Steel structures

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Summary

Steel is a ductile material and provides good resistance to progressive collapse. It has a relatively high strength to weight ratio that allows for reduced weight of construction which is advantageous in the case of member loss and the need of redistribution of loading. Designing steel connections to resist progressive collapse requires special attention. Sufficient ductile beam-to-column connections should be designed to allow development of the full capacity of members and activate the inherent plastic material reserves of structural steel [16].

Keywords

Progressive collapse, robustness, steel, ductility, redundancy, membrane effects, over-strength effects, plastic material reserves.

Background / Introduction

Different structural systems exhibit different degrees of sensitivity toward progressive failure. The same applies for different kind of construction materials. Within this paper the material steel is considered in detail concerning its structural properties and their behaviour for structural robustness demands. Especially the structural properties; geometry, redundancy and ductility are described in more detail for the material steel. A distinction is also made between the local and global level of the structure by looking at the resistance, redundancy or ductility.

The implied assumption that the adequate resistance of the structure is guaranteed by the resistance of its elements (cross-section, joints) is generally not valid, if the global stability of the system is not proofed separately.

Additional considerations are therefore necessary to ensure structural safety after an initial local failure. Concerning the geometrical properties of steel (high strength but at the same time great weight) steel structures are usually framed structures, trussed girders or space trusses.

The redundancy of the material steel for structural robustness analysis can be seen in the inherent plastic reserves. A condition for activation of plastic reserves is sufficient ductility. And the big advantage of structural steel is the overall ductile material behaviour.

Structural properties - general

A brief summary gives an overview of the properties of the material steel under the aspect of a structural robustness or large displacement analysis.

By considering progressive collapse mitigation as additional design criteria for a structure the used material has to provide even more requirements than for basic design criteria. Beside high strength and good ductility further properties like great plastic reserves, high residual strength and energy dissipation are of high importance. All these characteristics are provided by steel.

Another aspect to have in mind is that in comparison to the design under ULS and SLS where the material is taken into account with nominal values including safety factors, the structural robustness analysis should be performed with mean values of the actual yield and tensile strength. Especially for the determination of the maximum deformation or rotation capacity of bolted beam-to-column connection the actual properties should be used, because the nominal values might lead to an overestimation of the deformation capacity.

Properties of steel: Geometry

The geometries of steel cross-sections in steel structures are either welded structural steel or rolled structural steel. Furthermore the cross-sections for vertical and horizontal members could consist of pure steel or composite material. In comparison to concrete members the steel members are usually more slender which results in a larger susceptibility to stability failure for high degree of utilization [1].

Depending on the type of cross-section the classification of the cross-section is also varying which leads to different ductile behaviour of the member.

The global geometry of steel structures is usually a framed structure with prefabricated vertical and horizontal steel profiles which are mostly assembled on site by bolted beam-to-column connections. The properties of the joints have again decisive influence on the redundancy and ductility of the whole structural system.

Material models

For the design in normal ULS and SLS the material steel is usually sufficiently described by its stress-strain relationship. Depending on the steel grade the ultimate strain is varying. For the common steel grade used for structural steel S235 or S355 the ultimate strain is up to 20-25% whereas high strength steel or bolts has only very limited ultimate strain, see Figure 1.

The main characteristic values for the stress are the yield strength f_y and the tensile strength f_u. For normal design (ULS, SLS) the nominal materials values have to be considered according the corresponding standard.

For progressive collapse analysis it is more reasonable to consider material mean values instead of nominal values. So it is possible to activate additional material reserves (see chapter redundancy) and for the connections over-strength effects were taken into account which is very important in terms of ductility and capability of redistribution (see chapter ductility and over-strength effects) [5], [7], [8].

