Recent developments regarding the next version of Eurocode 3 Part 1-1 on steel structures

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Recent developments regarding the next version of Eurocode 3 part 1-1 on steel structures.

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Abstract

This paper gives an overview of the work necessary and underway for the next version of part 1-1 of Eurocode 3 on steel structures: EN 1993-1-1. This work is done by Working Group 1 (WG1) of subcommittee CEN/TC250/SC3 and by Project Team 1 (PT1) responsible for the technical content of the next version of EN 1993-1-1. In the past, WG1 collected a longlist of items that may need improvement and recently carried out a systematic review that also yielded topics that need to be considered for the next version of EN 1993-1-1. The work of WG1 already resulted in amendments for EN 1993-1-1 which were accepted by CEN/TC250/SC3. PT1 is currently implementing these amendments in the next version of EN 1993-1-1, that is due in a few years’ time. In this paper, an overview is given of the amendments and of other developments related to EN 1993-1-1. The amendments concern among others several strength and stability related design rules. This paper is an extended and updated version of [1].

Keywords: Eurocode, steel, structure, next version, update, amendment, stability, strength, design rule.

1. Introduction

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 to design buildings, bridges, etc. Working with the Eurocodes and getting experience with them 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 with Working Group 1 (WG1) being responsible for part 1-1 of Eurocode 3: EN 1993-1-1, Design of steel structures- part 1-1: General rules and rules for buildings [2]. WG1 worked on several technical topics to improve EN 1993-1-1 resulting in amendments. It was decided that these amendments – if approved by CEN/TC250/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. This was done to keep working for a while with a stable version of the code instead of practicing structural engineers having constantly to deal with changes in the code. Later in this paper examples of these approved amendments are given. Of course, when there is a safety issue in a design rule of the code, this needs to be dealt with immediately meaning that safety related corrections to the code can be published any time. But amendments, i.e. improvements to the code which are not safety related, are on hold till the next version of the code is published.

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Proposals for amendments came in from several sources but mainly through National Standardization Bodies, leading to a longlist of possible work items that WG1 should be looking into. Part of that longlist is shown in Table 1.

<table>
<thead>
<tr>
<th>Clause</th>
<th>Work Item</th>
<th>Source</th>
<th>Time</th>
<th>Responsible</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2.6</td>
<td>Improvement of rules for plastic shear strength of webs in HSS</td>
<td>[15]</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>6.2.3(2) b</td>
<td>The formula for the ultimate resistance of net cross-sections seems conservative for steel grades ≥ S355 and small holes (see also 6.2.5(4))</td>
<td>[14]</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>6.2.3(3)</td>
<td>Tension – The rule for capacity design leads to very conservative results due to the presence of the partial safety factors in the formulas for net and gross section resistance.</td>
<td>[1]</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>6.2.3(5)</td>
<td>Change EN 1993-1-8, 3.6.3 into EN 1993-1-8 3.10.3</td>
<td>[14]</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>6.2.4</td>
<td>New proposal for design of sections in compression</td>
<td>[23] [28]</td>
<td>P</td>
<td>SR SH CL</td>
</tr>
<tr>
<td>6.2.6(3)</td>
<td>Addition of the shear area for rolled I- and H-sections, loaded parallel to flanges</td>
<td>[14]</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>6.2.6(3)</td>
<td>Reconsider the definition of ( h_w ). For rolled I- or H-Profiles the distance between the flanges seems conservative.</td>
<td>[14]</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>6.2.5</td>
<td>New proposal for design of sections in bending</td>
<td>[23] [28]</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>6.2.5(4)</td>
<td>Bending moment – The rule for ignoring fastener holes is very conservative due to the partial safety factors not being equal; is this really necessary? Also see under 6.2.3(3).</td>
<td>[1]</td>
<td>S</td>
<td></td>
</tr>
</tbody>
</table>

The 1st column in Table 1 gives the clause in EN 1993-1-1 to which a possible work item relates; the 2nd column summarizes the work item; the 3rd column refers to the source containing background information (these do not refer to the literature given at the back of this paper); the 4th column states whether it concerns a possible work item that can be treated within short (S) time or an item that requires a long term project (P); and finally the 5th column gives the initials of the WG1 members responsible.

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 officially end of September 2014 the National Standardization Bodies could hand in comments for EN 1993-1-1 aiming for modifications resulting in amendments. The National Standardization Bodies were asked to come with suggestions to increase the ‘ease of use’ and to indicate if EN 1993-1-1 could be shortened or should be extended in scope and to identify design rules leading to uneconomic design. The questions to be answered by the National Standardization Bodies were:
- Does any clause require editorial or technical correction?
Which clause would benefit from improvements in clarity?
- Where should the scope of EN 1993-1-1 be extended?
- Where could EN 1993-1-1 be shortened?
- Are there any clauses leading to uneconomic design?
- Are there any clauses leading to excessive design effort?

The answers received from the National Standardization Bodies to these questions have to be dealt with by SC3 and WG1 is doing the preparatory work for that concerning EN 1993-1-1. This work is in progress and should ideally be ready by October 2017.

This was the situation until September 2015 when a Project Teams were established under mandate M/515 of the European Union: ‘M/515 Mandate for amending existing Eurocodes and extending the scope of structural Eurocodes’. PT1 is responsible for EN 1993-1-1. A PT consists of (about) 6 members including the convener and is responsible for the technical work and for writing the new draft of the code. The PT reports to CEN/TC250/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 CEN/TC250/SC3. On behalf of CEN/TC250/SC3, WG1 will monitor the work done by PT1 but final decisions on the content of the next version of EN 1993-1-1 are up to SC3. PT1 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 2020 at the earliest. Also time is needed for translations in other languages than English and for further implementation and embedding in national law where appropriate.

