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# Development of Eurocode 3 and Research Contributions

## *Desarrollo del Eurocódigo 3 y contribuciones a la investigación*

**Ulrike Kuhlmann [a], Christina Schmidt-Rasche [b], Jennifer Spiegler [c], Fabian Jörg [c], Vahid Pourostad [c], Mathias Euler [b]**

[a] *Prof. Dr.-Ing. Institute of Structural Design, University of Stuttgart, Germany*
[b] *Dr.-Ing. Institute of Structural Design, University of Stuttgart, Germany*
[c] *M.Sc. Institute of Structural Design, University of Stuttgart, Germany*

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ABSTRACT

This paper gives an overview on recent work regarding the revision of EN 1993 on European level including selected scientific and technical issues and a summary of the activities executed within the European Standardization committee CEN/TC250/SC3 "Design of Steel Structures" under the chair of Prof. Dr.-Ing. Ulrike Kuhlmann. This includes the description of current normative developments for the 2nd Generation of Eurocodes which aim at an evolution by improvements and harmonisation of the existing codes. In addition, a technical review of selected rules is given on a number of issues, which support the code revision and reflect well the recent tendencies in steel structures.



KEYWORDS: Mandate M/515, Working Group, Project Team, lateral torsional buckling, plate buckling, fillet and butt welds, fatigue, detail tables.

RESUMEN

En este documento se ofrece una visión general de los últimos trabajos de revisión de la norma EN 1993 a escala europea incluyendo una selección de cuestiones científicas y técnicas y un resumen de las actividades llevadas a cabo en el comité europeo de normalización CEN/TC250/SC3 "Design of Steel Structures" bajo la presidencia del Prof. Dr.-Ing. Ulrike Kuhlmann. Se incluye la descripción de los desarrollos normativos actuales para la 2ª Generación de Eurocódigos, cuyo objetivo es la evolución mediante la mejora y armonización de los códigos existentes. Además, se ofrece una revisión técnica de normas seleccionadas sobre una serie de temas, que apoyan la revisión de los códigos y reflejan bien las tendencias recientes en las estructuras de acero.



PALABRAS CLAVE: Mandato M/515, grupo de trabajo, equipo de proyecto, pandeo lateral, punzonamiento, soldaduras en ángulo y a tope, fatiga, despieces.

## 1. INTRODUCTION

The next generation of Eurocode 3 i.e. EN 1993 "Design of Steel Structures" is developed at the moment as part of the whole development of the 2nd Generation of Eurocodes. So, an overview is first given on the integration of Eurocode 3 in the whole system of Eurocodes, the organisational structure and its further development in general in the frame of the Mandate M/515. More specific in the following the normative development of Eurocode 3 is addressed.

Additionally, a technical review of selected rules is given on a number of issues, which support the code revision and reflect well the recent tendencies in steel structures. They open new chances for application and further development of design of steel structures.

* Persona de contacto / *Corresponding author*:
Correo-e / *e-mail*: Ulrike.Kuhlmann@ke.uni-stuttgart.de (Ulrike Kuhlmann).

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## 2. PROCEDURE FOR THE DEVELOPMENT OF 2ND GENERATION OF EUROCODES

### *2.1 General*

The Eurocodes were developed to enable the design of structural construction works, buildings and civil engineering works, on a harmonised European level. All 10 of the existing Structural Eurocodes from Basis of structural design (EC0) and Actions on structures (EC1) to Design of concrete (EC2), steel (EC3) and composite steel and concrete structures (EC4) up to Design of structures for earthquake (EC8), in altogether 58 parts, were published prior to June 2007. Their development was a great achievement and represented the culmination of over 30 years´ collaborative effort. Their impact has been considerable, affecting the day-to-day work of around 500 000 professional engineers across Europe, [1], [2]. In the Eurocodes, in order to allow countries to decide on own safety levels and to give national geographic and climatic data so-called Nationally Determined Parameters (NDPs) are open for choice in the frame of National Annexes. As a consequence, the full implementation of the Eurocodes in the European countries needed until 2010 and later when all national codes had been withdrawn and replaced by the Eurocodes and belonging National Annexes.

It is widely recognised that long-term confidence in the codes requires the Eurocodes to evolve in an appropriate manner. The accepted work programme [2] for the 2nd Generation of Eurocodes focuses on ensuring the standards remain fully up to date through embracing new methods, new materials, and new regulatory and market requirements. Furthermore, it focuses on further harmonisation and a major effort to improve the ease of use of the suite of standards for practical users. In order to show opportunities for participation in the development of these new design rules, the normative process is explained in detail in the following. Figure 1 gives an overview on the recent organisation structure of CEN/TC250, responsible for all Eurocodes.

### *2.2 Mandate M/515*

The further evolution of the Eurocodes is realised in the frame of the Mandate M/515 [1], which was agreed in December 2012 between the European Commission and CEN. Among others, aims of the mandate are the extension of the Eurocode rules in terms of new materials, products and construction methods, improving the practical use for day-to-day calculations and achieving a better harmonisation by reducing the number of NDPs.

The mandate started in 2015 will end in 2022. The first revised version of the Eurocodes should be available 2021/2022. However, due to the necessary procedure, publication including formal procedures such as CEN-Enquiry may last up to 2024.

Figure 2 shows the time schedule for the revision and the further evolution of the Eurocodes.

In general, the revision can be subdivided in the following two activities:

- General revisions and maintenance of the Eurocodes: This is the usual procedure for a code revision according