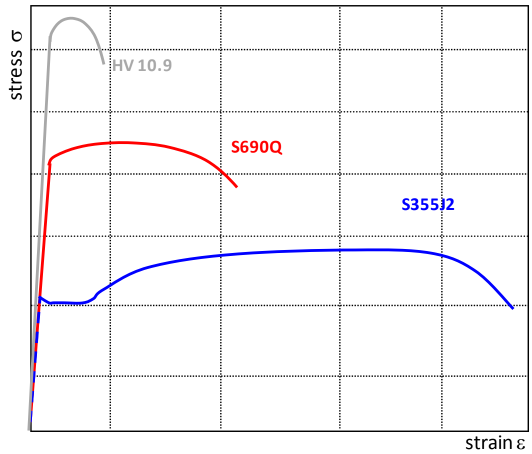


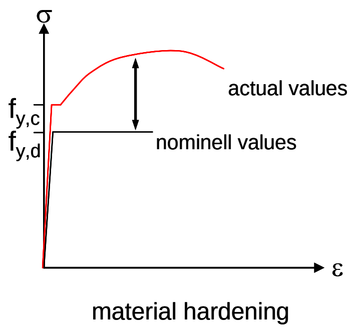
Figure 1: Stress-strain models for different steel grades

Furthermore for robustness issues it is of advantage to have materials with high deformation capacity that means with high ultimate strain. That allows large deformations within the structural system.

Further positive material characteristics for exceptional loading and progressive collapse mitigation besides the ductility are the high energy dissipation and high residual strength. This results in reduced impact factors for high dynamic loads (impact, blast) and leads also to less dynamic deformation demands (reduced dynamic amplification factor).

Redundancy of steel structures

Redundancy can be achieved by allowing for force redistribution within a structural member (local level) or within the structural system (global level). Force or stress redistribution requires large deformations. Large deformations of the structural system result in large plastic strain rates 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). On global level the redundancy of steel structures in a progressive collapse analysis is achieved by alternate load paths. e.g. by activation of catenary action in the horizontal members. Alternate load paths by catenary action demand for ductile members and joints, more about ductility is given in chapter ductility.



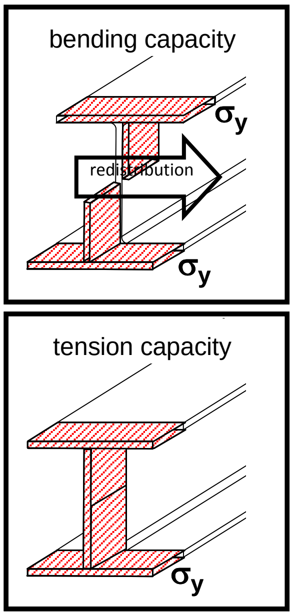


Figure 2: Plastic material reserves Figure 3: Stress redistribution within the cross-section

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_u/f_y (see *Figure 2*). In a structural robustness analysis the actual material properties are of main interest. Information about actual material resistance models of steel are available in the probabilistic modal code of the JCSS [3]. The static properties of structural (rolled) steel are derived from this document:

	f_y [N/mm^2]	f_u [N/mm^2]	f_u/f_y	ductility [%]
nominal value	235	360	1,53	25,0
actual mean value [3]	280	392	1,40	~ 35,0

Table 1: Comparison of nominal and actual material properties of S235

	f_y [N/mm^2]	f_u [N/mm^2]	f_u/f_y	ductility [%]
nominal value	355	510	1,44	25,0
actual mean value [3]	420	560	1,33	~ 35,0

Table 2: Comparison of nominal and actual material properties of S355

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 may be activated leading to further increase of the resistance. Furthermore having sufficient deformation capacity the joints are also able to redistribute the internal force from pure bending state into bending + tension force up to the more or less pure tension state which is conditional for the development of a catenary action in a framed structure.

Over-strength effects

Over-strength effects are describing on one hand the characteristics of the material, which means that the actual material properties (mean values) have a clearly higher strength than the nominal values given in the standards. On the other hand also additional local bearing effects like local membrane effects are included within the phenomena over-strength effects, see *Figure 4*.

In terms of resistance the over-strength effects usually cause an additional material reserve which can be activated in the case of progressive collapse analyses.

But considering connections where different types of steel grade are assembled the over-strength effects may result in unrequested negative effects [4], [11].

Figure 5 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).