In the next version of all Eurocodes, also in the next version of EN 1993-1-1, it is the ambition to have less Nationally Determined Parameters (NDP). EN 1993-1-1 has currently 25 NDP’s. The clauses where they apply are listed right before the start of the first chapter of the code. 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 so that each country should be able to make its own choice with respect to the safety level through the values of the relevant NDP’s. NDP’s can also relate to climatic and geographical data specific for a country. To minimize the number of NDP’s, one of the future tasks 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. Informative annexes are avoided in the next version of EN 1993-1-1. CEN/TC250/SC3 took the following decisions with respect to the annexes:

- Currently two methods for beam-column design are present in the code in cl. 6.3.3 of EN 1993-1-1: Method 1 with Annex A and Method 2 with Annex B. Since Annex B has been developed further and now has a wider scope, only Method 2, Annex B is kept in the code. Thus avoiding alternative design rules for the same phenomenon. Then large parts of Annex B can be included in the main text. Method 1 and Annex A will be transferred to a Technical Specification, which still has to be made: ‘CEN/TS 1993-1-101 Eurocode3 - Design of steel structures - Part 1-101: Alternative interaction method for members in bending and compression’. So, Annex A is removed from the code and Annex B is either partly or completely moved to the main text of EN 1993-1-1.
- Annex AB.1 contains clauses on how to perform the structural analysis in case of taking into account material non-linearities and is moved to the main text: chapter 5 of EN 1993-1-1. It is tried to move Annex AB.2 on load arrangements for continuous floor beams to other parts of Eurocode 3. These two actions make Annex AB superfluous.
- Annex BB.1 on elastic flexural buckling in lattice structures is kept, clarified where necessary and made normative. Annex BB.2 on restraint stiffness is made normative as well. Annex BB.3 on the stable length method for lateral torsional buckling has limited use throughout all countries using the Eurocode and is transferred into a Technical
Specification, which still has to be made: “CEN/TS 1993-1-102 Eurocode 3 - Design of steel structures - Part 1-102: Stable length method for members containing plastic hinges subject to out-of-plane buckling”. Thus, Annex BB is considerably shortened and made normative.

The next version of EN 1993-1-1 should also be easier to use. Therefore it is tried to:

- improve clarity with respect to structure and wording;
- harmonize and simplify rules: format, structure, denotations;
- provide all information that a user needs to apply a design rule;
- harmonize with other parts within Eurocode 3, with other Eurocodes and with other codes where possible;
- produce background documents justifying and explaining the design rules;
- simplify routes through the code;
- limit parallel alternative rules;
- revisit application rules to see if they are really necessary;
- remove impractical rules;
- shorten the content where possible;
- leave out informative annexes which are ‘nice to have’ but not really necessary.

It was decided to keep the overall structure of EN 1993 and its parts. One exception is EN 1993-1-12 [3] for high-strength steel, the content of which will be subdivided over the relevant parts of EN 1993. Another exception forms the new code part “EN 1993-1-13, Eurocode 3: Design of steel structures - part 1-13: Steel beams with large web openings”. CEN/TC250/SC3 decided to have this new code part and work on it is underway. Keeping the overall structure of EN 1993 and its parts as much as possible was done because in the meantime practicing structural engineers are used to this structure.

Sometimes the ambitions listed above can be 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. In the systematic review many countries asked for elastic critical buckling solutions for flexural and lateral torsional buckling to be included in EN 1993-1-1. However, it was decided by CEN/TC250/SC3 not to include extensive information on elastic critical buckling forces, buckling lengths and elastic critical lateral torsional buckling moments, which are necessary when applying the buckling design rules. Inclusion of this information would lead to EN 1993-1-1 being a textbook on applied mechanics instead of a code. But it was decided to make a Technical Report. Work is in progress on this Technical Report containing accepted solutions for elastic critical buckling: CEN/TR1993-1-103 “Eurocode 3 - Design of steel structures - Part 1-103: Elastic critical buckling of members”.

2. Amendments

The (accepted) amendments have been drafted following a specific format containing the following elements: topic, clause of EN 1993-1-1, reason for the amendment, proposed change and background information. The advantage of this is, that not only the amendment itself in the form of a changed 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), CEN/TC250/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.

Further, amendments are prepared 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.

The amendments are summarized below. The formulations of the amendments below may be subject to editorial changes.

2.1 Scope with respect to material thickness
See [1]. Relevant references are [4 to 6].

2.2 Shear resistance
See [1]. Relevant reference is [7].

2.3 Semi-compact cross-section design
See [1]. Relevant references [8 to 13].

2.4 Member buckling design rules
See [1]. Relevant references are [8, 14 to 21].

2.5 High-strength steel
It was decided by subcommittee CEN/TC250/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 [22 to 24] concern the consequences of this decision for EN 1993-1-1.

In clause 1.1.1(6) of EN 1993-1-1, being part of the scope of Eurocode 3, part EN 1993-1-12 is removed.

In clause 1.2.2 of EN 1993-1-1 on weldable structural steel reference standards, two standards are added:
- EN 10149-1, ‘Hot-rolled flat products made of high yield strength steels for cold forming – Part 1: General delivery conditions;
- EN 10149-2, ‘Hot-rolled flat products made of high yield strength steels for cold forming – Part 2: Delivery conditions for thermomechanically rolled steels.

In clause 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 Tables 3.2 and 3.3. The following tables with allowed steel grades will be added after Table 3.1 in EN 1993-1-1 (modifications in italics):

‘Table 3.2: Nominal values of yield strength $f_y$ and ultimate tensile strength $f_u$ for hot rolled structural steel with grades higher than S460.