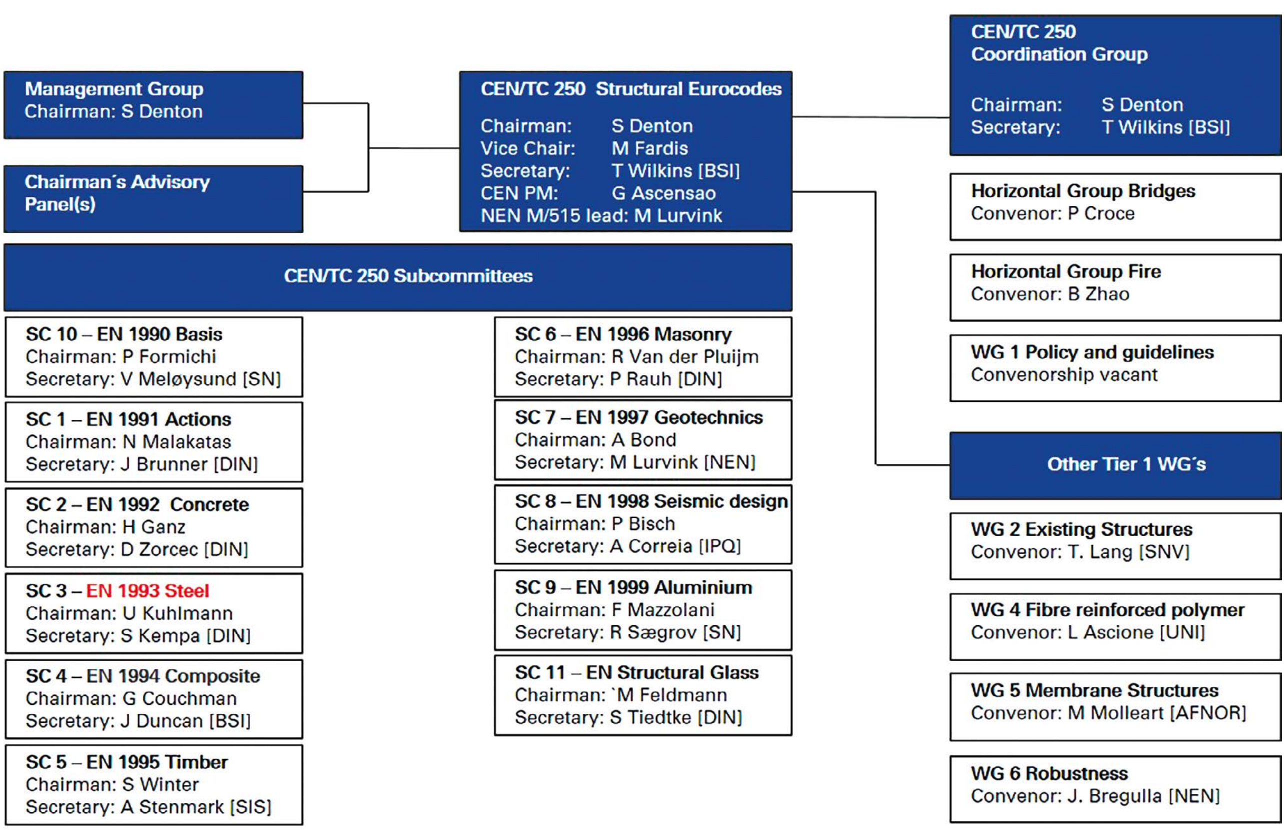



Figure 1. Organization structure of CEN/TC250 [3].

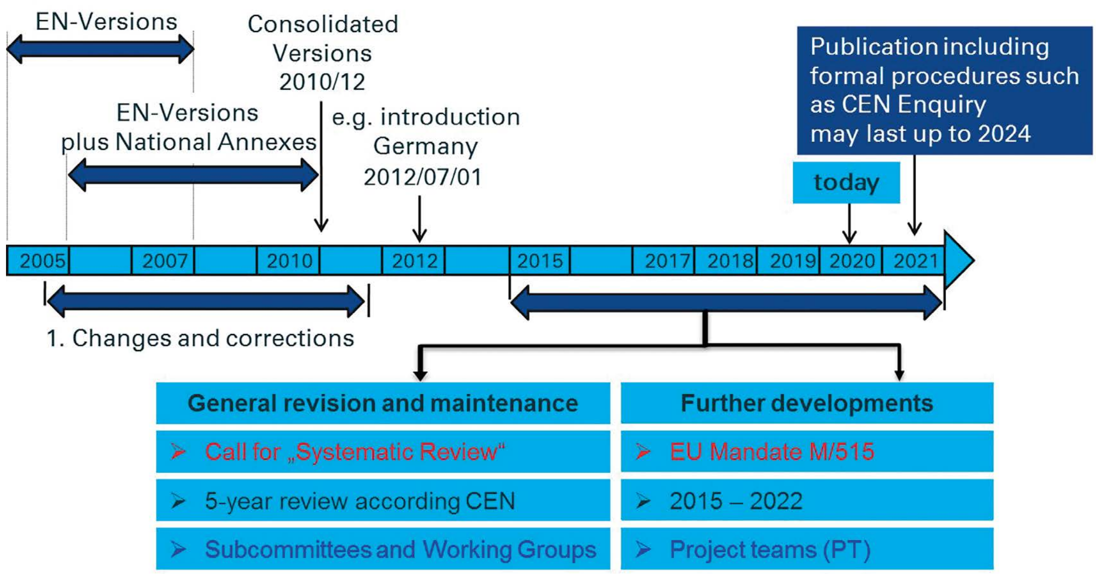



Figure 2. Planned time-table for the revision of the Eurocodes.

to CEN, which is launched in form of a call for 'Systematic Reviews' to the NSBs (National Standardisation bodies, such as DIN, AFNOR, BSI, AENOR). The evaluation and implementation of the suggestions and comments is then carried out by the CEN TC250 Subcommittees and Working Groups.

- Technical enhancements of the Eurocodes in the frame of the Mandate M/515: The further development takes place simultaneously to the general revision within Mandate M/515. Similar to the transfer of the ENV-versions into the EN-version, the realisation is conducted by Project Teams (PT) that consist of a maximum of five to six members.

The CEN/TC 250 work programme has been split into four overlapping phases, as illustrated in figure 3. This has been done to enable the interdependencies between activities to be effectively managed, and ensure that the work is undertaken as efficiently as possible.

Phase 1 includes those parts of the work program upon which other activities are primarily dependent for reasons of overall coordination, technical scope or because they are essential for achieving the target dates for delivery of the next generation of Eurocodes. Phase 1 of the mandate started in 2015 and has ended in 2018 after a 3-years term.

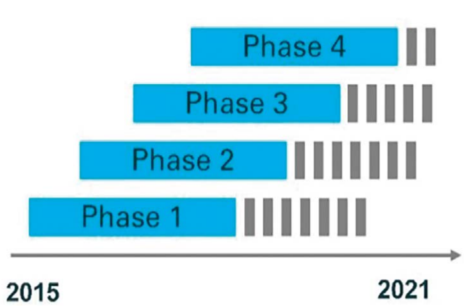



Figure 3. Indicative phasing of the work.

Phase 2 has started 2017 also for a term of 3 years. Phase 3 and Phase 4 started last year in 2018 [3]. First experiences with the project teams' work and the evaluation of the systematic reviews show an enormous need of further development and harmonisation.

TABLE 1.
Analysis of NDPs in the current ECs [2]

| Eurocodes | Nº of parts | Nº of pages | Nº of NDP`s |
|---|---|---|---|
| EN 1990 | 1+Annex A2 | 90+30 | 54 |
| EN 1991 | 10 | 770 | 292 |
| EN 1992 | 4 | 450 | 176 |
| EN 1993 | 20 | 1250 | 236 |
| EN 1994 | 3 | 330 | 42 |
| EN 1995 | 3 | 225 | 21 |
| EN 1996 | 4 | 300 | 31 |
| EN 1997 | 2 | 340 | 42 |
| EN 1998 | 6 | 600 | 103 |
| EN 1999 | 5 | 500 | 58 |
| EN 1999 | 5 | 500 | 58 |

There are two main aims of the mandate work concerning the improvement and harmonisation of existing rules: Reduction of the number of NDPs (Nationally Determined Parameters) and enhancing Ease of Use. Table 1 gives a summary of the number of NDPs in the current Eurocodes, relative to the number of parts in each Eurocode and its number. The very uneven distribution also shows that for some Eurocodes NDPs form a means to overcome different views on technical items. In these cases, the document N1250 [2] recommends a procedure to overcome these differences in order to reach a better harmonisation.

As a second point "Enhancing Ease of Use" has been defined as a major aim of the development of the 2nd Generation of Eurocodes. A number of principles and related priorities have been defined after long discussions in TC250 as responsible committee for Structural Eurocodes in CEN, see table 2.

