [5] leads to the mentioned upper limit of the bearing strength.

Mozë and Beg [6, 7] performed a comprehensive investigation of the effect of geometric parameters on the bearing resistance of bolted connections. Experimental research of 38 tension splices with one and two bolts made from high-strength S690 steel and 19 single-bolt connections made from S235 were conducted. They proposed a new method to control the excessive hole elongation base on the threshold value of \( d_0/6 \). At this hole elongation the connection is at the beginning of the yield plateau or starts losing its initial stiffness. The resistance at \( d_0/6 \) is very similar to the maximum resistance for shear and splitting failures, while for net cross-section failures this resistance was reached in post-critical region.

This paper presents part of the results of 32 single-bolt connections fabricated from four different steel grades – S355J2N, S355M, S460M, and newly developed steel grade with the commercial designation S355M-slimfit (S355M-SF) produced by voestalpine Grobblech GmbH in Linz, Austria. The influence of the hardening characteristic on the hole bearing resistance is investigated in detail. A new approach to determine the transition point between acceptable and excessive deformations is presented from which new limits for the hole bearing resistance are derived.

The complete tests are published in the full publication by the authors [8].

2 Experimental investigations

Hole bearing tests were performed to investigate the load-carrying behaviour depending on different strain-hardening characteristics.

2.1 Specimens and test setup

Specimens with a hole with varying edge distances parallel and perpendicular to the load direction were produced. Resulting in a total of eight different specimen geometries for each steel grade. The geometry of the specimens can be seen in Figure 1.

The geometry of the specimens can be seen in Figure 2. CG effects were carried out to investigate the load-carrying behaviour depending on different strain-hardening characteristics.

2.1 Specimens and test setup

Specimens with a hole with varying edge distances parallel and perpendicular to the load direction were produced. Resulting in a total of eight different specimen geometries for each steel grade. The geometry of the specimens can be seen in Figure 1.

2.2 Materials

2.2.1 Tensile properties

Coupon tests were conducted to obtain the tensile properties of the four different steel types considered in the present study. The tests as well as the evaluation were carried out in accordance to EN ISO 6892-1 [9]. The yield strength was defined as the 0.2 % proof stress of the material. Two tests were conducted in longitudinal direction and for the investigations the mean value of these two tests were taken. They are summarized in Table 1.
Table 1 Material properties of the four different steel types

| Material | \( f_y \) [MPa] | \( f_u \) [MPa] | \( \varepsilon_u \) [%] | \( \varepsilon_f \) [%] | \( f_u / f_y \) | \( E \) [MPa] |
|----------|----------------|----------------|-----------------|----------------|----------------|----------------|
| S355 J2N | 393            | 537            | 16.7            | 28.2           | 1.37           | 212'738        |
| S355 M   | 507            | 563            | 6.4             | 15.3           | 1.11           | 211'334        |
| S460 M   | 543            | 593            | 8.0             | 17.2           | 1.09           | 211'766        |
| S355M-SF | 370            | 620            | 15.5            | 22.6           | 1.67           | 204'372        |

The pronounced hardening behaviour of the S355M-SF can be seen in Table 1 as the ratio between ultimate- to yield strength with a high value of 1.67. Additionally, the stress-strain-curve for the four different steel grades can be seen in Figure 3.

Figure 3 Stress-strain-curve for the four different steel grades

The newly developed steel grad S355M-SF has a similar yield strength as a S355J2N and a similar tensile strength as a S460M as it can be seen in Figure 3.

3 Test results

In this section, the test results of a part of the hole bearing test are presented. Namely the results of the test specimens with a variable distance in the direction of force and a fixed distance of 1.5\( d_0 \) perpendicular to the direction of force are shown. For the complete test results the reader is referred to [8].

3.1 Load deformation behaviour

The force deformation curve for the different specimens can be seen in Figure 4. There, the different line styles and colours stand for the four different steel grades. The force is normalised with \( f_{u,i} \). After a first steep linear branch, the curves merge into the plastic regime and flattens out quickly. The similarity between the S355J2N and S355M-SF, which can already be seen in the stress-strain-curve in Figure 3 is also visible in the force displacement curves of the hole bearing tests. The same is true for the two steel grades S355M and S460M.