<table>
<thead>
<tr>
<th>EN10025-6 Steel grade and qualities</th>
<th>Nominal thickness of the element $t$ [mm]</th>
<th>$f_y$ [N/mm²]</th>
<th>$f_u$ [N/mm²]</th>
<th>$f_y$ [N/mm²]</th>
<th>$f_u$ [N/mm²]</th>
<th>$f_y$ [N/mm²]</th>
<th>$f_u$ [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S500Q/QL/QL1</td>
<td>$t \leq 50 \text{ mm}$</td>
<td>500</td>
<td>590</td>
<td>480</td>
<td>590</td>
<td>440</td>
<td>540</td>
</tr>
</tbody>
</table>
Table 3.3: Nominal values of yield strength $f_y$ and ultimate tensile strength $f_u$ for hot rolled flat products.

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>$f_y$ [N/mm²]</th>
<th>$f_u$ [N/mm²]</th>
<th>$f_y$ [N/mm²]</th>
<th>$f_u$ [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S500MC</td>
<td>500</td>
<td>550</td>
<td>500</td>
<td>550</td>
</tr>
<tr>
<td>S550MC</td>
<td>550</td>
<td>600</td>
<td>550</td>
<td>600</td>
</tr>
<tr>
<td>S600MC</td>
<td>600</td>
<td>650</td>
<td>600</td>
<td>650</td>
</tr>
<tr>
<td>S650MC</td>
<td>650</td>
<td>700</td>
<td>630</td>
<td>700</td>
</tr>
<tr>
<td>S700MC</td>
<td>700</td>
<td>650</td>
<td>680</td>
<td>750</td>
</tr>
</tbody>
</table>

NOTE The National Annex may specify additional rules for steels according to Tables 3.2 and 3.3.

EDITORIAL NOTE by WG EN 1993-1-12: Tables 3.2 and 3.3 need to be checked for published amendments and corrigenda.

Clause 3.2.2 on ductility requirements is modified as follows (modifications in italics):

‘3.2.2 Ductility requirements

(1) For steels a minimum ductility is required that should be expressed in terms of limits for:
- the ratio $f_u/f_y$ of the specified minimum ultimate tensile strength $f_u$ to the specified minimum yield strength $f_y$;
- the elongation at failure on a gauge length of $5.65 \sqrt{A_o}$ (where $A_o$ is the original cross-sectional area);
- the ultimate strain $\varepsilon_u$, where $\varepsilon_u$ corresponds to the ultimate strength $f_u$.

NOTE The limiting values of the ratio $f_u/f_y$, the elongation at failure and the ultimate strain $\varepsilon_u$ may be defined in the National Annex. The following values are recommended:

a) For plastic global analysis
   - $f_u/f_y \geq 1.10$;
   - elongation at failure not less than 15%;
   - $\varepsilon_u \geq 15 \varepsilon_y$, where $\varepsilon_y$ is the yield strain ($\varepsilon_y = f_y/E$).

b) For elastic global analysis
   - $f_u/f_y \geq 1.05$;
   - elongation at failure not less than 12%.

(2) Steel conforming to one of the steel grades listed in Table 3.1 should be accepted as satisfying these requirements for plastic global analysis. Steels conforming to one of the steel grades listed in Tables 3.2 and 3.3 should be accepted as satisfying the requirements for elastic global analysis.’

The clauses 5.4.1(3) and 5.4.1(4)B of EN 1993-1-1 are modified as follows (modifications in italics):

‘(3) Plastic global analysis may be used for structures with members made of steels according to Table 3.1 and where the structure has sufficient rotation capacity at the actual locations of the
plastic hinges, whether this is in the members or in the joints. Where a plastic hinge occurs in a member, the member cross sections should be double symmetric or single symmetric with a plane of symmetry in the same plane as the rotation of the plastic hinge and it should satisfy the requirements specified in 5.6. Where a plastic hinge occurs in a joint the joint should either have sufficient strength to ensure the hinge remains in the member or should be able to sustain the plastic resistance for a sufficient rotation, see EN 1993-1-8.

(4)B As a simplified method for a limited plastic redistribution of moments in continuous beams where following an elastic analysis some peak moments exceed the plastic bending resistance of 15 % maximum, the parts in excess of these peak moments may be redistributed in any member, provided, that:

a) the internal forces and moments in the frame remain in equilibrium with the applied loads, and
b) all the members in which the moments are reduced are of steels according to Table 3.1 and have Class 1 or Class 2 cross-sections (see 5.5), and
c) lateral torsional buckling of the members is prevented.’

Clause 5.4.3(1) of EN 1993-1-1 is supplemented as follows (modifications in italics):

‘(l) Plastic global analysis allows for the effects of material non-linearity in calculating the action effects of a structural system. The behavior should be modelled by one of the following methods:
a) by elastic-plastic analysis with plastified sections and/or joints as plastic hinges,
b) by non-linear plastic analysis considering the partial plastification of members in plastic zones,
c) by rigid plastic analysis neglecting the elastic behavior between hinges.

NOTE 1 In case the method according to 5.4.3(1)b) is followed, also steels according to Tables 3.2 and 3.3 may be used because the real stress-strain curves including strain limitations are then considered. If steels according to Tables 3.2 and 3.3 are used, geometric imperfections on the level of cross-sections should be included in the analysis because local bending of flanges and webs can become important in the plastic domain.

NOTE 2 Rules for design with FEM are given in Informative Annex C of EN 1993-1-5.’

