Trends in steel structures concerning materials, codes and applications

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Trends in steel structures concerning materials, codes and applications

Trends im Stahlbau bezüglich Material, Normierung und Anwendung

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Summary

This paper gives an overview of recent trends in steel structures concerning materials, codes and applications. There is a trend towards using higher strength steel grades, and this asks for a different approach to the design of steel structures. Also work is underway for the next version of part 1-1 of Eurocode 3: EN 1993-1-1 [1]. Many design rules need improvement and the so-called ‘systematic review’ yielded topics that need to be considered. Amendments for EN 1993-1-1 were accepted already by the committee responsible for Eurocode 3, i.e. CEN/TC250/SC3, led very effectively by Prof. Ulrike Kuhlmann. The paper gives an impression of some of these amendments. The scope of the design rules will be extended, amongst others by including high-strength steel grades. Apart from trends in materials and codes, also trends can be observed regarding the applications of steel structures. Of course these trends in materials, codes and applications mutually influence each other.

Keywords: high-strength steel, trends, codes, design rules, applications

Zusammenfassung


1 Towards higher strength steel grades

1.1 Material properties

Steel grade S235 is gradually losing ground to S355 and even the higher strength grades S460 and S690. S355 is hardly any more expensive than S235 and its weldability and ductility are good. There is a clear tendency towards higher strength steel grades. Higher
strength, may also mean smaller dimensions of cross-sections and therefore saving of weight, easier transportation and erection and therefore potentially also cost reduction. If cross-sections and plate thicknesses are smaller, also the amount of welding effort reduces. Higher strength and therefore smaller cross-sections and plate thicknesses also means less environmental impact contributing to a sustainable future. Figure 1 shows different measured engineering stress-strain diagrams for the steel grades mentioned. It can be seen that with increasing strength, the ductility decreases but for the steel grades shown, the ductility is still sufficient for structural purposes. It can also be observed in Fig. 1 that the elastic branch for all steel grades has the same slope indicating that the material stiffness expressed in the Young’s modulus is more or less constant independent of the steel grade. High strength, a fine microstructure and good weldability and ductility can be achieved through the thermomechanical rolling process. High-strength steel grades that also have good weldability and ductility are also called high-performance steels [2]. The quenching and self-tempering (QST) process can be regarded as an extension of the thermomechanical rolling process and allows for high-strength steel with greater material thickness. Generally, the yield stress decreases with increasing material thickness. But for steel produced by the QST process the decrease of the yield stress is far less severe. As an example, Fig. 2 shows the decrease of the yield stress of ‘S460-QST’, S460M and S500M for increasing material thickness. It can be observed that for ‘S460-QST’ this decrease in yield stress with increasing material thickness is limited.
1.2 Design implications

High-strength steel is used to its best advantage when the ultimate limit state is the governing design criterion. Then, high-strength steel makes more slender and lighter structures possible for bridges and buildings. However, the fact that the Young’s modulus does not increase for higher strength steel grades means that the stiffness behaviour (serviceability limit state) may become the decisive design criterion. Of course, structural forms that have a larger stiffness can be used, like truss structures, see Fig. 3. Truss structures also have the advantage that they transfer forces largely through normal force in the members meaning that the benefit of higher strength can be exploited better. The latter also holds for arched structures.

In fatigue prone structures like bridges, the use of higher strength steels with smaller dimensions may lead to higher stress ranges and the fatigue limit state may rather become decisive for the design. Therefore, notches should be avoided and transitions between plates and between chords and braces in trusses should be made smooth to avoid stress concentrations. Also, weld improvement techniques like grinding, TIG dressing and needle or hammer peening have the potential to improve the fatigue behaviour such that the higher strength can be utilised better.

1.3 Availability

Steel sections are readily available in S235 and S355. Commercial steel suppliers have these sections on stock and can deliver almost immediately. But for higher strength steel grades, especially for heavy sections in QST quality, this is not the case. These sections require special ordering at the steel producer and delivery usually takes 6 to 8 weeks. Commonly, also a minimum amount of tonnes should be bought. For plate material, e.g. for bridge structures, timely ordering is also required to obtain higher strength steel grades in the right prescribed quality. For these reasons the practical use of higher strength steel grades than S355 is still limited despite their promising advantages. Here lies a challenge for the complete steel production and supply chain to further promote the use of high-strength steel.
2 Amendments for Eurocode 3, EN 1993-1-1

