AN ADVANCED MODEL OF BOLTS IN STRUCTURAL STEEL CONNECTIONS

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1. ABSTRACT

Issues concerning connections are of great importance in the design of steel structures. In recent years there has been a constant rise in the use of the CBFEM method to model joints, an approach in which the correct modeling of bolts plays a role. The contribution describes the influence of shear-tension interaction on the correct design of a group of bolts. The second main topic is an advanced model of preloaded bolts.

2. THE CBFEM METHOD GENERALIZES THE STANDARD COMPONENT METHOD

The finite element method (FEM) was first applied to the structural design process and static calculations back in the 1980s. It has gradually become the basis of every 3D structural engineering software product used around the world. Although the FEM is an approximate numerical method, it has been accepted unconditionally by engineers in the construction industry. It can be said that today the global analysis of whole structures is not executed in any other way than via the FEM. However, assessment methods remain based on formulas that in the main are defined in a relevant national standard. It is generally true that internal forces acting on a structure are calculated using the FEM, while members are dimensioned using formulas. Several years ago, a team of developers from IDEA StatiCa, the Faculty of Civil Engineering of the Czech Technical University in Prague and the Faculty of Civil Engineering of the Brno University of Technology originated the idea of also using the FEM for the evaluation of structural members and details. A completely new design method combining the standard component method with the FEM was developed for the design of joints and connections used in steel structures. It was named the CBFEM – Component-Based Finite Element Model [1]. Steel plates are modeled using standard finite elements, but special models had to be developed for other components such as bolts, preloaded bolts, welds and contacts. The article examines a design model for standard and preloaded bolts. Fig. 1 shows an example of an FEM model along with numerical analysis results.

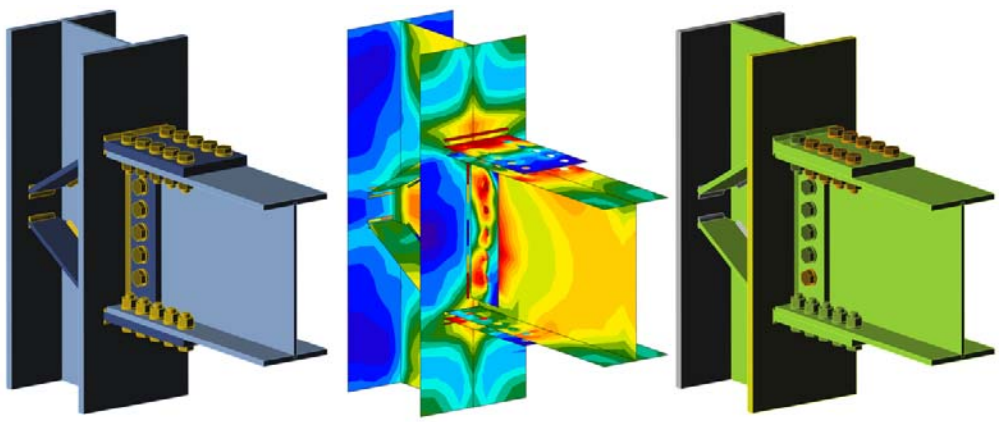


Fig. 1: Joint shape; FEM analysis of stress in steel; evaluation *displayed in "traffic lights" form*

3. DESIGN MODEL OF A BOLT

A modeled bolt is divided into three sub-components which simulate the tensile behavior of the bolt shank, the contact between the plate and the bolt head, washer or nut, and the contact between the shank of the bolt and the plate. The first component is the shank of the bolt itself, which is modeled as a non-linear spring between two nodes. The spring representing the shank of the bolt does not transfer pressure. Pressure is imposed via the contact between the joined plates.

The spring representing the shank of the bolt behaves nonlinearly in tension and shear. The tensile and shear deformation of the shank of the bolt is described bilinearly. A load-deformation diagram of the bolt in tension is shown in Fig. 2. The solution corresponds to experimental findings summarized in the literature [2]. The interaction between shear and tension in the shank of the bolt is considered in a nonlinear solver. The internal forces acting within the bolt are verified according to the EN 1993-1-8 standard [3].