The clauses 6.2.3(2) and 6.2.3(3) of EN 1993-1-1 are modified as follows (modifications in italics):

‘(2) For sections with holes the design tension resistance \( N_{i,Rd} \) should be taken as the smaller of:
a) the design plastic resistance of the gross cross-section
\[
N_{pl,Rd} = \frac{Af_f}{\gamma_M0}
\]
b) the design ultimate resistance of the net cross-section at holes for fasteners
\[
N_{u,Rd} = \frac{0.9A_{net}f_u}{\gamma_{M2}} \text{ for steels according to Table 3.1}
\]
\[
N_{u,Rd} = \frac{0.9A_{net}f_u}{\gamma_{M12}} \text{ for steels according to Tables 3.2 and 3.3}
\]
where \( \gamma_{M12} \) is the partial factor for net section resistance for steels according to Tables 3.2 and 3.3.

NOTE The National Annex may specify the value of \( \gamma_{M12} \). The value \( \gamma_{M12} = \gamma_{M2} = 1.25 \) is recommended.

EDITORIAL NOTE by WG EN 1993-1-1: Research indicates that the factor 0.9 can be lowered with some restrictions. The latest proposal of May 2017, not yet accepted as an amendment, is as follows:
Replace the factor 0.9 by a factor \( k \) where:

- \( k = 1.0 \) for sections with smooth holes (i.e. holes without notches), for example holes fabricated by drilling or water jet cutting;
- \( k = 0.9 \) for sections with rough holes (i.e. holes with notches), for example holes fabricated by punching or flame cutting;
- \( k = 0.9 \) for structures subjected to fatigue.

(3) Where capacity design is requested, see EN 1998, the design plastic resistance \( N_{pl,Rd} \) (as given in 6.2.3(2) a)) should be less than the design ultimate resistance of the net section at fasteners holes \( N_{u,Rd} \) (as in 6.2.3(2) b)). Steels according to 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 should be added to the column where the materials S235, S275, S355 and S420 are mentioned while S460 up to and including S700 should be written in the column where S460 is mentioned.

2.6 Buckling curves for angles

See [1]. Relevant references are [25].

2.7 Buckling curves for heavy sections

This amendment [29] 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 \( t_f > 100\text{mm} \). However, these sections are available nowadays. The present gap in Table 6.2 of EN 1993-1-1 hampers the use of these innovative European products. Table 2 shows the part of the current Table 6.2 of EN 1993-1-1 for rolled I- and H-sections.

Based on research reported in [30 to 32] Table 6.2 of EN 1993-1-1 is now supplemented for heavy sections with height to width ration \( h/b > 1.2 \) and flange thicknesses \( t_f > 100\text{mm} \), see Table 3 (modifications in italics). Note that the steel grades up to and including S700 have been added to the table.

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>Limits</th>
<th>Buckling about axis</th>
<th>Buckling curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolled sections</td>
<td>( h/b &gt; 1.2 )</td>
<td>( t_f \leq 40 \text{ mm} )</td>
<td>y-y</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 40 &lt; t_f \leq 100 \text{ mm} )</td>
<td>y-y</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( t_f \leq 100 \text{ mm} )</td>
<td>z-z</td>
</tr>
<tr>
<td></td>
<td>( h/b \leq 1.2 )</td>
<td>( t_f &gt; 100 \text{ mm} )</td>
<td>y-y</td>
</tr>
</tbody>
</table>

In order to extend the application range of Table 6.2 of EN 1993-1-1, a research project was carried
out by Eindhoven University of Technology in the Netherlands. Its primary goal was to arrive at realistic buckling curves for heavy sections with \( h/b > 1.2 \) and \( t_f > 100 \text{mm} \) based on residual stress measurements and finite element analyses. Residual stresses were measured in heavy HISTAR (HIgh-STrength ARcelorMittal) Quenched and Self-Tempered (QST) sections (Fig. 1) from which a residual stress model was derived [31]. This model serves as the initial stress state for non-linear finite element analyses to simulate flexural buckling. Since the manufacturing process of heavy S460 sections is identical to that of heavy HISTAR sections, the developed residual stress model is also applied to the S460 analyses. For steel grade S355 two different existing residual stress models were selected to define the initial stress state for the investigated sections: the ECCS model for hot-rolled members and the QST model originally developed for the heavy QST HISTAR wide flange sections. For the S235 sections only the ECCS model was applied.

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. A yield stress of 195 N/mm\(^2\) was used for S235, of 295 N/mm\(^2\) for S355, and a yield stress of 385 N/mm\(^2\) was used for S460.

A finite element model (Fig. 2) was created in the ANSYS v.11.0 implicit environment to obtain the elastic-plastic buckling response (Fig. 2) for a wide set of column configurations. A database containing the elastic-plastic buckling resistance for a set of heavy sections failing by weak- and strong-axis buckling was created with non-linear finite element analyses. The residual stress model was used to define the initial stress state of the member, prior to loading. The numerical results were normalized against theoretical values obtained from suggested buckling curves. Buckling curve selection was based on the existing buckling curves as given in EN 1993-1-1. The resulting ratio was used to obtain the partial factor \( \gamma_{Rd} \) in accordance with Annex D of EN 1990, which accounts for the uncertainty in the resistance model.

Based on the requirement that the \( \gamma_{Rd} \) values for a selected buckling curve should not exceed 1.05 it was found that the buckling resistance of:

- heavy S460 HD sections failing by weak-axis buckling should be designed according to buckling curve ‘b’. Buckling curve ‘a\(_0\)’ is suggested for the design of HD sections subjected to strong-axis buckling;

Table 3: Part of adjusted Table 6.2 of EN 1993-1-1 for the selection of a buckling curve for rolled sections [29].