2.1 General aspects

The Eurocodes are in force now for some time in the different member countries of the European Union and they are used by structural engineers working in practice. This gave rise to proposals for change and possible improvement. These proposals were brought forward mainly by the National Standardization Bodies (like DIN, BSI, AFNOR, NEN, etc.) and – for as far as they concern Eurocode 3 on steel structures – they are dealt with by subcommittee CEN/TC250/SC3 (CEN = Comité Européen de Normalisation, TC = Technical Committee, SC = Sub Committee). To distribute the work load associated with these proposals, the work has been split up over several Working Groups (WG) of CEN/TC250/SC3 (SC3) with Working Group 1 (WG1) being responsible for the general part EN 1993-1-1 [1]. WG1 worked on several technical topics to improve EN 1993-1-1 resulting in amendments. It was decided that these amendments – if approved by SC3 - are kept 'in the basket' to be used for the next version of EN 1993-1-1 to be published in a few years. Of course, when there is a safety issue in a design rule of the code, this needs to be dealt with immediately.

Apart from the proposals for change and possible improvement mentioned above, also several technical issues that may lead to amendments came in through the so called 'systematic review'. Every 5 years there is a systematic review when comments are asked from the National Standardization Bodies. Till end of September 2014 the National Standardization Bodies could hand in comments for EN 1993-1-1 and suggestions to increase the 'ease of use' and to indicate if EN 1993-1-1 could be shortened or should be extended and to identify design rules leading to uneconomic design. SC3 and WG1 have to respond to these comments and suggestions. This work is in progress and should be ready by October 2017.

In September 2015 a Project Teams (PT) was established for EN 1993-1-1, consisting of 6 members including the convener. The PT is responsible for writing the new draft of the code. The PT reports to SC3 and takes into account the approved amendments so far and the results from the systematic review. The work done by the PT needs the approval of SC3. On behalf of SC3, WG1 will monitor the work done by the PT. The PT has to complete its work by June 2018 resulting in a draft for the next version of EN 1993-1-1. Then some time is necessary for administrative purposes so that the next version of EN 1993-1-1 is expected to be published in 2020 at the earliest.

It is the ambition to have less Nationally Determined Parameters (NDP) in the next version of EN 1993-1-1. EN 1993-1-1 has currently 25 NDP’s. The values of these NDP’s are given in National Annexes (NA). NDP’s exist because the safety of building structures is still a national responsibility. NDP’s can also relate to climatic and geographical data specific for a country. To minimize the number of NDP’s, one of the tasks of the PT is to compare the NA’s to see which national choices have been made and to try to harmonize these. NA’s may also contain non-contradictory complementary information (NCCI). It is also the ambition to see if this NCCI is relevant or not and can be either omitted or harmonized. Further, NA’s can change the status of an informative annex into normative or not applicable. It is tried to avoid informative annexes. SC3 took decisions such that only the Annexes BB.1 and BB.2 on elastic flexural buckling in lattice structures and on restraint stiffness respectively, are kept as normative annexes.

SC3 decided to keep the overall structure of EN 1993 and its parts (with some exceptions) since practicing structural engineers are used to this structure.
Sometimes the ambitions for the new version of EN 1993-1-1 are contradictory, e.g. to provide all relevant information for the application of a design rule versus shortening the content where possible. An example of this is elastic critical buckling. SC3 decided not to include extensive information on elastic buckling, which is necessary for applying the buckling design rules. Inclusion of this information would lead to EN 1993-1-1 being more a textbook on applied mechanics than a code. It was decided to make a Technical Report: CEN/TR1993-1-1-103 “Eurocode3 - Design of steel structures - Part 1-103: Elastic critical buckling of members”.

2.2 Accepted amendments

The (accepted) amendments have been drafted following a specific format such that not only the change of a clause is laid down, but also the reason for the amendment and the background information on which the amendment is based. This will help the code drafting process in the future. Up to now (May 2017), SC3 accepted amendments on the following topics: scope with respect to material thickness, shear resistance, semi-compact cross-section design, member buckling design rules, high-strength steel, buckling curves for angles, buckling curves for heavy sections, buckling curves for rolled I- and H- sections in S460, parameter $\alpha$ for cross-section classification, torsion and its interaction with other internal forces. Only the accepted amendments for high-strength steel and buckling curves for heavy sections are summarized below. More information on the accepted amendments is given in [4]. Further, amendments are under preparation on the following topics: local load introduction without stiffeners, tubular members under bending and axial compression, elliptical hollow sections, initial bow imperfections of table 5.1 of EN 1993-1-1.

2.2.1 High-strength steel

It was decided by SC3 that EN 1993-1-12 containing supplementary rules for high-strength steel shall not be a separate document and that its content shall be included in the relevant parts of EN 1993. The amendments of [5] concern the consequences of this decision for EN 1993-1-1.