Figure 4 Force displacement curves for specimens with \( \varepsilon = 1.5\cdot d_0 \) and varying edge distance \( \varepsilon_1 \)

In Figure 5 the different failure mechanism can be seen. The specimens with different edge distance in the direction of force are presented. From \( \varepsilon_1 = 1.0d_0 \) in Figure 5a to \( \varepsilon_1 = 3.0d_0 \) in Figure 5d. While for the specimen with a small edge distance \( \varepsilon_1 \) the failure can be described as an end tear-out failure, it shifts to a net cross-section failure for a larger edge distance, whereby a mixture of these two types of failure can also occur.

Figure 5 Failure modes Series 1: a) end tear-out failure, b) end tear-out failure, c) mixed failure, and d) net cross-section failure

3.1.1 Strain distribution

The strain distribution on the surface of the test specimens is evaluated at three different load levels i) \( 0.6F_u \), ii) \( 0.8F_u \), and iii) \( 1.0F_u \), where \( F_u \) stands for the maximum load.

In the strain distribution in the net cross-section and below the hole can be seen for the test specimens made of S460M. The different colours correspond to the different load levels which are also indicated on the force-displacement curve. Tensile strains are positively defined, and compressive strains are negatively defined. Additionally, the strain distribution at the maximum load (orange point) can be seen in the respective figure at the top right.
In the net cross-section a strain distribution with the maximum value at the edge of the hole and a sharp drop towards the edge of the specimen can be seen. The strains also increase with increasing load level. The strain distribution below the hole shows compressive strains underneath the bolt which then rise sharply and become tensile strains at the edge of the screw. For more detailed information about the strain distribution the reader is referred to the full publication by the authors [8].

4 Comparison with normative resistances

In this section, the outcome of the experimental tests is compared with the normative resistance according to EN 1993-1-8 [4] and prEN 1993-1-8 [10]. Two points are examined more closely. Firstly, whether the required normative resistance can actually be achieved and, secondly, what deformations occur at these points.

In Figure 7a the different symbols stand for the three different normative cases: i) resistances according to EN 1993-1-8 [4] (currently valid standard) (circles), ii) resistances according to prEN 1993-1-8 [10] (draft version) if the bearing deformations are not a design criterium (squares) and iii) resistances according to prEN 1993-1-8 [10] (draft version) if the bearing deformations of the bolt hole need to be limited (triangles). The different colours stand for the different verifications that can be decisive in this case: green stands for the hole bearing verification, blue stands for the net cross-section verification and orange for the gross cross-section verification.

If the normative resistances without partial safety factor (i.e. $\gamma_{M0} = \gamma_{M2} = 1.0$) are applied to the results of the experimental tests, it can be seen that, irrespective of the steel grade, the hole bearing resistance becomes decisive for specimens 10_15, 15_15 and 20_15 (green symbols in Figure 7a), if the resistance is taken from EN 1993-1-8 and from prEN 1993-1-8 with limiting the bearing deformations of the bolt hole. For specimen 30_15 and for specimen 20_15, if the resistance is taken from prEN 1993-1-8 without limiting the bearing deformations, either the net cross-sectional resistance (blue symbols in Figure 7a) or the gross cross-sectional resistance (orange symbols in Figure 7a) becomes decisive, depending on the steel grade. Due to the high yield strength ratio of the S355M slimfit steel, no longer the net cross-section is decisive but the gross cross-section. The force-deformation curve clearly shows that the normative resistances are below the maximum reached force and the normative resistances are thus reachable for all specimens. In Figure 7b the corresponding deformations at the decisive normative resistance can be seen. In addition, two limits have been inserted, one at $d_0/6 = 5.00$ mm and the other at 6.35 mm (0.25 in) according to the limitation postulated by Frank and Yura [1].

Figure 6 DIC-measured strain distribution for steel grade S460M for specimens: a) 10_15 b) 15_15, c) 20_15 and d) 30_15
The beforehand presented procedure is shown. The deformation curve with indicated points and b) corresponding deformations at the decisive normative resistance and orange: gross cross-sectional resistance (i.e. \( F/F_{\text{max}} \) and \( u/u_{\text{fmax}} \)).