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>Limits</th>
<th>Buckling about axis</th>
<th>Buckling curve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>S235</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S275</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S355</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>S420</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S450</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S460 to S700</td>
</tr>
<tr>
<td>Rolled sections</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h/b &gt; 1.2</td>
<td>( t_f \leq 40 \text{ mm} )</td>
<td>y-y, z-z</td>
<td>a, a(_0)</td>
</tr>
<tr>
<td></td>
<td>( 40 &lt; t_f \leq 100 \text{ mm} )</td>
<td>y-y, z-z</td>
<td>b, a</td>
</tr>
<tr>
<td></td>
<td>( t_f &gt; 100 \text{ mm} )</td>
<td>y-y, z-z</td>
<td>b, a</td>
</tr>
<tr>
<td>h/b \leq 1.2</td>
<td>( t_f \leq 100 \text{ mm} )</td>
<td>y-y, z-z</td>
<td>b, a</td>
</tr>
<tr>
<td></td>
<td>( t_f &gt; 100 \text{ mm} )</td>
<td>y-y, z-z</td>
<td>b, a</td>
</tr>
</tbody>
</table>
Figure 1. Residual stress measurements in section HD 400x1202 [31].

Figure 2. Finite element model to determine the flexural buckling response [32].

- S460 HL section is best represented by buckling curve ‘c’ and buckling curve ‘a’ for weak-axis and strong-axis buckling respectively;
- heavy HL sections failing by strong-axis buckling should be designed according to buckling curve ‘a’ for S235 and S355. However, it is recommended to use curve ‘b’ due to the high degree of uncertainty associated with the residual stresses that apply. For weak-axis buckling curve ‘c’ seems to be appropriate.

These suggested buckling curves have been deduced with a conservative value of 1.0 for the material partial factor $\gamma_m$. A smaller value of $\gamma_m$ and therefore more favorable buckling curves may be adopted if justified by a convincing statistical study on the yield stress values for heavy S460 sections. According to the results presented in [33], a value $\gamma_m = 0.966$ is justified for thicknesses greater than 100 mm. This value is safe sided compared to the data presented in [34]. Using the material partial factor $\gamma_m = 0.966$ leads to buckling curve ‘b’ for HL sections in S460 subject to weak-axis buckling. It was decided that no distinction is made between HD and HL sections and therefore to adopt buckling curve ‘a’ for strong-axis buckling whereas ‘a0’ was the result of the study for HD sections.
2.8 Buckling curves for rolled I- and H- sections in S460
See [1]. Relevant references are [35 to 37].

2.9 Parameter α for cross-section classification
This amendment [38] facilitates the determination of the parameter α in Table 5.2 of EN 1993-1-1 for the cross-section classification. This parameter is used to determine the cross-section class of internal parts subjected to bending and compression. A note is added to Table 5.2 (sheet 1/3) of EN 1993-1-1 explaining how to determine the parameter α, as follows (modifications in italics):

*Note: for I or H sections with equal flanges, under axial force and bending moment about the main axis parallel to the flanges, the parameter α that defines the position of the plastic neutral axis may be calculated as follows:
If \( N_{Ed} \geq c \ t_w \cdot f_y \) then \( α = 1,0 \);
If \( N_{Ed} \leq -c \ t_w \cdot f_y \) then \( α = 0 \);
In other cases: \( α = 0,5 \left[ 1 + \frac{N_{Ed}}{(c \ t_w \cdot f_y)} \right] \)
Where \( N_{Ed} \) is the design axial force taken as positive for compression and negative for tension.*

2.10 Torsion and its interaction with other internal forces
Amendment [39] concerns the interaction of torsion with other internal forces. There is a lack in EN 1993-1-1 concerning the consideration of torsion and its interaction with other internal forces. A simple formulation to take bending-warping torsion interaction and bending-shear-torsion interaction into account for doubly symmetrical I-sections with class 1 and class 2 cross-sections is introduced. This is based on the formulation already provided in EN1993-1-1 for the consideration of shear-torsion interaction in clause 6.2.7(9) of EN 1993-1-1. To clause 6.2.7 (6) of EN 1993-1-1 the following is added (modifications in italics):

*The reduced design plastic resistance moment allowing for the bimoment \( B_{Ed} \) may be obtained for I-cross sections with equal flanges and bending about the major axis as follows:

\[
M_{c,B,Rd} = \sqrt{1 - \frac{\sigma_{w,Ed,\text{max}}}{1,25 f_y / \gamma_{M0}} M_{pl,Rd}}
\]

where \( M_{pl,Rd} \) is given in 6.2.5 and \( \sigma_{w,Ed,\text{max}} \) is the maximum direct stress \( \sigma_{w,Ed} \) due to the bimoment \( B_{Ed} \).

Clause 6.2.8(5) is changed as follows (modifications in italics):

*For doubly symmetrical I-sections with class 1 and class 2 cross-sections, when torsion is present, the reduced design plastic resistance moment should be taken as the design resistance of the cross-section calculated using a reduced yield strength as follows:

\[
(1 - \rho) f_y \frac{M_{c,B,Rd}}{M_{c,Rd}} \quad \text{for the shear area}
\]

\[
f_y \frac{M_{c,B,Rd}}{M_{c,Rd}} \quad \text{for the rest of the cross-section}
\]

where \( M_{c,B,Rd} \) is given in 6.2.7 (6) and \( \rho = \left( \frac{2 V_{Ed}}{V_{pl,T,Rd}} - 1 \right)^2 \), see 6.2.7, but should be taken

as 0 for \( V_{Ed} \leq 0,5 V_{pl,T,Rd} \).
When warping torsion is not present, then \( M_{c,B,Rd} = M_{c,Rd} \).
Alternatively, the reduced design plastic resistance moment allowing for the shear force and the bimoment may be obtained for doubly symmetrical I-sections with class 1 and class 2 cross-sections, bending about the major axis y-y, as follows:

\[
M_{y,B,Y,Rd} = \frac{W_{pl,y} - \frac{\rho A_w^2}{4t_w}}{\gamma_{M0}} f \frac{M_{y,c,B,Rd}}{M_{y,c,Rd}} \quad \text{but} \quad M_{y,B,Y,Rd} \leq M_{y,c,B,Rd}
\]

where \(M_{y,c,Rd}\) is obtained from 6.2.5 (2) and \(M_{y,c,B,Rd}\) is obtained from 6.2.7 (6), and \(A_w = h_w t_w\). When warping torsion is not present, then \(M_{y,c,B,Rd} = M_{y,c,Rd}\).