TABLE 2.
Principles and related priorities [2].

| | |
|---|---|
| **General principles** | |
| 1 | Improving clarity and understandability of technical provisions of the Eurocodes. |
| 2 | Improving accessibility to technical provisions and ease of navigation between them. |
| 3 | Improving consistency within and between the Eurocodes. |
| 4 | Including state-of the-art material the use of which is based on commonly accepted results of research and has been validated through sufficient practical experience. |
| 5 | Considering the second Generation of the Eurocodes as an “evolution” avoiding fundamental changes to the approach to design and to the structure of the Eurocodes unless adequately justified. |
| **Specific principles (secondary)** | |
| 6 | Providing clear guidance for all common design cases encountered by typical competent practitioners in the relevant field. |
| 7 | Omitting or providing only general and basic technical provisions for special cases that will be very rarely encountered by typical competent practitioners in the relevant field. |
| 8 | Not inhibiting the freedom of experts to work from first principles and providing adequate freedom for innovation. |
| 9 | Limiting the inclusion of alternative application rules. |
| 10 | Including simplified methods only where they are of general application, address commonly encountered situations, are technically justified and give more conservative results than the rigorous methods they are intended to simplify. |
| 11 | Improving consistency with product standards and standards for execution. |
| 12 | Providing technical provisions that are not excessive sensitive to execution tolerances beyond what can be practically achieved on site. |

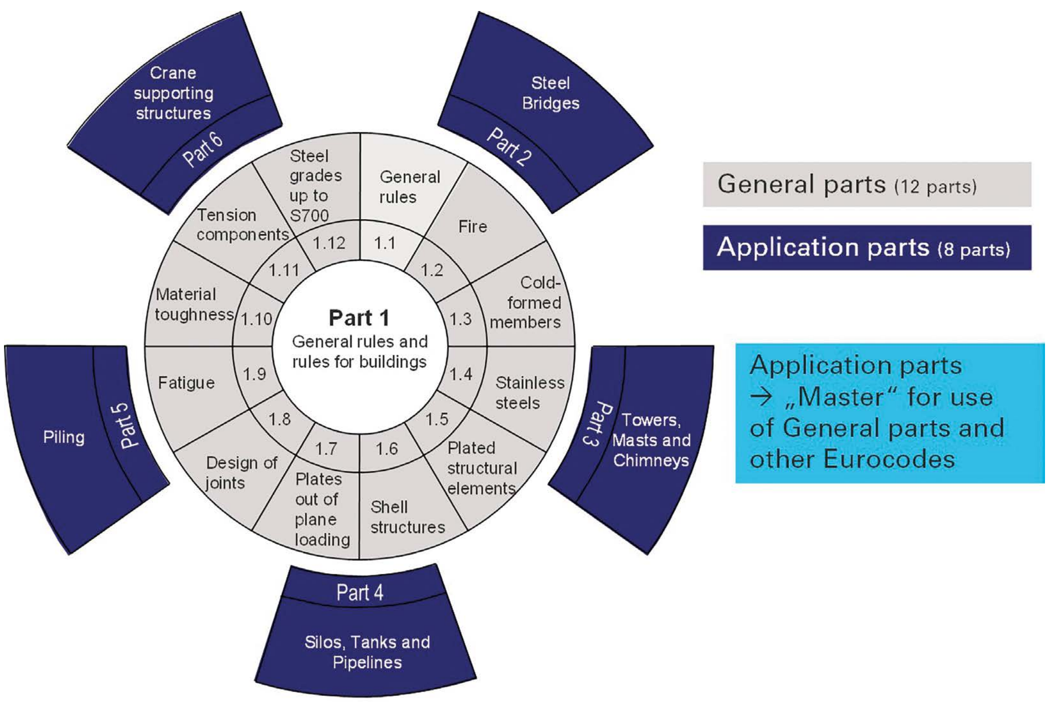



Figure 4. Structure and overview of existing Eurocode 3.

# 3. EUROCODE 3 – DEVELOPMENT OF 2ND GENERATION

## *3.1 Overview*

Of all Eurocodes (EN 1990 – EN 1999), Eurocode 3 (EN 1993) with its 20 parts and approximately 1.250 pages is the most extensive one. Figure 4 gives an overview on the structure of Eurocode 3 showing the “Application parts”, such as Part 2 for bridges or Part 3 for tower, masts and chimneys, which refer to the “General parts” within Part 1 as well as to the relevant parts in Eurocode 1 for Actions.

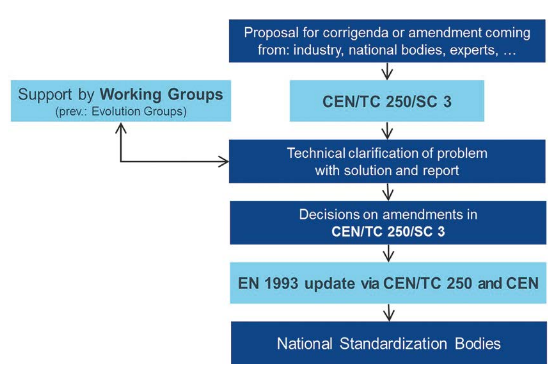



Figure 5. Revision of EN 1993 within TC250/SC3.

**TABLE 3.**
**Structure of future Eurocode 3 on steel structures and responsible SC3 Working Groups.**

| Part of Eurocode 3 | Type | Topic | Working Group |
|---|---|---|---|
| EN 1993-1-1 | General parts | General rules and rules for buildings | WG1 |
| EN 1993-1-2 | | Structural fire design | WG2 |
| EN 1993-1-3 | | Supplementary rules for cold-formed members | WG3 |
| EN 1993-1-4 | | Stainless steels | WG4 |
| EN 1993-1-5 | | Plated structural elements | WG5 |
| EN 1993-1-6 | | Strength and stability of shell structures | WG6 |
| EN 1993-1-7 | | Plate assemblies with elements under transverse loads | WG7 |
| EN 1993-1-8 | | Design of joints | WG8 |
| EN 1993-1-9 | | Fatigue | WG9 |
| EN 1993-1-10 | | Material toughness and through-thickness properties | WG10 |
| EN 1993-1-11 | | Design of structures with tension components | WG11 |
| EN 1993-1-12 | | Additional rules for steel grades up to S960 | WG12 |
| EN 1993-1-13 | | Steel beams with large web openings | WG20 |
| EN 1993-1-14 | | Design assisted by finite element analysis | WG22* |
| EN 1993-2 | Application parts | Steel bridges | WG13 |
| EN 1993-3 | | Towers, masts and chimneys | WG14 |
| EN 1993-4-1 | | Silos | WG15 |
| EN 1993-4-2 | | Tanks | WG16 |
| EN1993-5 | | Piling | WG18 |
| EN 1993-6 | | Crane supporting structures | WG19 |
| EN 1993-7 | | Design of sandwich panels | WG21 |

* before AHG FE

In the frame of the TC250/SC3 meeting in Stuttgart in April 2010 the approach shown in figure 5 for the revision and harmonisation of Eurocode 3 was scheduled.

The questions relating to the revision and harmonisation of Eurocode 3 are solved in cooperation between the CEN/TC250/SC3 and the Working Groups of SC3 and are elaborated in the form of proposals for amendments. These proposals are then sent to CEN for approval and to finally enter the Eurocode. The members of the Working Groups consist of experts for the particular area of expertise and are nominated by the National Standardisation Bodies (NSBs) of the different member countries.

The SC3 submitted its last technical review in form of amendments to the already existing parts of Eurocode 3 within the meeting of the CEN/TC250 in November 2013 in Delft. For the future, technical modifications are to be carried out in the frame of the mandate work. Exception is made just for safety-relevant amendments, which can still be submitted and decided for the existing versions of Eurocode 3.

