Partial-strength and highly ductile steel and composite joints as robustness measure

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ABSTRACT:

The paper reports briefly on the experimental and numerical investigations of steel and composite joints aiming at the development of semi-rigid and partial-strength joint solutions allowing large deformations and rotations for redistribution of internal forces in the structural system when local damage e.g. “Loss of a column” occurs. Investigations of steel and composite joints with highly ductile behaviour are presented. Thereby special focus is given to the adjustment of the single joint components to ensure a high deformation capacity during pure bending as well as combined bending and tension exposure. The highly ductile and partial-strength joint solutions allow placing the plastic hinges into the joints instead of the former concept to strengthen the joints in order to achieve a development of the plastic hinges in the beams. These ductile joint configurations enable large deformations in the structural system for an exceptional event which are necessary to activate catenary action as alternate load path to redistribute the internal forces.

1 INTRODUCTION

The highly ductile and partial-strength joint solutions allow placing the plastic hinges into the joints instead of the former concept to strengthen the joints in order to achieve a development of the plastic hinges in the beams. These ductile joint configurations allow for redistribution of internal forces within the structural system by enabling large deformations so that they are suitable to follow the design strategy of the alternate load path method for progressive collapse mitigation. The alternate load path method is realized in this case by activating plastic system reserves by transition from flexural loading to tensile load in the members and joints and initiating of catenary action. Therefore the joints have to be designed in detail and all single joint components have to be adjusted in such a manner that under biaxial loading at each time of loading the weakest component has to be always ductile. This is feasible with only small additional effort by using the inherent plastic reserves of the material steel.

2 ALTERNATE LOAD PATHS AS DESIGN STRATEGY

2.1 General

There are different design approaches to achieve the mitigation of progressive collapse [14]. One method of achieving this goal effectively is the redundancy approach (alternate load path method). The redundancy approach is well suitable for structural steel and composite buildings with inherent sufficient ductile material behaviour allowing deformations when local failure occurs. Results of re-
cent research projects [13], [11] of the authors demonstrated that the former concept to strengthen the joints in order to achieve that the plastic hinges are placed in the beams is not a necessary condition for activation of catenary action in a frame structure. It is also possible to place the plastic hinges into the joints by designing partial-strength joints with sufficient ductility. The paper is discussing first basics concerning requirements for ductile joints to resist resulting stresses of exceptional events like loss of a vertical member.

The approach, suggested in the following, is part of the design strategy to assume local failure and to prove that the loading of the damaged part can be redistributed and transferred by alternate load paths. This approach realizes the alternate load paths by large deformations of the structural system. The joints considered here are assumed as partial-strength ones and not as full-strength. Therefore the joints have to be designed sufficiently ductile taken into account the different behaviour and properties of all relevant joint components.

2.2 The alternate load path method

This method means that the structure is designed for the load case “local failure” and has the ability to redistribute the internal moments and forces due to sufficient redundancy. This strategy is well suitable if high local resistance cannot be achieved, or at least not without disproportionate effort, especially for building structures. Alternate load paths may be achieved by various measures. In the here described case (framed structure with vertical member loss) alternate load paths can be formed by use of plastic reserves, the transition from flexural to tensile forces (see Figure 3), i.e. catenary action, or from planar to spatial structural behaviour. This demands sufficient ductile behaviour of members and especially of joints. Steel and composite members benefit from the ductile material behaviour of structural steel. So steel has the capability to combine strength, ductility and energy absorption capacity which are basic properties for designing robust and redundant buildings.

Redundancy can be achieved by allowing for force redistribution within a structural member (local level) or within a structural system (global level). Force or stress redistribution requires large deformations. Large deformations of the structural system result in large plastic strain of material which enables the activation of additional plastic material reserves. So on local level the material steel has the capability to activate plastic material reserves as well as plastic system reserves (stress redistribution).