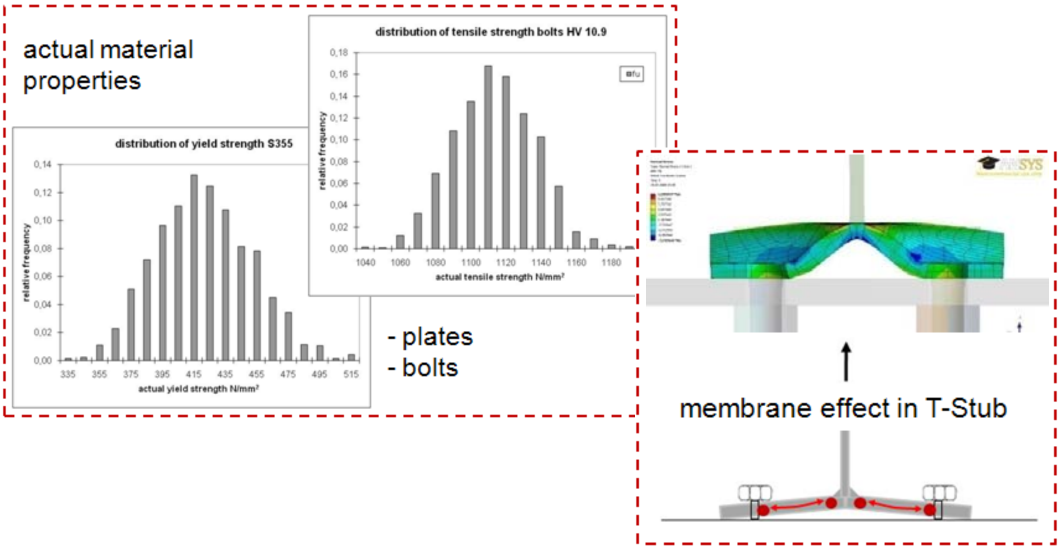
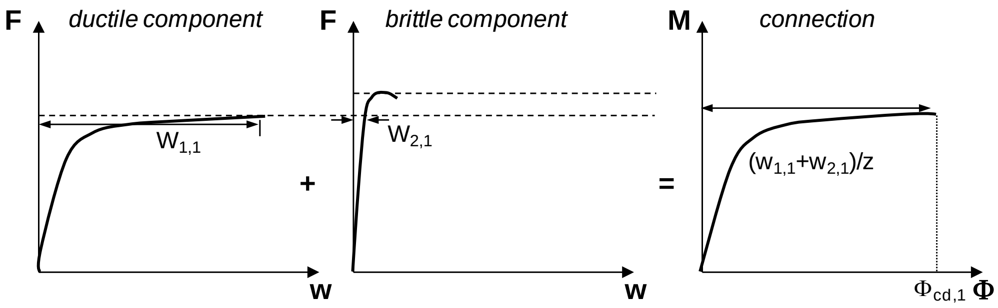
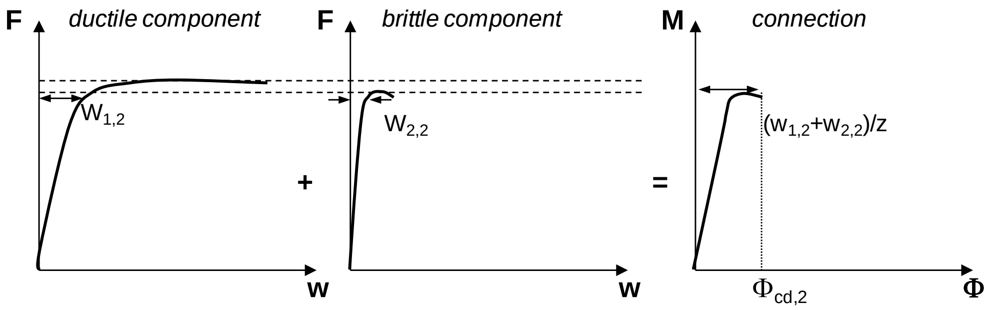


Figure 4: Possible over-strength effects influencing the joint behaviour

However the actual values of strength may exceed the nominal values (over-strength effects) 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. Thus disregarding over-strength effects of 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 [8], [10].