Meanwhile SC3 has agreed to follow the same procedure as given in figure 2 also for the development and agreement on technical changes, which are to be implemented in the new version of Eurocode 3. These agreed “amendments” are put into the “basket” for the time when the Project Team starts its work and are implemented then in the new version. Also, to advise and follow the work of the Project Teams the Working Groups of SC3 play an important role. Table 3 gives an overview on the structure of Eurocode 3 and the different Working Groups of SC3 responsible for the different parts.

In general, the structure of Eurocode 3 is kept the same compared with the existing code, see figure 4. Small modifications to the structure of Eurocode 3 are explained in the following. The current content of EN 1993-1-12 on additional rules for the extension of EN 1993 up to steel grades S700 has been redistributed over the relevant other parts of Eurocode 3 (since the application of these parts has been extended to high strength steels (HSS)), meaning that the current version of EN 1993-1-12 could be withdrawn. However, SC3 decided to develop a new EN 1993-1-12 with a different scope, namely high strength steels up to grade S960. This activity does not belong to the mandate given by the EU, but will be finalised later, when sufficient knowledge and experience have been collected. EN 1993-1-13 is a new part on steel beams with large web openings (e.g. cellular and castellated beams). The current draft has mainly been developed within the mandate as a special task and by a Project Team of CEN / TC250 / SC4 responsible for steel-concrete composite construction. Also, a new part is EN 1993-1-14 on Design assisted by finite elements, which is and anticipates on a wider use of finite element analysis in the design of steel structures in the future. Here, first an Ad-Hoc-Group (AHG FE) existing of members of various Working Groups of SC3 had developed a first draft, transferring among others rules from other parts of Eurocode 3 such as Annex C of EN 1993-1-5 to this general part. Meanwhile, an own Working Group WG22 is dealing with this subject. Further, the current parts EN 1993-3-1 on masts and towers and EN 1993-3-2 on chimneys have been merged into one EN 1993-3, thus avoiding the overlap in the content of the current two parts. Also, a new part EN 1993-7 on design of sandwich panel will be added in addition to the mandated work.

### 3.2 *Mandate M/515*

For the work within the mandate the 20 parts of Eurocode 3 have been subdivided into 13 Tasks. For these 13 Tasks the technical contents were developed in form of so-called 'Project Proposals' in collaboration with the convenors of the respective 'Working Groups' and coordinated within the SC3 [1].

As EN 1993-1-1 and EN 1993-1-8 are the basic parts of Eurocode 3 there is the necessity of harmonisation in a number of issues with other parts, so that these two parts are dealt right at the beginning in Phase 1. Furthermore, four SC3 tasks most of them dealing with stability are assigned to the early Phase 2 of the mandate. The material specific parts of Eurocode 3, e.g. EN 1993-1-4 and EN 1993-1-10 are assigned to Phase 3, while in Phase 4 of the mandate primarily the application parts, such as e.g. EN 1993-2 Steel bridges, are covered. The assignment of the tasks to the phases is shown in table 4.

### 3.3 *Status of development Eurocode 3 and its parts*

As part of the contract of the Project Teams within the mandate they have to deliver a "Final Draft" at a certain point of time, which is sent out to the NSBs for the so-called Informal Enquiry. National Mirror groups can comment on these drafts,

**TABLE 4.**
**Tasks of Mandate M/515 concerning Eurocode 3.**

| Task-Ref. | Task-Phase Part of EN 1993 | Corresponding | Task-Name |
|---|---|---|---|
| SC3.1 | 1 | EN 1993-1-1 | Design of Sections and Members according to EN 1993-1-1 |
| SC3.2 | 1 | EN 1993-1-8 | Joints and Connections according to EN 1993-1-8 |
| SC3.3 | 2 | EN 1993-1-3 | Cold-formed members and sheeting. Revised EN 1993-1-3 |
| SC3.4 | 2 | EN 1993-1-5 | Stability of Plated Structural Elements. Revised EN 1993-1-5 |
| SC3.5 | 2 | EN 1993-1-6, -1-7 | Harmonisation and Extension of Rules for Shells and Similar Structures. Revised EN 1993-1-6 and EN 1993-1-7 |
| SC3.6 | 2 | EN 1993-1-2 | Fire design of Steel Structures. Revised EN 1993-1-2 |
| SC3.7 | 3 | EN 1993-1-4 | Stainless Steels. Revised EN 1993-1-4 |
| SC3.8 | 3 | EN 1993-1-9 | Steel Fatigue. Revised EN 1993-1-9 |
| SC3.9 | 3 | EN 1993-1-10 | Material and Fracture. Revised EN 1993-1-10 |
| SC3.10 | 4 | EN 1993-2, -1-11 | Steel bridges and tension components. Revised EN 1993-2 and EN 1993-1-11 |
| SC3.11 | 4 | EN 1993-3 | Consolidation and rationalisation of EN 1993-3 |
| SC3.12 | 4 | EN 1993-4 | Harmonisation and Extension of Rules for Storage Structures. Revised EN 1993-4-1 and EN 1993-4-2 |
| SC3.13 | 4 | EN 1993-5, -6 | Evolution of EN 1993-5 Piling and EN 1993-6 Crane supporting structures |

**TABLE 5.**
**Planned timetable for development of EC3.**

| Task-Phase | Corresponding Part of EN 1993 | Start of Informal Enquiry | Draft available for SC3 | Technical Approval SC3 | SC3 Decision for start of CEN-Enquiry | Start of Formal CEN-Enquiry |
|---|---|---|---|---|---|---|
| 1 | EN 1993-1-1 | December 2017 | June 2018 | October 2018 | October 2019 | September 2020 |
| 1 | EN 1993-1-8 | December 2017 | June 2018 | March 2019 | March 2020 | March 2021 |
| 2 | EN 1993-1-3 | October 2019 | June 2020 | October 2020 | March 2021 | March 2022 |
| 2 | EN 1993-1-5 | October 2019 | June 2020 | October 2020 | March 2021 | March 2022 |
| 2 | EN 1993-1-6, -1-7 | October 2019 | June 2020 | March 2021 | March 2022 | March 2023 |
| 2 | EN 1993-1-2 | October 2019 | June 2020 | October 2020 | March 2021 | March 2022 |
| 3 | EN 1993-1-4 | October 2020 | June 2021 | October 2021 | March 2022 | March 2023 |
| 3 | EN 1993-1-9 | October 2020 | June 2021 | October 2021 | March 2022 | March 2023 |
| 3 | EN 1993-1-10 | October 2020 | June 2021 | October 2021 | March 2022 | March 2023 |
| 4 | EN 1993-2, -1-11 | March 2021 | February 2022 | October 2022 | March 2023 | March 2024 |
| 4 | EN 1993-3 | March 2021 | February 2022 | October 2022 | March 2023 | March 2024 |
| 4 | EN 1993-4 | March 2021 | February 2022 | October 2022 | March 2023 | March 2024 |
| 4 | EN 1993-5, -6 | March 2021 | February 2022 | October 2022 | March 2023 | March 2024 |

the comments are collected and the Project Teams have to consider them and, if possible, modify the drafts accordingly. These modified drafts are given at the end of the Project Team contract in the hands of the relevant subcommittee in order to solve still open question and find a harmonised view on them, but also to prepare the text for the official CEN-Enquiry. SC3 has decided at a relatively early stage on a "publication plan" for the various drafts to schedule this procedure, see SC3 Decision 20/2018. Also it was decided to have an official Technical Approval of SC3 on the single drafts before starting the final editing and correction. So, for example there was a Technical Approval on prEN1993-1-1 in October 2018, which allowed the other Project Teams in the following phases to rely on the content of this basic general part of Eurocode 3 for the development of their own parts.