Figure 3 shows the effect of several clauses of EN 1993-1-1 and the amendments mentioned on the bending-shear-torsion interaction diagram.
2.11 Local load introduction without stiffeners

This amendment [40] treats a new topic in EN 1993-1-1 namely local load introduction without...
stiffeners. Simplified rules existed in the past in national codes (e.g. DIN 18800, ÖNORM B4300, NEN6770 …) but now only the rules of EN 1993-1-5 apply. These rules were specifically developed for welded plate girders and are not straightforward to apply to simple load introduction design checks, such as the verification that no stiffeners are required in rolled beams under a purlin. EN 1993-1-8 [41] contains additional rules within the “component method” of rigid frame connections, specifically the rule for the component “compression in unstiffened column web”. These rules are more similar to previous national regulations for the “patch loading” case in rolled sections.

A simplified synthesis of the previous national rules that covers the EN 1993-1-8 rule, with a clear scope and application limits, is introduced in EN 1993-1-1 as a means to perform simple design verifications for transverse load introduction in typical rolled or smaller welded sections.

The following new clause is added to clause 6.2 of EN 1993-1-1 (modifications in *italics*):

**6.2.x Resistance to transverse forces**

(1) The resistance of unstiffened webs against the introduction of transverse forces \( F_{z,Ed} \) may be determined using the rules in EN 1993-1-5.

(2B) For structural elements in buildings, for which the web slenderness \( d_w/t_w \) fulfils the criterion “6.y”, it may alternatively be verified that the transverse force \( F_{Z,Ed} \) does not exceed the value of \( F_{z,Rd} \) given by Eq. (“6.x”)

\[
F_{z,Rd} = \frac{l_y t_w f_y}{\gamma_{M0}} \quad \text{ (“6.x”)}
\]

\[
\frac{d_w}{t_w} \leq 23.1 \varepsilon \sqrt{F_{z,Ed} / F_{z,Rd}} \quad \text{ (“6.y”)}
\]

Where:

- \( F_{z,Rd} \): design value of the resistance against transverse loads \( F_{z,Ed} \)
- \( l_y \): effective length for the resistance against transverse loads, see Fig. “6.x”
- \( t_w \): web thickness
- \( d_w \): web depth between fillets or weld toes, see Fig. “6.x”
- \( s_s \): rigid load introduction length in accordance with EN 1993-1-5, section 6.3, see Fig. “6.x”
- \( \varepsilon = \sqrt{235/f_y} \)
2.12 Tubular members under bending and axial compression

In [42] amendment proposals are made and extensively motivated for tubular members under bending and axial compression. Here only the results are summarized.

For the cross-section classification of tubular members, a distinction is made in cross-sections in compression and in bending. Table 5.2 (sheet 3 of 3) of EN 1993-1-1 is modified accordingly [42] (modifications in *italics*):

<table>
<thead>
<tr>
<th>Class</th>
<th>Section in compression</th>
<th>Section in bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{d}{t} \leq a_{c_1} = 50\varepsilon^2$</td>
<td>$\frac{d}{t} \leq a_{b_1} = 50\varepsilon^2$</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{d}{t} \leq a_{c_2} = 70\varepsilon^2$</td>
<td>$\frac{d}{t} \leq a_{b_2} = 70\varepsilon^2$</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{d}{t} \leq a_{c_3} = 70\varepsilon^2$</td>
<td>$\frac{d}{t} \leq a_{b_3} = 140\varepsilon^2$</td>
</tr>
</tbody>
</table>

For class 1 and 2 cross-sections, the moment normal force interaction as proposed is [42]:

$$M_{N,pl,Rd} = 1 - \left( \frac{N_{Ed}}{N_{pl,Rd}} \right)^2 + \left( \frac{N_{Ed}}{N_{pl,Rd}} \right)^p \left( \frac{N_{Ed}}{N_{pl,Rd}} \right)^2$$

Where:

$$p = 3.81 - 14.5 \frac{L}{d}$$

$$b = 3.67(p - 2) - 0.74(p - 2)^2 - 0.048$$

For class 3 cross-sections, the moment normal force interaction as proposed is [42]:

Fig. 6.x: Definition of the lengths $l_y$, $d_w$ and $s_s$
\[ M_{N,\text{ep}, \text{rd}} = \frac{M_{N, \text{pl}, \text{rd}}}{M_{\text{pl}, \text{rd}}} \left[ 1 - (1 - s) \left( \frac{a - a_2}{a_3 - a_2} \right)^{0.68} \right] d^2 t f_y \]

Where:

\[
s = 0.785 \left( \frac{1 - N_{\text{Ed}}}{N_{\text{pl}, \text{rd}}} \right) \left( \frac{M_{N, \text{pl}, \text{rd}}}{M_{\text{pl}, \text{rd}}} \right)
\]

\[
a = \frac{d}{t}
\]

\[
a_2 = ka_{e2} + a_{b2} (1 - k)
\]

\[
a_3 = ka_{e3} + a_{b3} (1 - k)
\]

\[
k = \frac{2}{\pi} \arctan \left( \frac{N_{\text{Ed}} M_{\text{pl}}}{M_{\text{Ed}} N_{\text{pl}}} \right)
\]

### 2.13 Elliptical hollow sections

Elliptical hollow sections (EHS) are available and EN 1993-1-1 anticipates on this innovation by inclusion of design rules for them [43]. The design rules concern various clauses in EN 1993-1-1.