a) nominal values of strength



b) actual values of strength

Figure 5: Influence of over-strength-effects on the rotation capacity of the connection

Ductility of members and connections

For the material steel with its common profiles for structural engineering diverse categories of ductility classes exist depending on the rotation capacity of the cross-section. 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 the slenderness ratio of cross-section. Therefore for plastic analysis of a steel structure the requirements according the EN 1993-1-1 [1] are to use only class 1 cross-sections that means cross-section with sufficient moment bearing capacity as well as rotation capacity for sections which might develop for plastic hinges except the final one for which class 2 (developing full plastic moment) suffices.

Whereas when using rigid or full strength joints the plastic hinges are located in the beams for partial-strength joint configurations the plastic hinges may initially develop in the joint which requires also high rotation capacities of the joints.

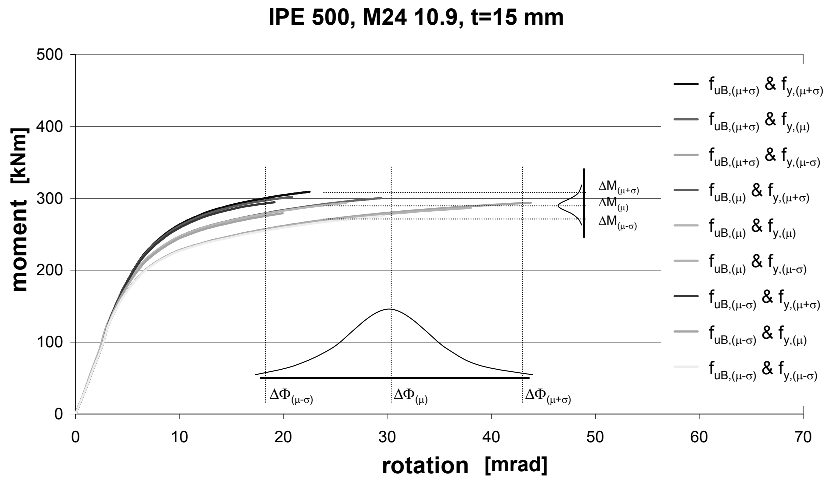


Figure 6: Influence of the actual material strength distribution on the joint behaviour

The moment-rotation curves in *Figure 6* show the range of statistical 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. The distribution of the bolt strength has very little random variable. Whereas the rotation capacity in Fig. 6 is mainly influenced by the distribution of the structural steel strength which has a bit higher 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 below the 5%-fractile value [4], [8], [11]. Therefore the rotation capacity is clearly reduced (up to 50%) in comparison to a computation of the joint with nominal material values [8].

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, see also Figure 5.

So a ductile design of connections is of high importance because ductile joint solutions are contributing to the robustness as characteristic of the structure, see *Figure 7*

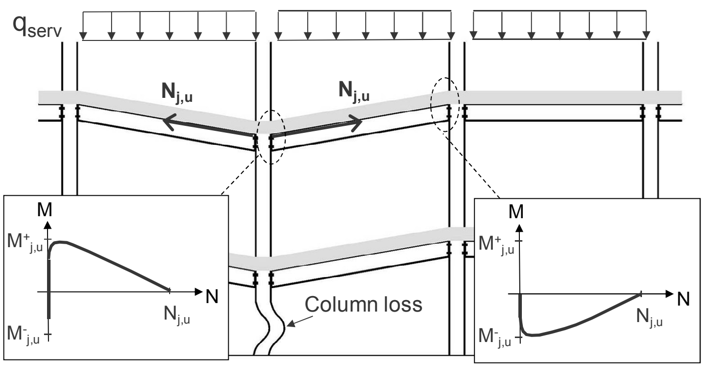


Figure 7: Allowing of alternate load path by sufficient ductile behaviour of members and joints

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.

Strain rate effects

Another characteristic common to steel and other metal alloys is strain rate sensitivity, which means that the stress-strain relationship depends of the strain rates. The main features of this behaviour are the following:

1. the elastic modulus is unaffected,
2. the ultimate tensile strength increases slightly with strain rate,
3. the yield strength has a much higher increase, in comparison, and
4. the ultimate tensile strain can reduce with strain rate.