Thereby, an optimal harmonisation can be achieved within the different parts of Eurocode 3. Reference groups of 4 to 7 experts were established in WG1 and WG8 to give advice or seek confirmation of the Working Groups if needed for the necessary editorial changes or small technical corrections during the preparation of the drafts by DIN as responsible SC3 Secretariat for CEN- Enquiry. In the SC3 meeting in October 2019 finally, there was an official decision in SC3 to proceed prEN 1993-1-1 to CEN-Enquiry. The planned timetable for all parts and phases of Eurocode 3 is given in table 5.

CEN/TC250 has fixed for all Eurocodes possible dates for the start of the Formal CEN-Enquiry and necessary preparatory times beforehand. This preparatory includes phases for the checking of the draft by the TC250 secretariat, for the editing by CCMC (the responsible CEN institution) and for the translation into German and French by DIN and AFNOR. During the CEN-Enquiry of about 16 weeks the draft is distributed in all member countries and official agreement and comments are requested by all NSBs. In the following the draft is given back to the subcommittee for review of the comments and possibly modification of the text if necessary. This modified draft is then running through the same procedure as for the Formal CEN-Enquiry in order to be then sent out to the member countries for the Formal Vote, which lasts about 8 weeks. The agreement by the NSBs to the Formal Vote should not contain any technical comments, but only editorial remarks. After editorial corrections if necessary by CCMC and translation the draft is sent out to the NSBs to be published in the different countries together with a National Annex.

The whole procedure of implementation of new Eurocodes may seem a rather long lasting effort, however the various possibilities of commenting and correction represent an important chance to influence the content and to ensure a high quality of this very important set of codes.

## 4. RESEARCH CONTRIBUTIONS

### *4.1 General*

The following sections show some research contributions for different parts of Eurocode 3. They represent some of the new developments based on recent research which open new chances for application and further development of design of steel structures. Due to the limited space of this paper, only a small extract is shown here.

### *4.2 EN 1993-1-1*

The simplified method of verification of lateral torsional buckling by the verification of flexural buckling of the equivalent compression flange dates back to the early 1950s. The basic idea of this concept was subsequently adopted from the former German code for member stability DIN 18800-2 [5], which was transferred to EC 3.

This traditional approach still plays a decisive role in both EN 1993-1-1 and EN 1993-2 due to the simplification of the complex structural stability behaviour of lateral torsional buckling to flexural buckling of an equivalent compressed part, which allows an easy-to-use method by a straightforward hand calculation. The model is still based on DIN 18800-2 and its lateral torsional buckling curves. The simplified method is therefore neither consistent with the "general" or "specific case" of the current lateral torsional buckling verification nor with the new reduction factors of the Final Draft prEN 1993-1-1 [3]. Furthermore, despite the popularity of this design model, deficiencies have also been discovered in recent years. On one hand, an additional application limit is required for mono-symmetric cross-sections and steel beams with a load application on the compression flange due to the resulting destabilizing effect. On the other hand one has to mention the high inefficiency of the method for cross-sections with thick flanges.

Within a German research project [6] the simplified method has been modified on the basis of a comprehensive experimental study on the lateral torsional buckling behaviour and residual stress measurements on welded doubly- and mono-symmetric I-shaped steel beams. A major concern in the development was to keep the method as simple as possible and to avoid the determination of complex cross-sectional values for mono-symmetric cross-sections. A detailed description of the investigations and the modifications of the equivalent compression flange is given in [7].

The basic concept of the simplified method is equal to the current model in Eurocode 3 where the lateral torsional buckling resistance of a member $M_{b,Rd}$ is determined by considering the reduction factor $\chi_{c,z}$ for flexural buckling of an equivalent compression flange. Similar to the current procedure, the reduction factor $\chi_{c,z}$ for flexural buckling is derived from the modified related slenderness of the equivalent compression flange $\lambda_{c,z}$,mod with buckling curve c for hot rolled cross-sections and buckling curve d for welded cross-sections. The related slenderness ratio of the equivalent compression flange $\lambda_{c,z}$ is obtained from Eq. 1, whereby the load application point can be taken into account by the considered size of the web area. Afterwards the related slenderness of the equivalent compression flange is modified by multiplying with the two correction coefficients kc and $\beta_c$. The coefficient $k_c$ considers the moment distribution between the restraints and coefficient $\beta_c$, see Eq. 2, the influence of the torsional stiffness by the ratio $h/t_{max}$.

The ratio of the flange thicknesses allows to capture the change of the torsional stiffness for mono-symmetric cross-sections. The modified simplified model may be used for cross-sections of class 1 to 3 and the current application limit of h/t smaller than 44 ε for welded cross-sections may be omitted.

In order to present the results of the modified simplified model, figure 6 shows a comparison of the reduction factors obtained with numerical simulations (triangle marks), the design results of the modified simplified method (solid line) and the lateral torsional buckling verification of the Final Draft prEN 1993-1- [3] (dashed line) for a doubly-symmetric welded cross-section of steel grade S355. The modified simplified model leads to a satisfactory agreement and good design results.

$$\bar{\lambda}_{c,z} = \sqrt{\frac{A_c f_y}{N_{cr,c,z}}} \tag{1}$$

$$\beta_c = \sqrt{\frac{0.06\ \dfrac{h}{t_{max}}}{\bar{\lambda}_{c,z} + \dfrac{t_{max}}{t_{min}}}} \leq 2 \tag{2}$$

where $A_c$

is the area of the equivalent compression flange

$$A_c = \begin{cases} A_f + \dfrac{1}{2} A_w & \text{Load application on the compression flange} \\ A_f + \dfrac{1}{6} A_w & \text{Load application in the shear centre} \\ A_f & \text{Load application on the tension flange} \end{cases}$$

### *4.3 EN 1993-1-5*

Non-rectangular steel plates are increasingly used in the design of new bridges due to architectural and / or structural advantages. At large spans, in order to save material and consequently to decrease the impact on the environment, the girders are curved in elevation with a maximum depth at intermediate support and minimum depth at midspan. Steel bridges built up of slender panels which tend to buckle may be designed based on EN 1993-1-5 [8], which offers different methods for verification such as "Effective Width Method" (EWM), "Reduced Stress Method" (RSM) or "Verification based on Finite Element Methods of analysis". Among the mentioned methods EWM is based on the reduction of the cross-section area considering the local buckling of the subpanels between the stiffeners and the global buckling of the longitudinal stiffeners. As a consequence of the optimized shape of the bridges, non-rectangular plates occur, most commonly as web panels of girders with a lower flange curved in the longitudinal direction.

The application of EWM according to EN 1993-1-5 [8] is limited to rectangular panels with parallel flanges. According to the existing rules [8], the method EWM may only be applied for an angle **Φ** up to 10°, see figure 7. This section is concerned with clarifying and enhancing the design of non-rectangular panels so that the influence of the shape of the panel is considered in the design. Investigations of non-rectangular panels have been conducted at the University of Stuttgart in the frame of the European research project Outburst [9]. A summary of the experimental and numerical investigations is introduced in [10] [11].