In Table 5.2 (sheet 3 of 3) Fig. 4 is added with the following text and formulas (modifications in italics):

‘Equivalent diameters \(d_e\):

For CHS \(d_e=d\); for EHS \(d_e\) depends on the nature of loading.

For EHS in compression: \(d_e = h \left[ 1 + \left( 1 - 2.3 (t/h) \right)^{0.6} \left( \frac{h}{b} - 1 \right) \right] \) or conservatively \(d_e = \frac{h^2}{b}\).

For EHS in major (y-y) axis bending: if \(\frac{h}{b} \leq 1.36\) then \(d_e = \frac{h^2}{b}\), if \(\frac{h}{b} > 1.36\) then \(d_e = 0.4 \frac{h^2}{b}\).

For EHS in minor (z-z) axis bending or compression and minor axis bending: \(d_e = \frac{h^2}{b}\).

For EHS in compression and major (y-y) axis bending, \(d_e\) may be determined by linear interpolation between the equivalent diameter for compression and that for bending based on the factor \(\alpha\) for Class 1 and 2 cross-sections and \(\psi\) for Class 3 and 4 cross-sections.’

Figure 4. Elliptical hollow section (EHS) definitions [43]

Clause 6.2.2.5 of EN 1993-1-1 is modified and extended as follows (modifications in italics):

‘(5)a) For class 4 circular or elliptical hollow sections in compression, the effective cross-sectional area \(A_{\text{eff}}\) may be determined as:
\[ A_{\text{eff}} = \frac{\left[ 90 \frac{235}{d_e/t f_y} \right]^{0.5}}{d_e/t} \text{ for } d_e/t \leq 240 \varepsilon^2 \]

b) For class 4 circular or elliptical hollow sections in bending, the effective section modulus \( W_{\text{eff}} \) may be determined as:
\[ W_{\text{eff}} = \frac{140 \frac{235}{d_e/t f_y}^{0.25}}{d_e/t} \text{ for } d_e/t \leq 240 \varepsilon^2 \]

(6) For circular or elliptical hollow sections exceeding the specified limits see EN 1993-1-6.

Clause 6.2.6(3) of EN 1993-1-1 is extended defining the shear area for EHS (modifications in italics):
‘h) rolled elliptical hollow sections of uniform thickness:
load parallel to the depth \( 2(h-t)/t \)
load parallel to width \( 2(b-t)/t \)

Clause 6.2.6(6) of EN 1993-1-1 is extended adding design rules for shear buckling as follows (modifications in italics):
‘(6)a) In addition…

b) For circular or elliptical hollow sections of uniform thickness, shear buckling resistance should be according to section 8 of EN 1993-1-6, when:
\[ \frac{d-t}{t} > 100 \varepsilon^2 \text{ for CHS} \]
\[ \frac{h-t}{t} > 100 \varepsilon^2 \text{ for EHS loaded parallel to the height} \]
\[ \frac{b-t}{t} > 100 \varepsilon^2 \text{ for EHS loaded parallel to the width} \]

Clause 6.2.8 of EN 1993-1-1 for combined bending and shear resistance is extended as follows (modifications in italics):
‘(3)a) Otherwise…

b) For circular and elliptical hollow sections of uniform thickness, the reduced moment resistance should be taken as the design resistance of the cross-section, calculated using a reduced yield strength from Equation (6.29) for the full cross-section area.’

Clause 6.2.9.1 of EN 1993-1-1 is extended to include a design rule combined bending and axial force for EHS (modifications in italics):
‘(7) For elliptical hollow sections of uniform thickness, the following criterion may be used:
\[ 2 \left( \frac{N_{\text{Ed}}}{N_{c,Rd}} \right)^{1.75} \left( \frac{N_{\text{Ed}}}{N_{c,Rd}} \right)^{3.5} + \left( \frac{M_{r,\text{Ed}}}{M_{c,\text{pl},y,Rd}} \right)^2 + \left( \frac{M_{z,Rd}}{M_{c,\text{pl},z,Rd}} \right)^{1.7} \leq 1.0 \]

Clause 6.2.10 of EN 1993-1-1 for combined bending, and axial force is extended as follows (modifications in italics):
‘(3)a) Where…

b) For circular and elliptical hollow sections of uniform thickness, where \( V_{\text{Ed}} \) exceeds 50% of \( V_{\text{pl,Rd}} \) the design resistance of the cross-section to combinations of moment and axial force should be calculated using a reduced yield strength from Equation (6.45) for the full cross-section area.’
Table 6.2 of EN 1993-1-1 for buckling curve selection is extended by a figure of an EHS where the hollow sections are shown. This means that buckling curve ‘a’ may be applied for hot finished EHS buckling about any axis with steel grade less than S420. Buckling curve ‘a0’ applies for higher strength steels. Buckling curve ‘c’ applies for cold-formed EHS.

For lateral torsional buckling in clause 6.3.2.2 of EN 1993-1-1 (general case) EHS fall into the category ‘Other cross-sections’ meaning that curve ‘d’ applies.

For the buckling resistance, Annex B rules for uniform members in bending and axial compression of RHS may be safely applied for EHS.