In cl. 3.1(2) and 3.2.1(1) of EN 1993-1-1 on materials, besides reference to Table 3.1, also reference is made to new Tables 3.2 and 3.3 for steel grades up to S700 according to EN10025-6 and EN 10149-2, respectively.

Cl. 3.2.2 of EN 1993-1-1 on ductility requirements is modified to distinguish between plastic and elastic global analysis. Mild steel of Table 3.1 qualifies for plastic global analysis while high-strength steel of Tables 3.2 and 3.3 qualify for elastic global analysis. Relevant clauses in Chapter 5 of EN 1993-1-1 are modified accordingly. Steels of the Tables 3.2 and 3.3 should not be used for applications where capacity design is required.

Finally, in Table 6.2 of EN 1993-1-1 for the selection of buckling curves, the material S450 is added to the column where the materials S235, S275, S355 and S420 are mentioned while S460 up to and including S700 is written in the column where S460 is mentioned.

2.2.2 Buckling curves for heavy sections

This amendment [6] fills a gap in the current buckling curve selection Table 6.2 of EN 1993-1-1. For rolled sections with height to width ratio $h/b > 1.2$ buckling curves are not specified
for flange thicknesses $t_f > 100$mm. However, these heavy sections are available nowadays. Based on research reported in [7-9], Table 6.2 of EN 1993-1-1 is supplemented for these heavy sections.

A research project was carried out by Eindhoven University of Technology in the Netherlands to arrive at realistic buckling curves for heavy sections with $h/b > 1.2$ and $t_f > 100$mm based on residual stress measurements and finite element analyses. Residual stresses were measured by the sectioning method in heavy HISTAR sections (Fig. 4) from which a residual stress model was derived [8]. The same residual stress model was used for S460. For S355 either this residual stress model was used or the one proposed by the ECCS and for S235 the ECCS residual stress model was used. Two different sections types were investigated: stocky HD and more slender HL sections. Due to the thickness of the flanges, the yield stress of the material is lowered to account for reduced material properties present in heavy sections (Fig. 2). A finite element model (Fig. 5) was created in the ANSYS v.11.0 implicit environment to obtain the elastic-plastic buckling response (Fig. 5) for a wide set of column configurations.

Fig. 4. Residual stress measurements in section HD 400x1202 [8]

Fig. 5. Finite element model to determine the flexural buckling response [9]
Buckling curve selection was based on the existing buckling curves as given in EN 1993-1-1. Partial factors $\gamma_{Rd}$ in accordance with Annex D of EN 1990 were derived, which account for the uncertainty in the resistance model. If the $\gamma_{Rd}$ values for a selected buckling curve should not exceed 1.05 and making use of a material partial factor of $\gamma_m = 0.966$ [10] for thicknesses greater than 100mm and making no distinction between HD and HL sections, conservatively:

- for S460 sections buckling curve ‘b’ applies for weak-axis buckling and buckling curve ‘a’ for strong axis buckling;
- for S235 and S355 buckling curve ‘c’ applies for weak-axis buckling and buckling curve ‘b’ for strong axis buckling.

3 Trends in applications

3.1 Composite and hybrid structures

Steel is an excellent material to be combined in composite and hybrid structures, where composite is defined as two materials acting together as one material at the cross-sectional level and hybrid as two materials supporting each other at the structural level. More and more, composite and hybrid structures, with steel as one of the two materials involved, are made to utilise the full benefit of the respective materials.

3.1.1 Steel and concrete

It has been recognised since long that steel can be combined in composite structures with concrete where both materials are optimally used. Steel in compression is prone to instability phenomena and concrete can only take very limited tension. Therefore, preferably steel is placed in the tension zone and concrete in the compression zone. Steel dowels like headed studs take the shear between both materials. Thus ‘traditional’ steel-concrete composite columns, beams and floors are made. Examples of steel-concrete composite beams and floors are shown in Fig. 6. Spans of composite floors vary depending on plate height and function of the building but can reach about 9.5m.

![Fig. 6. Examples of steel-concrete composite beams and floors (illustrations and photo: Dutch Engineering)](image-url)

Another steel-concrete application is the hybrid infilled frame structure where the pinned steel frame is stabilised by the concrete wall which acts as a diagonal strut. A fully integral infilled frame consists of a steel frame filled with cast in place concrete and has a continuous connection by means of strong bonding or dowels at the structural interface between
steel frame and infill panel. But more interesting is a semi-integral infilled frame where a precast concrete infill panel is connected to a steel frame at discrete locations, Fig. 7 [11].