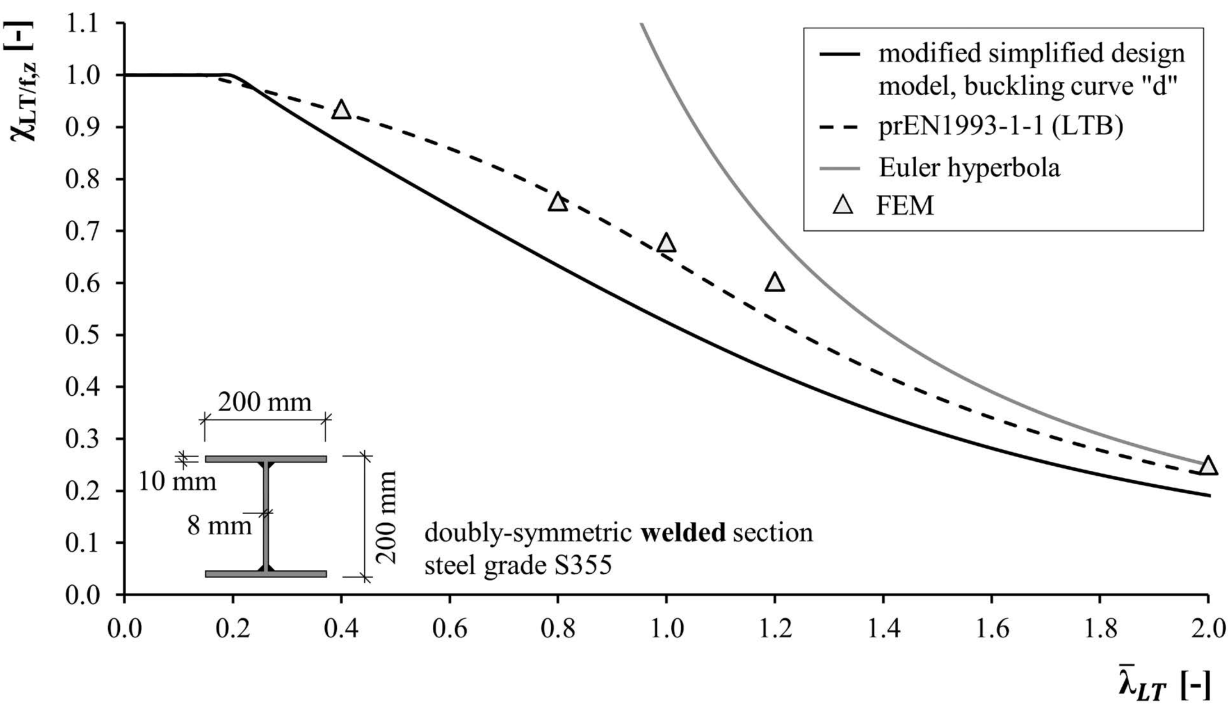



Figure 6. Comparison of load reduction factors of the modified simplified model, the lateral torsional buckling verification according to prEN 1993-1-1 [4] and numerical simulations.

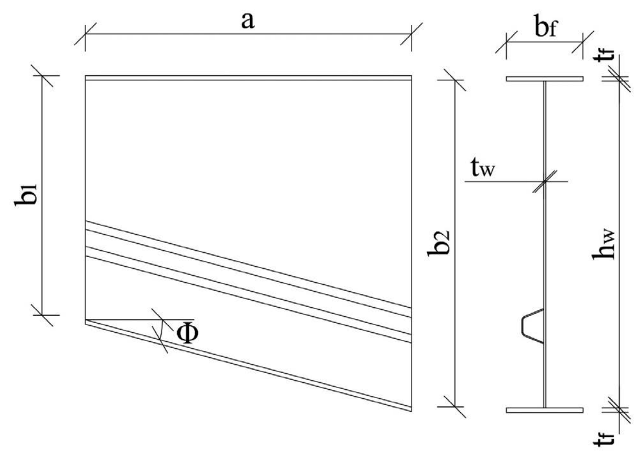



Figure 7. Definition of dimensions of a non-rectangular panel.

To evaluate the current design rules acc. to EN 1993-1-5 and especially the method EWM a numerical parametric study has been conducted using the validated model [9]. Following parameters were considered in order to investigate the buckling behaviour of stiffened non-rectangular panel: width $b_2$ = 2100 [mm]; panel length a = 2100 [mm]; web thickness $t_w$ = 8, 10, 12, 15, 20 [mm]; flange $b_f$ x $t_f$ = 350x36, 490x36, 560x36 [mm]; stiffness of stiffener $\gamma_{sl,i}{}^*$ = 25, 50, 80, 150 and angle of web panel $\Phi$ = 0, 10, 12.5, 15, 17.5°. The panels were subjected to bending, shear and interaction of bending and shear.

Based on the numerical and experimental investigations, design rules for the non-rectangular buckling were proposed [9]. In this paper, the results of the proposal are compared with the existing rules applying EN 1993-1-5 for the angle up to 17.5°. To obtain the ultimate loads the verifications are transformed as a function of shear force V and compared with numerically calculated V.

Figure 8 shows the position of sections of verifications. According to EN 1993-1-5 the bending (M), shear (V) and M-V interaction should be verified. Additionally, the gross cross-section should be checked to the corresponding acting forces at sections 1 and 2. For bending, a minimum distance of 0.5b2 (section 3) and 0.4a (section 4) should be verified. Section 3 is also relevant for M-V interaction.

In the case of non-rectangular panels, the height of the web varies in the panel. Therefore, the cross-section properties and the resulting stresses in the panel vary. The stresses at the smaller side may be higher than on the larger side. Therefore, according to the proposal the bending (M), shear (V) and M-V interaction should be verified at both sides of the panel. So the panel should be checked for the resulting stresses at a section located at each end of the panel:

$$\text{at } 0.5b_2 \quad \text{if} \quad \frac{M_{0.5b_2}}{M_{f,0.5b_2}} \geq \frac{M_{0.4a}}{M_{f,0.4a}} \quad \textit{or}$$

$$\text{at } 0.4a \quad \text{if} \quad \frac{M_{0.5b_2}}{M_{f,0.5b_2}} < \frac{M_{0.4a}}{M_{f,0.4a}}$$

from the panel end with larger width ($b_2$) (section 3 or 4 according to figure 8), where

$M_{0.5b_2}$ is the acting bending moment at the section with a distance 0.5b2 and $M_{0,4a}$ is the acting bending moment at a distance 0.4a from end of panel. The comparsion of these moments to the flange bending resistances allows to check beforehand, which is the decisive verification in section 3 or section 4.

This approach applies to all verifications. The gross cross-section should be checked also at sections 1 and 2.

Due to the geometry of the inclined compression flange, the acting shear force may be modified. The force distribution due to inclined compression flange is shown in figure 9.

$N_{x,f}$ is the horizontal force resulting from the bending moment. The inclined flange force $N_{Flange}$ is composed of this horizontal force $N_{x,f}$ and the vertical force $V_{z,f}$, which acts on the web.

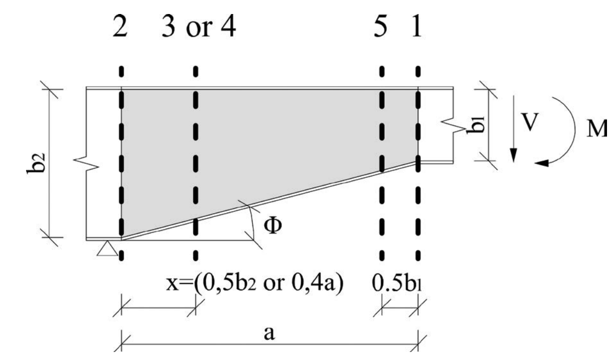



Figure 8. Position of sections for verification of non-rectangular panel according to the proposal.