2.14 Initial bow imperfections of Table 5.1 of EN 1993-1-1
This amendment [44] modifies the initial bow imperfections of Table 5.1. Numerical investigations [45] show, that the current recommended values of initial local bow imperfections for rolled and welded sections in steel grades S235/S420 and S460 lead to an overestimation of the load bearing capacity. Examples are shown in Fig. 5 for members loaded by axial force, in Fig. 6 for members subjected to axial forces and bending moments M_y (steel grade S235) and in Fig. 7 for members subjected to axial forces and bending moments M_z (steel grade S460).

![Figure 5. Overestimation η for centrally loaded members – Fig. 17 in [45]](image)

![Figure 6. Overestimation η for members subjected to axial compression and bending moments M_y, S235 – Fig. 21 in [45]](image)
More details are given in [45]. Due to these overestimations, the values and the design of Table 5.1 should be adapted. Especially for plastic analysis, a limitation of the plastic interactions in case of strong axis bending and a maximum of the plastic shape factor $M_{pl}/M_{el}$ in case of weak axis bending should be introduced.

Clause 5.3.2(3)b and Table 5.1 for sections with steel grades 235 to S420 and S460 are modified in the following way (modifications in italics):

*b) relative local bow imperfections of members for flexural buckling, where $L$ is the member length

\[
\frac{L}{e_0} = \frac{\beta \varepsilon}{\alpha}
\]

$\alpha$ imperfection factor depending on the relevant buckling curve from Table 6.1

$\beta$ according to Table 5.1

$\varepsilon = \sqrt{235/f_y}$

### Table 5.1. Values $\beta$ for initial bow imperfections

<table>
<thead>
<tr>
<th>Buckling direction</th>
<th>elastic cross section utilization</th>
<th>plastic cross section utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>y-y</td>
<td>110</td>
<td>75</td>
</tr>
<tr>
<td>z-z</td>
<td>200</td>
<td>68</td>
</tr>
</tbody>
</table>

if advantage is taken for the plastic cross section utilization:

- for buckling about the y-y-axis: the linear plastic cross-section interaction, given in clause 6.2.1(7) must be used. All CHS and RHS sections are part of this group

- for buckling about the z-z-axis: any plastic cross section interaction may be used, but the plastic shape factor be limited:

\[
\frac{M_{pl}}{M_{el}} \leq 1.25
\]

**Note:** The values $\beta$ may be further simplified in the National Annex. The recommended values are given in Table 5.1.

### 3. Other ongoing work

Working group WG1 of subcommittee CEN/TC250/SC3 is still working on several topics to find agreement on, among others the following topics:
- Moment shear interaction.
- Use of the elastic critical buckling mode of the structure as global and local imperfections. This concerns clause 5.3.2(11) of EN 1993-1-1 where clarifications are necessary.
- Buckling design rules for equal legged angles.
- Simplified assessment methods for lateral torsional buckling of beams with restraints.

PT1 is working on the next version of EN 1993-1-1 and the 2nd draft is currently (August 2017) available for commenting on [46]. Many of the amendments treated in section 2 have been included in this 2nd draft, but not all of them yet.

Now that just one method for verifying the stability of beam-columns is kept in the code, the content of Annex B has been moved to the main text of [46]. The former Annex C on the selection of the execution class has been renamed in Annex A in [46]. The new Annex B treats the design of semi-compact sections.

In the 2nd draft of the next version of EN 1993-1-1 [46], clause 5.2 on structural analysis has been modified substantially and in such a way that better reference is given to the design rules to be used in connection to the method of structural analysis applied. For this reason a new Figure 5.3 has been added containing a flow-chart addressing the structural analysis methods available (Fig. 8).

The final next version of EN 1993-1-1 should be available in June 2018. Then the technical content is available. Editorial work can be done afterwards and 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. Also time is needed for translations in other languages than English and for further implementation.

4. Conclusions

Using EN 1993-1-1 in the past decade led to many proposals for change and possible improvement. Working Group 1 (WG1) of subcommittee CEN/TC250/SC3 worked on these proposals. Some of these proposals turned into accepted amendments. These amendments have been handed over to Project Team 1 (PT1) for EN 1993-1-1, that is responsible for the next version of EN 1993-1-1, due in a few years, in 2020 at the earliest. Also the recently carried out systematic review resulted in work items that can lead to amendments. Both WG1 and PT1 work with as starting point improvement of the ease of use of EN 1993-1-1. Currently, August 2017, the 2nd draft of the next version of EN 1993-1-1 is available for commenting on. In this 2nd draft many of the amendments mentioned in the paper have been included, but not all of them yet.

In the paper an overview is given of the amendments so far, concerning: 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 and finally buckling curves for rolled I- and H-sections in S460, parameter $\alpha$ for cross-section classification, torsion and its interaction with other internal forces, local load introduction without stiffeners, tubular members under bending and axial compression, elliptical hollow sections and, initial bow imperfections of table 5.1 of EN 1993-1-1.

5. Acknowledgement

The author wishes to thank the members of Working Group 1 of the Eurocode 3 subcommittee
## 6. Literature


EN 10210, Hot finished structural hollow sections of non-alloy and fine grain steels.

EN 10219, Cold formed welded structural hollow sections of non-alloy and fine grain steels.


Greiner R, Kettler M, Lechner A, Design proposal for the transition of cross-section and member resistances from class 2 to class 4, Doc. TC8-2011-06-007, TC8 Meeting, Lisbon, June 2011.


[27] Beg D, Rejec K, Sinur F, *Determination of buckling curves for large angle profiles considering different steel grades and different residual stress patterns*, University of Ljubljana, Faculty of Civil and Geodetic Engineering, 2013.