If the resistance is taken from EN 1993-1-8 and from prEN 1993-1-8 for the case with limited bearing deformations, similar observations can be made with slightly smaller deformations when limiting the bearing deformations of the bolt hole according to prEN1993-1-8. The curve shows practically identical values for the test specimens 10_15 and 15_15, which are clearly below the two inserted limits at 5.00 and 6.35 mm. With increasing edge distance in the direction of the force, the corresponding deformations also increase and, depending on the steel grade, are in the range of the two limits and, for test specimen 15_30, clearly above them. The values of the deformations that occur when the resistance according to prEN 1993-1-8 is reached without limitation of the deformations are considerably larger than in the other two cases. The values for test specimens 10_15 and 15_15 are again nearly identical. Specimen 20_15 then has significantly greater deformation and a drop in deformation is then evident for specimen 30_15. This point is identical for all three types of verification, as the net cross-sectional resistance or the gross cross-sectional resistance is decisive here.

5 Definition of the transition point between acceptable and excessive deformations

5.1 Determination of the transition point

The definition of the point between the linear stage and the following nonlinear hardening stage of the load-deformation curve of the hole bearing tests is a key aspect when assessing whether limiting the resistance as proposed in code regulations, i.e. implicitly through strength limitations, can really keep the deformations small. A procedure for determining this transition point is presented in this section and applied to the results of the experimental investigations. Further, the procedure from Lyu et al. [11] is also applied to the outcome of the experimental test and the two approaches are compared with each other.

The newly defined determination of the transition point is based on the change of inclination of the normalised and approximated load-deformation curve. The following steps are required to determine this transition point:

1. Normalization of the ascending part of the load-deformation curve (i.e. \( F/F_{\text{max}} \) and \( u/u_{\text{fmax}} \))
2. Approximation of the normalised load-deformation curve with the Richards [12] growth model (RGM)
3. Calculation of the derivative of this approximated curve \( f' \)
4. Determining the point at which the curve has an inclination of one (\( f' = 1 \))

Due to the presented procedure, where the inclination of the normalised and approximated load-deformation curve is used, this approach is named INC1 as abbreviation for “inclination is equal to one”. Before this point, the strength is increasing disproportionately to the deformations and vice versa after this point. The beforehand presented procedure is shown schematically in Figure 8. The deformation at the transition point \( (u_{\text{tp}}) \), where the inclination is equal to one, divides the curve into the two mentioned parts: on the left of this point, all stiffnesses in terms of needed force differential to cause further deformation increases are larger than a linear relationship between maximum strength and corresponding deformation, and to the right the stiffness is lower. This transition point also represents the point, where the stiffness is equal to the secant stiffness between the origin and the peak load in the normalized and approximated load displacement curve.

If both definitions of the transition point are applied to the results, the obtained points can be seen in Figure 9 as red diamonds and purple squares respectively.
As can be seen in Figure 9, the two definitions lead to resistances that are quite close to each other. Depending on the steel grade and its stress-strain behaviour, the procedure according to Lyu et al. results in different deformations meaning the purple squares in Figure 9 are arranged approximately horizontally within the same edge distance. In contrast, the procedure presented here, in which the arrangement of the red diamonds in Figure 9 is rather vertical, keeps the deformations at the defined load level at closer levels for specimens with the same edge distances.

6 Proposal for adjustment of the normative resistance

In order to meet the newly determined transition point in section 5 and thus describe a rationally defined “deformation-based resistance point” as accurately as possible, an adapted formulation for the corresponding resistance is presented in this section of the paper.

The proposed formulation takes the hardening behaviour of the steel into account but is structured similarly to the verification contained in prEN 1993-1-8 for cases where the hole bearing deformations are to be kept small. Instead of the value \( \alpha_{\text{base}} \), an adjusted value \( \alpha_{\text{ad}} \) is used. The adjustment of the resistance is based on the experimental results and results from numerical simulations serve to verify the postulated procedure. The numerical simulations can be found in the authors’ full publication [8].

6.1 Comparison with current normative verifications

The comparison between the resistances associated with the transition point and the resistances from the standards EN 1993-1-8 [4] and prEN 1993-1-8 [10] can be seen for the test specimens in Figure 10.

The transition points that have been determined with the procedure presented in this paper and the different symbols stand for the different types of steel. As black lines the normative resistances with \( \gamma_y = 1.0 \) can be seen and the net cross-sectional resistance as well as the hole bearing resistance are indicated.

In case of the hole bearing resistance, the standard under draft prEN 1993-1-8 [10] distinguishes between two cases: i) deformations are a design criterion and ii) deformations are not a design criterion. The first case is lower and the second case higher than the hole bearing resistance of the current standard EN 1993-1-8 [4].