The second sub-component of the bolt transfers tensile forces from the bolt to the plate. The equivalent surface load is determined under the head of the bolt. The multi-point constraint between the node of the shank and the nodes of the connected plate is derived from the equivalent load. The shape of the equivalent load under the head of the bolt influences the bending of the plate under the bolt head. This shape is demonstrated the most when the forces in the bolt increase under prying action.

The third sub-component of the bolt deals with shear in the bolt connection. The shank of the bolt leans against only one side of the opening. This is modeled with the aid of contact elements between the node of the bolt shank and the nodes of the edges of the opening. The stiffness of the shell elements around the opening is designed in such a way that a corresponding bearing strength is achieved when plastic material of the plate is used. The solution also evaluates the symmetrical and non-symmetrical pullout of a group of bolts.

This model is completely unique in the construction industry and is therefore protected by a patent.

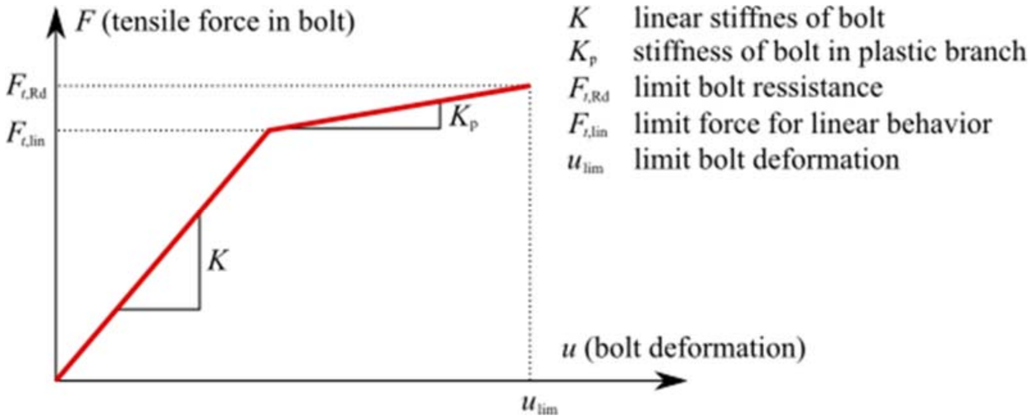


Fig. 2: Load-deformation diagram of a bolt model in tension

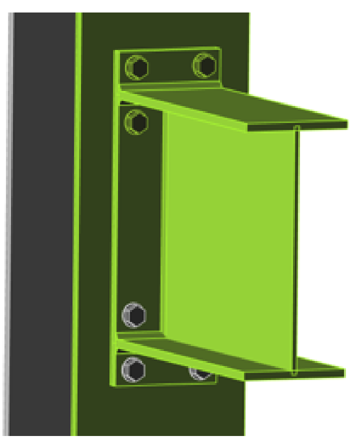
4. SHEAR-TENSION INTERACTION IN A GROUP OF BOLTS

A bolt can generally be stressed by tensile or shear force, or a combination of the two. The evaluation of a bolt considers the stresses individually, as well as their interaction. This is shown in Table 3.4 in Chapter 3 of EN1993-1-8.

For bolted, riveted and pin joints, the following interaction between the tensile and shear strain of a bolt applies:

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.4\,F_{t,Rd}} \leq 1.0 \qquad (1)$$

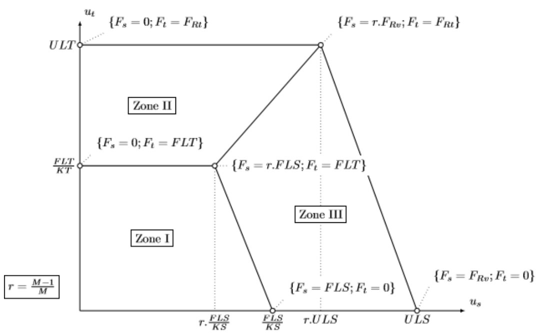
(In practice, a situation can occur when a bolt has a sufficient load-bearing capacity in tension and shear but not when subjected to a combination of both loads. Bolts under great tension are no longer capable of exhibiting sufficient load-bearing capacity under the interaction of both strain types, see Fig. 3. One possible solution is either to use a greater bolt diameter or higher class of material, or to alter the computational model (specifically: the slotted hole) so that interaction already occurs during the calculation of the internal forces in the bolt.