Plastic material reserves of steel depend on one hand of the distance between the level of the nominal values and the actual values and on the other hand on the ratio of $f_y/f_t$ (see Figure 2). In a structural robustness analysis the actual material properties are of main interest. Information about actual material resistance of steel are available in the probabilistic model code of the JCSS [3].
The redundancy of bolted connections is derived by the interplay of hardening effects and deformation capacity of single components. By ensuring that especially the components “endplate in bending” and “column flange in bending” have a certain ductility additional membrane effects on local level (in the T-Stub) may be activated leading to further increase of the resistance (having sufficient capacity of the bolts). Furthermore having sufficient deformation capacity the joints are also able to redistribute the internal force from pure bending state into mixed bending + tension state, up to a more or less pure tension state which is conditional for the development of catenary action in a framed structure.

2.3 Ductility demands for members and joints

For common steel profiles in structural engineering depending on the rotation capacity of the cross-section diverse categories of ductility classes exist. That means that the capability of the cross-section to undergo locally a total plastification (to develop a plastic hinge and additional sufficient rotation capacity) without premature stability failure is ensured by slenderness ratio of cross-section. Therefore for plastic analysis of a steel structure the requirements according EN 1993-1-1 are to use only class 1 cross-sections. Those are cross-sections with sufficient moment bearing capacity as well as rotation capacity. Particularly by using rigid and full-strength joints the plastic hinges are located in the beams.

Using partial-strength joint configurations the plastic hinges are developing initially in the joint which requires high rotation capacities of the joints. Therefore a detailed joint design is necessary considering the interaction of all joint components including over-strength effects to ensure that under the whole loading sequence of the joint the weakest component is always ductile.

According to the basic design criteria (ULS + SLS) members and joints are designed assuming nominal material values. This is justified by the present safety concept. However for large displacement analysis considering only nominal values may lead to results which are non-conservative. So aside of the plastic behaviour of the material and the stability sensitivity of the sections which dominate the ductility of the members, the joint behaviour is decisive. Composed of various components the aim should be that only ductile components control the overall joint behaviour. For this not only the component behaviour itself is of importance but the interplay of the various components considering also possible over-strength effects play an important role.

3 EXPERIMENTAL INVESTIGATION OF DUCTILE JOINTS

3.1 General

Within two research projects [13], [11] the joint deformability and ductility as well as the combined bending and tensile resistance have been investigated. Beside experimental tests numerical simulations were performed to determine the decisive components as well as the optimal adjustment of important components to each other to ensure an overall ductile behaviour of the joint.

3.2 Steel joint tests

The performed steel joint tests mainly aimed at the investigations of increasing the joint ductility by varying different parameters. The main parameters influencing the deformability in the tension zone of the joint are the ratio of the endplate thickness and the bolt diameter (under consideration of the individual material strength) and the arrangement of the bolts depending on the distance to the web. Two different subseries investigated the moment-rotation behaviour and the maximum available rotation capacity of the joints.
The first subserie checked the influence of ratio of the bolt - ∅ and the endplate thickness as well as the influence of the bolt arrangement. The second subserie examined the influence of the steel strength and the simultaneous activation of the components endplate and column flange. The results of subseries two are given in Figure 4. Deformed shape of the test specimen Z3 of subserie two is presented in Figure 3. The detected influence of the relevant components to the deformability/ductility of the joint are given qualitatively in Table 1.

### Table 1. Detected influence of the main joint parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influence on rotation capacity</th>
<th>Influence on bearing capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{bol}/t_{EP}$</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Bolt arrangement</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Steel grade EP</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>$t_{EP}/t_{CF}$</td>
<td>0</td>
<td>n.n</td>
</tr>
<tr>
<td>+ disproportionate</td>
<td>o proportionate</td>
<td>- little</td>
</tr>
</tbody>
</table>

Table 1 describes the quantity of influence concerning the rotation capacity as well as the bearing capacity of the investigated variation of parameters of the joint components from the point of view of quality. So small changes of these named parameters might positively influence the ductility of the joint in a significant way whereas at the same time the bearing capacity is only decreased marginally. This is resulting from the fact that all the listed parameters are influencing mainly the components “endplate in bending” and “column flange in bending” which are able to activate additional local membrane effects under great deformations. These additional bearing effects compensate the decrease of the bending capacity of the components by reducing e.g. the endplate thickness or the steel grade.