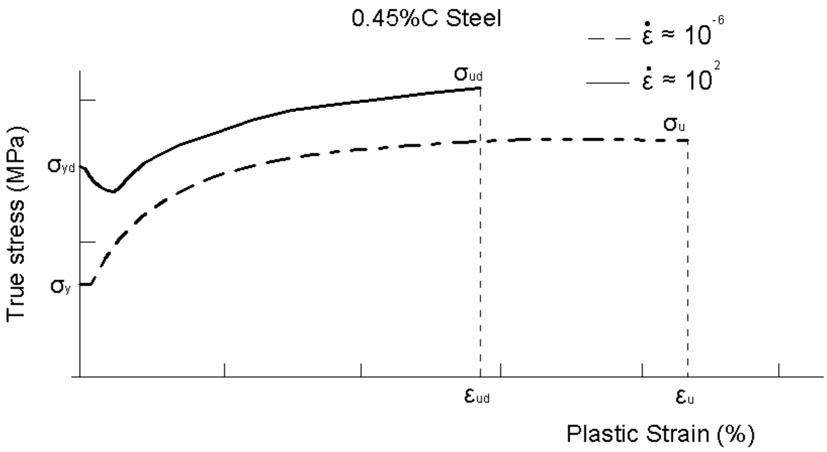


Figure 8: Monotonic curve flow curve for low and high strain rates

Progressive collapse scenarios involve large deformations over a short time period and therefore relatively high strain rates are expected, either in the beams (for rigid connections) or connection component level (for partial strength connections). Dynamic overstress models, such as those of Malvern, Cowper-Symonds or Johnson-Cook, determine the increase in the yield strength as a function of the strain rate, and these can be employed in elasto-plastic models typically using visco-plastic theory. Such models were developed by Izzuddin & Fang [12] which were successfully calibrated against experimental results, and which were then used for a comprehensive study of the rate-sensitive response of framed structures [13].

The design-oriented framework for the assessment of building robustness under sudden column loss developed by Izzuddin *et al.* [14] was recently extended to account with material rate sensitivity. This has allowed extensive numerical investigations of the influence of rate-sensitivity in different end-plate connections on the overall resistance to progressive collapse of steel-concrete composite buildings [15]. For a T-stub in tension [2], an enhancement of the tensile yield strength has been observed under 10^1-10^2 mm/s deformation rates, thus leading to a noticeable increase of around 25% in the progressive collapse resistance under sudden column loss. While these T-stubs failed by the complete yielding of the flange (ductile failure) as opposed to bolt failure (brittle failure), it is always necessary to ensure that the joint ductility is not compromised by the dynamic overstrength of the ductile mode of failure.

Example

Typical details of framed steel structures are beam-to-column connections. The *Figure 9* and *Figure 10* are illustrating some of the above described advantageous characteristics of the material steel, like ductility, plastic material reserves and in *Figure 10* also a high residual strength after buckling of the column web in compression.

Figure 9: Ductile tension components of bolted beam-to-column-connection

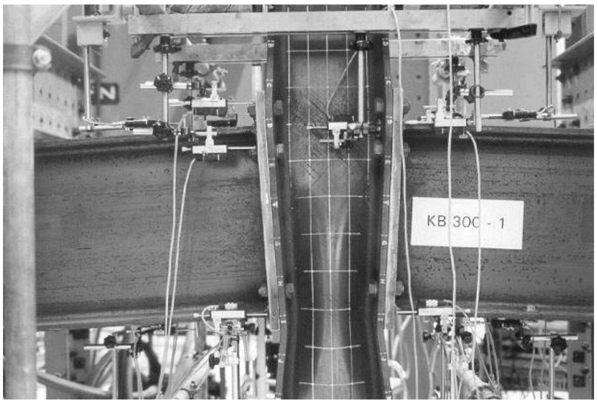


Figure 10: Ductile compression components of a bolted beam-to-column connection

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