Due to the similar concept, the transition points are hereafter compared with the normative resistance according to prEN 1993-1-8 [10] where deformations are a design criteria. In the ascending part of the resistance model between \( \epsilon_{y}/d_{0} = 1.0 \) and \( \epsilon_{y}/d_{0} = 2.0 \) the transition points are, depending on the steel grade a bit higher than the normative resistance (dotted line). In the plateau region, at higher edge distances, the resistances associated with the transition points are somewhat smaller than the normative resistance.

6.2 Introduction of a factor to account for the hardening behaviour of the steel

Due to the difference between the resistance at the transition points determined in this paper and the normative resistance an adapted version of normative resistance is presented.

It has become apparent that the hardening behaviour of the steel after exceeding the yield strength is relevant. Because of this, a correction factor is introduced to consider the material behaviour, in this case the yield strength ratio, and determined based on the results of the experimental investigations. The adjusted hole bearing resistance is calculated using Eq. (1). As this is a verification to limit the deformations, it is not useful to integrate a safety factor \( \gamma_y \), which is why it is assumed and defined as \( \gamma_y = 1.0 \).

\[
F_{b,\text{ad}} = \frac{\alpha_{\text{ad}} f_{y} d t}{Y_{M,\text{NC1}}} \tag{1}
\]

Based on the results of the experimental investigations the correction factor \( \alpha_{\text{ad}} \) is determined by a least-squares fitting procedure using MATLAB’s curve fitting tool and a distinction has been made, between the ascending part and the plateau region of the resistance model. The detailed determination of the correction factor can be found in [8].

\[
\alpha_{\text{ad}} = \min \left( \frac{(1 - 0.13 f_{u}/f_{y}) a_{b}}{f_{u}/f_{y}} \left( 2 \varepsilon_{y}^{2}/d_{0} - 1.1 \right) \left( 22 - 10 \varepsilon_{y}^{2}/d_{0} \right) \right) \tag{2}
\]

\[
\text{with } \varepsilon_{y}^{2} = \min \left( \varepsilon_{y}^{2}/d_{0} \right)
\]

The first part of Eq. (2) determines the ascending part of the
resistance for small edge distances $e_1$. Therefore, the factor $\alpha_0$ (which is taken from prEN 1993-1-8) is reduced depending on the yield strength ratio of the steel.

The plateau value, which is reached at larger edge distances $e_2$, can be determined with the second part of Eq. (2). Since this plateau value is dependent on both, the yield strength ratio and the edge distance perpendicular to the direction of force $e_2$, these two parameters are included in the calculation. However, the edge distance $e_2$ is limited to a maximum value of $2d_0$, as no further influence could be observed with larger edge distances. In Figure 11 the dependency of the correction factor $\alpha_0$ on the yield strength ratio $f_y/f_y^M$, can be seen for different edge distances $e_1$.

**Figure 11** Correction factor $\alpha_0$ as a function of the yield strength ratio for different edge distances $e_1$

The proposed adjusted hole bearing resistance can be seen in Figure 12. The normalised resistance is indicated as a function of the normalised edge distance $e_1$. Additionally, the determined transition points of the experimental tests are indicated as different symbols, representing the different steel grades. As dashed blue line, the normative resistance according to prEN 1993-1-8 for the case when the hole deformations are a design criterion, is shown in the diagram.

**Figure 12** Adjusted hole bearing resistance

Because the hardening behaviour of the steel is considered when calculating the correction factor $\alpha_0$, a certain difference in the resistance between the various steel grades can be observed. In case of Series 1, the ascending part of the resistance at smaller edge distances $e_1$ has only a small dissimilarity to the normative resistance according to prEN 1993-1-8. A big difference, however, occurs in the area of the plateau value, where the proposed resistance is significantly lower in normalized terms. The different symbols, representing the determined transition points for the different steel grades, are very close to the proposed adjusted resistance.

### 6.3 Verification of the proposed adjusted hole bearing resistance

Since the hole bearing resistance was adjusted using the results of the experimental investigations, the outcome of the numerical simulations (see [8] for more details) is used to verify the proposed adjusted hole bearing resistance. To do so, the transition points are determined from the load–displacement curves using the procedure presented in section 5.1. In Figure 13 the determined load at the transition points ($F_{\text{trans}}$) is compared with the theoretically obtained hole bearing resistance ($F_{\text{design}}$) according to prEN 1993-1-8, for the case when bolt hole deformations are a design criterion (Figure 13a) and with the theoretically obtained hole bearing resistance according to the proposed adjusted hole bearing resistance in section 6.2 (Figure 13b).