3.1.2 Steel and glass

Glass can be used to stabilise a steel structure. At the start of the industrial revolution, nineteenth century warehouses were built without any bracing and their stability was relying on the glass infill. This idea is currently further explored for railway station canopies where glued cold-bent glass [12] should stabilise the steel canopy. If flexural buckling can be suppressed by adding glass fins to a very slender steel column, the steel strength can be fully utilised in compression. The 3.6m long 32mm diameter high-strength Dywidag bar with steel grade St 950/1050 (Fig. 8) is able to carry more than 500 kN [13].

3.1.3 Steel and fibre reinforced polymers (FRP)

Steel bridge decks are prone to fatigue. One of the latest developments is to replace steel orthotropic decks by an FRP deck. Low maintenance and low self-weight are also important features of FRP structures. An example of an FRP bridge deck in a truss bridge is shown in Fig. 9 [14]. But many more applications exist. Because of their low self-weight, FRB bridge
decks are a good alternative in movable bridges [15]. Research on the fatigue behaviour of FRP road bridge decks was reported in [16].

Fig. 9. FRP bridge deck in a steel truss bridge, Utrecht, The Netherlands [14] (photos: FiberCore Europe)

3.2 Other trends

Another trend is that steel structures become more and more expressive and that in many cases more complex and rounded shapes are designed, Fig. 10. This is made possible by the extensive use of computer aided design (CAD) for drawing and analysis by the finite element method (FEM) on the one hand and of computer aided manufacturing (CAM) for fabrication on the other hand. To analyse if there are any conflicts between building parts including building services in the execution phase, all parties involved make use of a common model through Building Information Modelling (BIM) as an important tool for constructing these buildings.

Fig. 10. Expressive steel buildings

Torre Diagonal ZeroZero, Barcelona, Spain  DZ Bank, Berlin, Germany  Railway Station Arnhem, The Netherlands

New types of steel structures for renewable energy production appear. On- and off-shore wind turbine structures are already common but also support structures for PV panels are being built, Fig. 11.
The latest trend is 3D-printing of steel as a form of additive manufacturing. Until now successful results were obtained for optimised nodes (Fig. 12) where a considerable weight and size reduction was achieved [17]. 3D-printing of complete structures is under development. Attention needs to be paid to the material properties of 3D-printed steel in terms of strength and ductility.

4 Conclusions

A clear trend towards higher strength steel grades can be observed. To fully exploit this higher strength, the ultimate limit state should be decisive for the structural design. Stiffness or fatigue being decisive should be avoided. This means that stiff structural forms like trusses are advantageous and that fatigue mitigating measures get more importance. The codes, more specifically Eurocode 3, anticipate on this trend by including higher strength steels up to and including S700 in the basic code EN 1993-1-1. Also in the applications of structural steel, trends can be observed towards composite and hybrid structures and towards more expressive and new building types, that may benefit from higher strength steel grades.

Reliable high-strength steel grades of good quality are produced and the design rules are there to facilitate the design of structures in high-strength steel. The challenge to the steel
production and supply chain is now to enhance the availability of high-strength steel to further promote its application.

References


Figure captions
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Fig. 1. Typical stress-strain diagrams for different steel grades
Bild 1. Charakteristische Spannungs-Dehnungs-Diagramme für verschiedene hochfeste Baustähle

Fig. 2. Yield stress of ‘S460-QST’, S460 and S500 for increasing material thickness
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Caland Bridge, Rotterdam, The Netherlands    Hancock Building, Chicago, USA
Fig. 3. Truss structures in bridges and buildings to enhance stiffness
Caland Brücke, Rotterdam, Niederlanden    Hancock Gebäude, Chicago, USA
Bild 3. Fachwerkkonstruktionen in Brücken und Gebäuden zur Vergrößerung der Steifigkeit

Fig. 4. Residual stress measurements in section HD 400x1202 [8]

Fig. 5. Finite element model to determine the flexural buckling response [9]
Bild 5. Finite Elementenmodell zur Feststellung des Beigeknickverhaltens [9]

Fig. 6. Examples of steel-concrete composite beams and floors (illustrations: Dutch Engineering)

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Fig. 9. FRP bridge deck in a steel truss bridge, Utrecht, The Netherlands [14] (photos: FiberCore Europe)
Fig. 10. Expressive steel buildings

Fig. 11. New type of structure: Support structure for PV panels, Barcelona, Spain

Fig. 12. New production process: 3D node – from traditional (left) to optimized 3D-printed (middle and right) [17] (photo: Arup/Davidfotografie)

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