### 3.3 Composite joint tests

The composite joint tests were part of a test program within a RFCS-Project [10], [13] forming a unique chain from component tests (University of Trento) up to a complete substructure test (University of Liège). The objective of these tests was the determination of the simultaneous moment-tensile-resistance within the joint. The tests simulated the loading procedure from pure bending state to a mixed bending and tensile state up to a pure tensile state at the end. The tests were successful following the whole theoretical M-N-curve (as shown in Figure 6). The failure of the joints always occurred under mainly pure tensile exposure. From the results of the composite joint tests under combined bending and tension exposure it can be concluded that having a highly ductile joint behaviour due to well-advised adjustment of the single components the transition from pure bending state up to a membrane state in the joint is possible. The design of the joint specimens considered already over-strength effects and the bolts were intentionally oversized to exclude premature brittle failure of the connection.

The results of the joints tests have been also confirmed by a substructure tests executed by the project partner Ulg (Liège). Within this substructure test the activation of catenary action, after the event column loss happened, was possible due to the highly ductile performance of the joints [7].
Failure was mainly induced by the concrete slab: for the hogging moment joints by increased cracks and final rupture of the reinforcement, for the sagging moment joints by crushing of the concrete. In addition a remarkable residual resistance and ductility remained when the concrete slab had already failed. The tests even showed that the pure steel joints allowed a further increase of the joint rotation and resulting of this the membrane forces within the structure could be further increased.

4 SPECIFIC FEATURES AND REQUIREMENTS FOR DUCTILE JOINT SOLUTIONS

4.1 General

To be able to undergo from pure bending exposure to a pure tension exposure first it has to be ensured that sufficient rotational deformability of the joints is available. So large deformations to activate membrane forces in the structure could develop which lead to bending and tension loading of the joints. For the components of the joint which are under compression for the state of pure bending the loading gradually change from compression into tension by additional loading of the joint by membrane forces. So these components have a lot of plastic reserves in comparison to the tension components which are already strongly utilized for pure bending state when starting with additional tensile loading of the joint. The tension components have to provide sufficient deformation capacity because they are already highly stressed under pure bending and require for reserves for the additional tension exposure [4], [6], [7], [13]. Within the component tests the tension components like the “reinforcement in tension”, “endplate in bending” or “column flange in bending” have been investigated aiming to improve the deformation capacity of these components (e.g. using B 450C instead of B 500B, increasing distance of studs to the column, increasing distance of the bolts to the web, etc.). Within further numerical investigations the influences of material over-strength effects on the component and joint behaviour have been investigated. Consequences in general of disregarding over-strength effects are shown in chapter 4.2. Own results of numerical simulations considering the actual stochastic distribution of strength for bolts and structural steel are given in chapter 5.

4.2 Considering of over-strength effects

Figure 8 gives the example of a joint composed of a ductile and a brittle component, e.g. the endplate in bending acting together with bolts which usually fail in a brittle manner. The design according to the nominal values of strength lead to a moment rotation curve of the joint also acting ductile, see case a). However the actual values of strength may exceed the nominal values (over-strength effect) so that no longer the ductile component dominates the failure load, but the brittle one, see case b). As a consequence the overall behaviour of the joint shows a very limited rotation capacity. Disregarding over-strength effects the connection may lead to only limited ductility as shown and as consequence no redistribution of forces can take place that means the structure has only reduced redundancy. So aside of the plastic behaviour of the material and the stability sensitivity of the sections which dominate the ductility of the members, the joint behaviour is decisive. Composed of various components the aim should be that only ductile components control the overall joint behaviour. For this
not only the component behaviour itself is of importance but the interplay of the various components considering also possible over-strength effect play an important role.