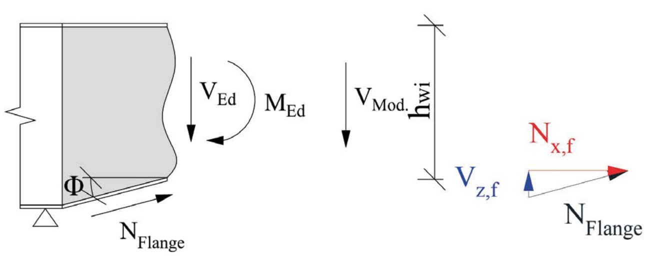



Figure 9. Influence of inclined compression flange.

The modification of the shear force of the web $V_{Mod}$ is calculated by Eq. (3) and (4). The shear (V) and M-V interaction should be verify using the modification $V_{Mod}$.

$$V_{z,f} = N_{x,f} \cdot \tan(\Phi) \tag{3}$$

$$V_{Mod} = \left| V_{Ed} - V_{z,f} \right| \tag{4}$$

In figure 10 numerical results are compared with the results of the proposal and EN 1993-1-5 for different angles of the panel ($\Phi$). On the x-axis values obtained by the resistance models are indicated and on the y-axis values derived from the numerical simulations. The red line shows $r_e$=$r_t$ , which means the resistance of the model is equal to the numerical resistance.

It should be mentioned for the verifications the partial factors have been assumed $\gamma_{M0}$ and $\gamma_{M1}$ equal to 1.0 and the buckling coefficients are calculated on the safe side assuming the panel as a rectangular with the larger width ($b_2$) using the formula in EN 1993-1-5 [8].

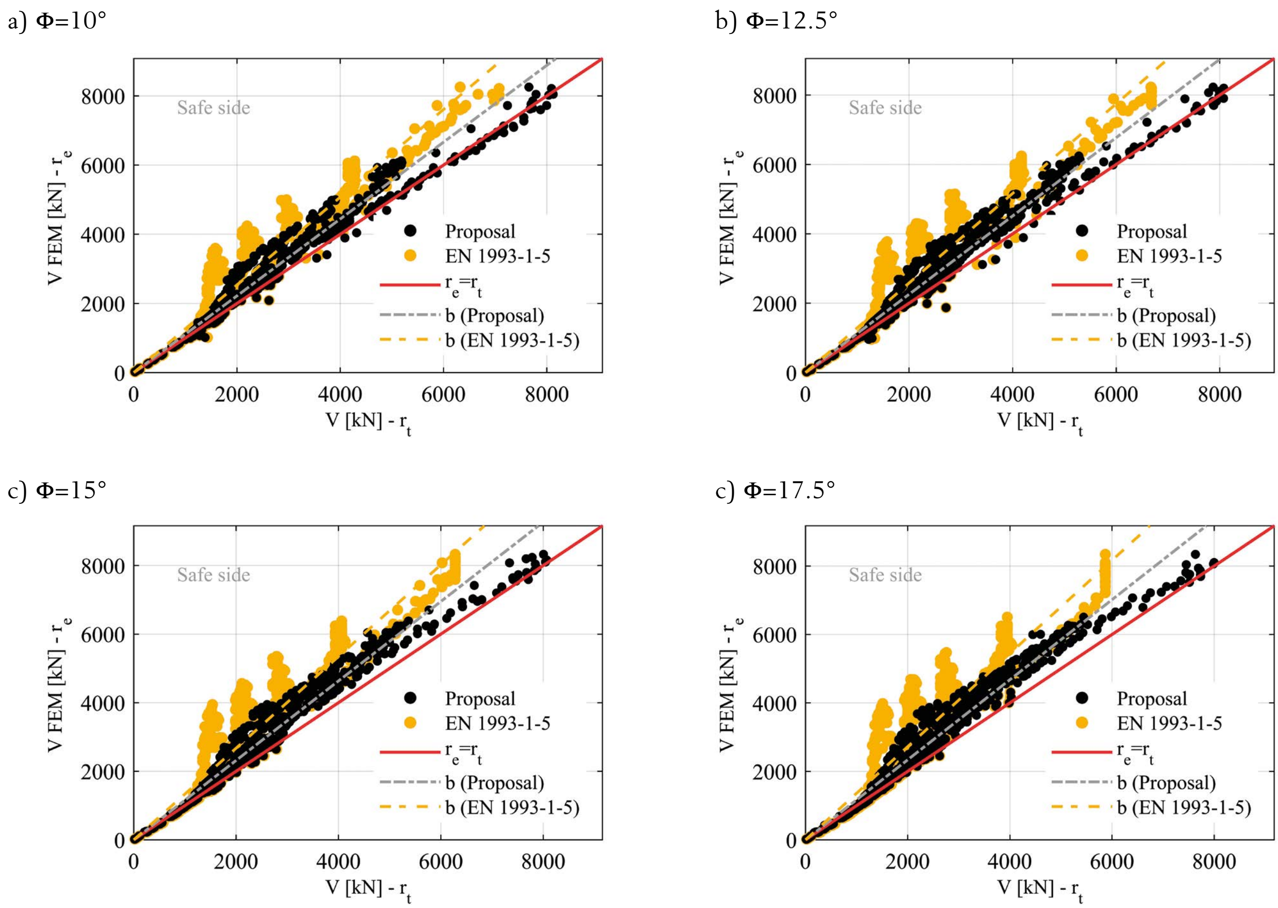



Figure 10. Comparison of the results of the EN 1993-1-5 and of the proposal with numerical results.

The results of EN 1993-1-5 and the proposal are generally on the safe side. Also, with increasing the angle EN 1993-1-5 gives more conservative results, while the proposal leads to a narrower distribution in comparison to EN 1993-1-5 and to more economic results. This proposal has been implemented in the second draft of EN 1993-1-5.

### *4.4 EN 1993-1-8*

The use of high strength steels (HSS) represents one of the main development for modern steel structures. However, for the particular situation of joining HSS elements the present design rules, e.g. in EN1993-1-8 are in many cases inadequate because the recent rules are developed for standard steels and then transferred to high strength steels. In the frame of three research projects including a high number of tests for fillet welds a realistic and coherent design model for determination of the load carrying capacity of welded connections made of HSS has been developed and meanwhile is accepted for the future version of Eurocode 3 by TC250 / SC3.

For EN 1993-1-8 an important change concerns the load bearing capacity of fillet welded connections of high strength steels. Based on several research projects [12], [13] new correlation factors βw have been defined for steels S460 and S690 to achieve a constant level of safety. This results in improved load bearing capacity for S460, but reduced load bearing capacity of S690. Correlation factors of S420 to S700 have been chosen accordingly. In addition based on [14] a new formula has been introduced, which differentiates between $f_{u,PM}$ (parent material) and $f_{u,FM}$ (filler material), see Eq. 5.

This design model can be used for fillet welded connections of steel grades equal to or greater than S460 and with different parent and filler metal strength.

For matching or overmatching butt welds made of high strength steels an adjustment of the present design rules has not yet been carried out. The current design rules according to EN 1993 require a verification of the adjacent cross-sections of the member according EN 1993-1-1 only. For butt welds with HSS undermatching connections are permitted and the verification should consider the filler metal strength, but a detailed procedure is not given.