Item	Loads	Ft [kN]	V [kN]	Utt [%]	Uts [%]	Utts [%]	Status
B1	LE1	0,0	55,8	0,0	59,4	59,4	✓
B2	LE1	0,0	55,8	0,0	59,4	59,4	✓
B3	LE1	9,9	44,9	7,0	47,8	52,8	✓
B4	LE1	9,9	44,9	7,0	47,8	52,8	✓
B5	LE1	120,1	58,8	85,1	62,5	123,3	✗
B6	LE1	120,1	58,8	85,1	62,5	123,3	✗
B7	LE1	118,4	42,5	83,9	45,2	105,1	✗
B8	LE1	118,4	42,5	83,9	45,2	105,1	✗

Fig. 3: Evaluation of the load-bearing capacity of bolts without the influence of interaction in the calculation

By including the interaction diagram within the computational model, a different distribution of tensile and shear forces is achieved and the evaluation of interaction functions well without further alterations to the joint, see Fig. 4.:



Item	Loads	Ft [kN]	V [kN]	Utt [%]	Uts [%]	Utts [%]	Status
B1	LE1	0,0	73,2	0,0	77,9	77,9	✓
B2	LE1	0,0	73,3	0,0	77,9	77,9	✓
B3	LE1	10,9	61,5	7,7	65,4	70,9	✓
B4	LE1	10,8	61,5	7,7	65,4	70,9	✓
B5	LE1	114,2	36,0	80,9	38,2	96,0	✓
B6	LE1	114,1	36,0	80,9	38,2	96,0	✓
B7	LE1	121,4	30,1	86,0	32,0	93,5	✓
B8	LE1	121,4	30,1	86,0	32,0	93,5	✓

Fig. 4: Evaluation of the load-bearing capacity of bolts when the interaction diagram is included in the calculation

5. MODELING OF PRELOADED BOLTS

With preloaded bolted connections, it is considered that the shear forces in the joint are transferred via friction in the contact between two plates. Compressive force is achieved by preloading the bolt during installation. One advantage of a preloaded joint is that it is a fixed connection without clearance and it has considerably better fatigue properties. This is exploited in bridge structures, for example. The disadvantage of such joints is that their installation is more technically demanding. The ultimate condition for the shear force is the moment when it overcomes the friction in the contact between the plates and the joint slips.
The calculation for preloaded bolts is carried out according to the EN 1993-1-8 standard, Chapter 3.9, with regard to which the following conditions apply:

- Bolts of strength classes 8.8 and 10.9 can be used.
- Bolts are preloaded to 70% of ultimate strength f_{ub} (formula 3.7 of the EN 1993-1-8 standard):

$$F_{p,C} = 0{,}7 f_{ub} A_S \qquad (2)$$

- External tensile load on the preloaded connection has an adverse effect on its slip resistance. When evaluating a preloaded joint, the influence of the external tensile force $F_{t,Ed}$ applied to the connection is therefore also considered.
- The ultimate shear strength when slippage occurs is determined according to the following formula (formula 3.8 of the EN 1993-1-8 standard):

$$F_{S,Rd} = \mathrm{k}_S . \mu \frac{F_{p,C} - 0.8 F_{t,Ed}}{\gamma_{M3}} \qquad (3)$$

In the above formula, the coefficient of friction μ between the plates and the reduction coefficient k_s are used. The friction coefficient is dependent on the class of the connection and the values recommended for it can be found in Table 3.7 in EN 1993-1-8. The influence of the shape of the opening is expressed using the coefficient k_s and its values can be found in Table 3.6 in EN 1993-1-8. It should be pointed out that the class of the connection or the shape of the opening cannot be distinguished automatically, and therefore the values for both coefficients must be entered into the application correctly by the user.