![Diagram showing interaction between ductile and brittle components](image)

a) nominal values of strength

b) actual values of strength

Figure 8. Influence of over-strength effects on the rotation capacity of connections

4.3 **Specific features for partial-strength steel and composite joints**

For partial-strength joint solutions highly ductile joint behaviour is really important due to the fact that the plastic hinge is located in the joint and all global deformations have to be realized more or less mainly by joint rotation. That means that the joints are the weakest link in the structure and their resistance and deformability defines the global redundancy of the structure. In comparison to nominally pinned joints there are less extra costs (material + labor) but much more redundancy of the structure, so by only small additional efforts the effectiveness concerning progressive collapse mitigation is improved.

It has to be underlined that these joint configurations might be relatively sensitive for small changes concerning the layout and material values due to the close interplay of the single components. So for using these joints in the field of large displacement analysis (beyond ULS/SLS) special focus has to be given to the arrangement and adjustment of all single components to avoid premature brittle failure of the joint leading to a missing of the aimed robust performance of the structure.

Advantage of these highly ductile joint solutions is their high energy absorption capacity which reduces the dynamic amplification factor $\lambda$ under gravity loading clearly ($\lambda \ll 2$) [8], [16].

5 **FURTHER NUMERICAL INVESTIGATIONS OF THE JOINT DUCTILITY**

5.1 **General**

The numerical simulations were executed by the Finite Element software ANSYS 11.0. To be able to analyse the stress and strain distribution within the important components of the joint, the whole connection was modeled by 3-D 20-node structural solid elements. The area of the column and beam close to the connection as well as the complete connection (endplate, bolts) got a mesh refinement whereas the remaining parts of the modeled specimens were meshed more roughly. The boundary conditions as well as the loading were applied according to the performed steel joint tests. So first a recalculation was made to verify the FE-Model at the tests results and afterwards parametrical studies followed to extend the range of parameters as well as investigate the actual influence of material over-strength effects on the joint behaviour.
5.2 FE – results of the actual influence of over-strength effects

The influence of the material properties on the joint behaviour (ductility and bearing capacity) depending on stochastic distribution of the material strength was investigated in a first step by considering various combinations of characteristic values \[18\]. Numerical simulations were used due to the fact that the local membrane effect in the T-stub of the components “endplate in bending” or “column flange in bending” is not yet implemented in the analytical approach of the component method.

The distribution of the structural steel strength which has a bit greater coefficient of variation. The most unfavourable combination of characteristic values is having the structural steel strength above the 95%-fractile value and the bolt strength which has a bit greater coefficient of variation. The most unfavourable combination of characteristic material combinations of bolts and structural steel. The influence on the bearing capacity is relatively small due to the fact that the bolt strength is responsible for the ultimate bearing capacity of the joint. The distribution of the bolt strength has very little random variable. Whereas the rotation capacity in Figure 9 is mainly influenced by the distribution of the structural steel strength (structural steel, bolts) on the joint behaviour were performed to be able to evaluate the influence of over-strength effects to maximal available rotation capacity. It was demonstrated that the over-strength effects have to be considered by initial joint design. Neglecting these effects leads to non-conservative joint configuration in view of ductility requirements. The “T-stub” approach proposed by the Eurocode \[2\] neglects such important contributions, which can be considered as a reserve of strength and deformation capacity, contributing to fulfill the ductility requirements for joints in the case of exceptional loading conditions (robust systems). Criteria aiming at the evaluation of the performance of T-stub in the large displacements field are not provided by the Eurocode, and in effect are outside its scope. This requires the definition of adequate methods enabling control of the main parameters affecting the ultimate strength and ductility of T-stubs. Afterwards the joint with its actual characteristics also in large displacement field can be described by an analytical model which enables to combine the mechanical model with statistical dispersion and assess the reliability of the main parameters by a probabilistic analysis to translate them into indirect design criteria for robustness measure of beam-to-column connections. The suggested approach enables improving the robustness of framed structures with only small additional effort and less extra costs.

![Figure 9. Influence on the joint behaviour of the actual material strength distribution](image)

The curvatures in Figure 9 show the range of probabilistic distribution of the joint response for characteristic material combinations of bolts and structural steel. The influence on the bearing capacity is relatively small due to the fact that the bolt strength is responsible for the ultimate bearing capacity of the joint.
7 ACKNOWLEDGEMENT

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8 REFERENCES