In addition, typically failure modes of butt welds of HSS with strength >S460 occur in the seam or in the heat affected zone as shown in several research projects.

However, the design of full penetration butt welds is usually carried out in the parent metal and not in the seam or the heat affected zone. The load carrying capacity of welds, which showed failure in the seam or the heat affected zone, was sometimes lower than the strength of the parent metal. Therefore, the current rules for full penetration butt welds of HSS seem to be in-sufficient.

$$\sqrt{\alpha_\perp^2+3\,(\tau_\perp^2+\tau_\parallel^2)} \le \frac{0.25\, f_{u,PM}+0.75\, f_{u,FM}}{\beta_{w,mod}\,\gamma_{M2}}$$

where $f_{u,PM}$ nominal ultimate tensile strength of the parent metal (weaker part joined)

$f_{u,FM}$ nominal ultimate tensile strength of the filler metal, see table 6 or EN ISO 2560, EN ISO 16834 and EN 18276

$\beta_{w,mod}$ is a modified correlation factor that depends on the filler metal strength, see table 6

**TABLE 6.**
**Ultimate strength of filler metals $f_{u,FM}$ and modified correlation factor $\beta_{w,mod}$ [15]**

| Filler metal strength class | 42 | 46 | 69 | 89 |
|---|---|---|---|---|
| Ultimate strength $f_{u,FM}$ [N/mm²] | 500 | 530 | 770 | 940 |
| Correlation factor $\beta_{w,mod}$ [-] | 0.89 | 0.85 | 1.09 | 1.19 |

For filler metals different to those given in table 6 the correlation factor should be taken conservatively according to the given values.

A German research project [16] has started with the objective to investigate butt welds made of high strength steel under various influence parameters in order to avoid a premature failure. In order to guarantee and promote an economic, future-oriented and resource-saving application, it is necessary to develop efficient design rules and processing guidelines also for butt welds.

The experimental investigations of [16] focus on welds on steel S690 with plate thickness t=10mm and t=20mm and different filler metals. In order to examine the problem of a reduced load carrying capacity of high strength steel, reference tests were also carried out on butt welds of steels of S460ML.

The failure of the reference tests always occurred in the parent metal and the determined load carrying capacity corresponds to the strength of the parent metal.

The experimental investigations on butt welds of steel S690 show that the load carrying capacity of the butt welds are slightly lower than the parent metal. The failure of these butt welds occurred in the heat affected zone or, for example for undermatching connections, in the filler metal and not in the parent metal. So the problem of a reduced load carrying capacity of high strength steel with strength higher than 460 MPa could be confirmed according to the experimental results.

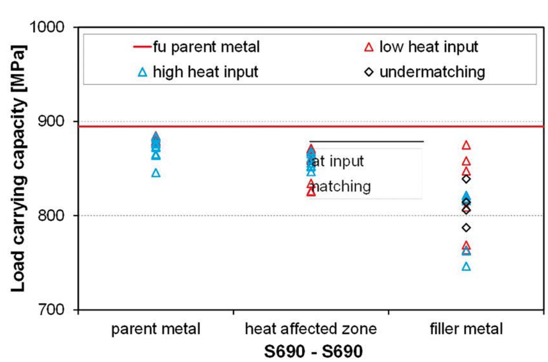



Figure 11. Location of failure of butt welds on high strength steel S690 with plate thickness t = 20mm.

In figure 11 the location of failure for each connection has been listed. The results show that the load carrying capacity of the butt weld depends on the location of failure. Due to the lower strength the failure occurs in the softening zone which leads to a lower load carrying capacity of the butt weld. In addition, it can be observed that the failure of butt welds on steel S690 with high heat input frequently occurs in the heat affected zone or in the filler metal.

The first experimental results show that it is necessary to develop an adapted design concept for butt welds on higher strength steels to take into account the different failure modes. The development of the design concept is currently in progress.

### *4.5 EN 1993-1-9*

In future, EN 1993-1-9 will distinguish between *fatigue design concepts* representing the design philosophies (such as damage tolerant concept and safe-life concept) and different *fatigue design methods* that are the tools used for the design concepts. A major change is the introduction of specific recommendations for other stress-based design methods, in particular the hot-spot stress method and the notch stress method, besides the well-known nominal stress method. To distinguish between the different stress methods, a far more precise stress definition has been added to clarify how hot-spot and notch stresses have to be computed.

As before, the main document of EN 1993-1-9 focuses on the fatigue verification based on the nominal stress method because of its great practical importance. Particular annexes are additionally provided for the hot-spot stress method and the notch stress method.

A further great change concerns the detail tables which are the heart of the nominal stress method and that have been completely revised (figure 12). Up to now the tables have represented the corresponding details in descending order of detail category. As a consequence, all details of a table are more or less mixed. In contrast, for user-friendliness the revised tables treat the details one after another. The user finds a better illustration and an improved and clarified compilation of different execution qualities and associated detail categories for each detail.

As before, the tables open with a column ‘detail category’ followed by a column ‘constructional detail’ with illustrations. In comparison to the current standard, the illustrations have essentially been reworked. For many constructional details, the illustrations have been scaled up to clearly point out the spot of potential fatigue failure and to support the literal characterisation in column ‘description’. Moreover, a column ‘symbol’ is added for welded details to indicate the appropriate weld quality compatible with the considered detail category. The introduction of weld symbols facilitates the communication between design office and workshop and far better prevents from misunderstandings.

In general, the usage of the detail tables requires a weld quality level B according to ISO 5817, an accredited assignment of personnel and an extent of non-destructive test-

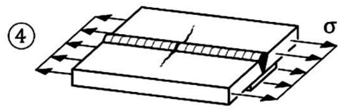
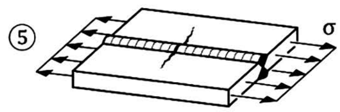
| Detail category | Constructional detail | Symbol | Description | Supplementary Requirements |
|---|---|---|---|---|
| 112 |  | | ④ Automatic or fully mechanised butt welds, welded from one side, with a continuous root backing, without stop-starts | |
| 100 | | | as forementioned, but with stop-starts or manual butt welds | |
| 125 |  | | ⑤ Butt welds, welded from both sides, ground flush parallel to load direction, without stop-starts | Extent of NDT according to EN 1090-2: 100%. |
| 112 | | | as forementioned, but no grinding | |
| 90 | | | as forementioned, but with stop-starts | |

Figure 12. Revised detail table for built-up members (draft).

ing (NDT) as specified by EN 1090-2. Therefore, the last column of the tables only contains supplementary requirements beyond the specifications of EN 1090-2.

## 5. SUMMARY AND CONCLUSIONS

Within this paper, the normative evolution for steel structures in the frame of the development of the 2nd Generation of Eurocodes is shown. Thereby, the revision process in the frame of Mandate M/515 of the Eurocodes in general and the 20 parts of EN 1993 in specific is described aiming at improvement and harmonisation of the existing codes. Besides the general revision and maintenance of the Eurocodes, the technical review of some selected technical issues is explained. They represent also some of the new developments based on recent research, which open new chances for application and further development of design of steel structures, e.g. for the application of high strength steels. Steel structures form competitive structural solutions that are well equipped for the future also due to diverse international research activities and common harmonised efforts for the implementation in the future codes.

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