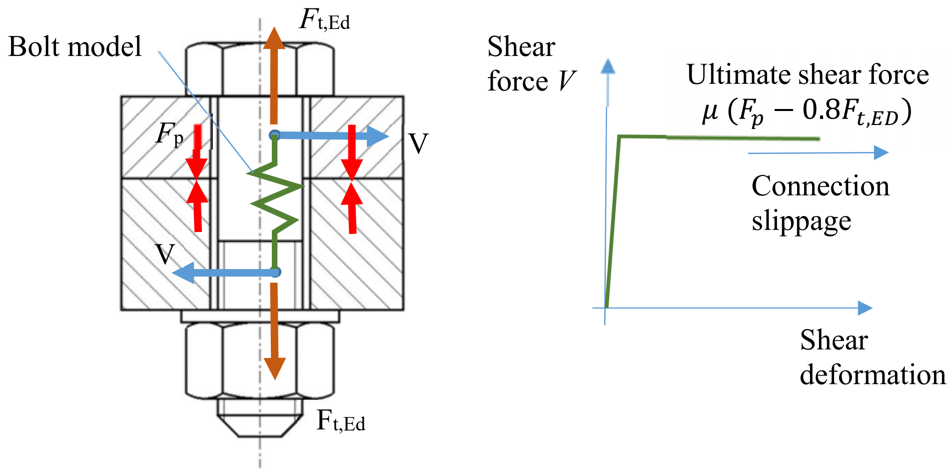


Fig. 5: Shear characteristics of the preloaded connection model

The FEM model of a preloaded bolt is realized in a similar manner to the model of a standard bolt, using a special nonlinear elastic bond that connects the shell elements of the connected plates. The axial characteristics are identical with those of the standard bolt model. The shear characteristics can be clearly seen in Fig. 5. The linear shear stiffness is determined from the stiffness of an equivalent pressure element under the bolt head. The ultimate shear strength includes the influence of the external tension load on the bolt in accordance with EN 1993-1-8, as shown in Fig. 5. It is a simplified model of a preloaded connection. The friction force is not realized in the contact between the plates but directly within the bolt model. An advantage of this solution is its stability and the low computational requirements of the FEM model. A disadvantage is that the model fails to simulate the real distribution of contact pressures between the plates. This demonstrates itself in the event that external moment load is imposed on a group of preloaded bolts. In reality, the contact pressure under the bolt decreases on the side that is in tension and increases on the side that is in compression. The external moment load does not actually have a significant effect on the bearing capacity in slippage, as is stated in the EN 1993-1-8 standard. The simplified model cannot include this phenomenon and the external moment load causes the bearing capacity of the preloaded connection in slippage to be lowered. As a result, the simplified model of a preloaded connection is conservative with regard to the effect of external moment load. An exact model of the contact which includes friction within the contact is currently being developed. It will enable the exact calculation of the preloaded connection and will be released in a subsequent version of the program. However, this will come with the cost of higher computational requirements for the FEM model. Nevertheless, the current simplified model can be applied to the majority of standard preloaded connections, and only in some cases may it be conservative compared to the standard.

6. IDEA STATICA CONNECTION HAS ITS SIGHTS SET ON BECOMING A GLOBAL PRODUCT

The CBFEM method is the foundation on which the IDEA StatiCa Connection program is built [4]. This program is the first of a new generation of design and evaluation programs based on higher and more exact computational methods, and not on formula-based simplification. The FEM can use very detailed material models based on measurement results which is very close to the behavior in real. The CBFEM does not do this. The models used by the CBFEM are those upon which today's design standards are based (EN, AISC). The result is not an analysis of reality but rather an exact implementation of the requirements of the relevant standards. The FEM is thus not used to analyze a given construction element, but to directly evaluate it. This is of key importance for the implementation of the method in practice. Designers and structural engineers need unambiguous information for their work: either a joint fulfills or does not fulfill the requirements of the relevant standard. The CBFEM method provides this information.

The CBFEM method has been verified through its use with many examples of standard joints; a set of verification studies are published in [5]. However, the real verification process is now taking place quite independently of the team of authors. The hardest and most uncompromising verification of all is that which is carried out by the market.

At present, the IDEA StatiCa Connection program is used by more than 1000 companies in 40 countries.

7. CONCLUSIONS

A new bolt model in the context of the CBFEM method was presented. The model accounts for the full interaction between tension and shear in the shank of the bolt, transfer of tensile forces to the supporting plate through the bolt head and transfer of shear through bearing to the bolt hole perimeter. Preloaded bolts are also supported. Calculation results are in good agreement with experimental findings in the relevant literature and are always on the safe side.

8. REFERENCES

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