**Figure 13** Comparison between determined load at the transition points ($F_{\text{trans}}$) and theoretically obtained hole bearing resistance ($F_{\text{design}}$): a) $F_{\text{trans}}$ according to prEN 1993-1-8 and b) $F_{\text{design}}$ according to the proposed adjusted hole bearing resistance in Section 6.2

In the case when the transition points are compared with the design resistance according to prEN 1993-1-8 (Figure 13a), one can see, that some of the points, especially at higher loads, are on the unsafe side (i.e. the design resistance at the transition point is bigger than the determined resistance at the transition point). This would mean that the connection has already overcome the transition point and would already be in the area of excessive deformations. Within the same specimen, the points are all lying on vertical lines, meaning there is no difference between the various steel grades. In Figure 13b the transition points are compared with the proposed adjusted hole bearing resistance, where the hardening behaviour of the steel is taken into account. The points are now mostly on the safe side, meaning that the load at the transition point determined from the experimental tests is now higher than the obtained one with the adjusted hole bearing resistance. It is also visible that the points are more distributed, since they are no longer differentiated only on the basis of geometry, but also on the basis of the hardening behaviour of the steel.

### 7 Summary, Conclusions and Outlook

The findings presented in this paper focus on the hole bearing resistance of single-bolt connections, taking the differences in the hardening behaviour of various steel grades into account. The main focus was on quantifying the limiting effect on strength of the hole bearing deformations as a function of the strength ratio between...
tensile and yield strength $f_y/f_p$, by defining the resistance accordingly. Experimental investigations on four steel grades with different technical stress-strain curves and hardening characteristics, as well as eight different geometries, have highlighted the differences in the load-deformation curves in function of the steel grades’ hardening behaviour. At the same deformation, steels with a low hardening behaviour (small yield strength ratio $f_y/f_p$) have already achieved a greater proportion of the tensile strength over the fictive contact area between the bolt and the hole (d$^4$). On the other hand, steels with a large $f_y/f_p$ ratio will reach a certain limiting deformation at a larger relative distance to the ultimate strength. For steels with high $f_y/f_p$, it is thus possible to use the high tensile strength as the basis for design in bolt bearing equations, however some reduction of the relative gain of strength when compared to steels with lower tensile strength and $f_y/f_p$ ratios is required whenever deformations at the ultimate limit state are design-critical.

A new approach is presented in this paper that leads to the definition of the point on the load-deformation curve between acceptable and excessive deformations. The derivative of the normalised and approximated curve is calculated and the point where this derivative has a value of one (i.e., a slope of 45 degrees) is defined as the point, which distinguishes between acceptable and excessive deformations.

Based on the results of the hole bearing tests, combined with the new approach to define the transition point between acceptable and excessive deformations, an adjusted resistance model for the hole bearing resistance in bolted joints was developed and presented. As the key addition, the hardening behaviour of the steel is taken into account, resulting in almost identical and mechanically consistently derived deformation levels for the different steel grades when reaching the postulated resistance. The core of the verification procedure according to prEN 1993-1-8 was thereby retained and modified with an adjusted correction factor.

The adjusted resistance model was checked with results from numerical simulations. These numerical simulations were verified with the outcome of the experimental investigations and through the examination of further geometries, the database could be enlarged. On the basis of this dataset, it could be verified that the proposed modifications to the resistance model in prEN 1993-1-8 lead to a significant improvement in the prediction accuracy of the hole-bearing resistance for deformation-limited cases.

By verifying the verification with a consideration of the hardening behaviour of the corresponding steel grade, the material can be optimally used and thus resources can be saved. With the adapted and proposed design procedure, the term “excessive deformation” for bolted connections governed by hole bearing can be mechanically described in a consistent manner, and therefore it can be determined whether or not there are excessive deformations. Current results of tests and simulations allow one to foresee that a consistent level of reliability with current design equations will be achievable. Finally, further tests on larger connections are going to be carried out in order to verify the applicability of the proposed equations to more complex joints.

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