Structures 92 (2026) 112810

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

Structural steel design assisted by finite element analysis – An introduction to EN 1993-1-14 and TR 1993-1-141

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A R T I C L E I N F O

Keywords:
Advanced calculation tools
Eurocode 3
EN 1993-1-14
Finite element analysis
Numerical model
Standardisation
Steel design
Technical report
TR 1993–1-141

A B S T R A C T

The application of design by finite element analysis (FEA) is becoming increasingly prevalent in engineering practice; however, codified provisions remain scarce. The vision of CEN/TC250/SC3 was to develop a new comprehensive document based on the existing provisions currently distributed throughout the different Eurocode 3 parts, and with extension where necessary to cover all fields of structural steel design. Within the development process, two documents were prepared: (i) the code, EN 1993-1-14 and (ii) a Technical Report, TR 1993-1-141. The new code provides rules on the use of finite element analysis and other numerical methods for verifying ultimate limit states, serviceability limit states and fatigue. In parallel, the Technical Report provides background information and explanations on all aspects of the code, as well as benchmark cases and design examples to support the correct application of the EN 1993-1-14 design rules and the necessary benchmarking required for model verification and validation. The assumed stakeholders are mainly designers who can find direct guidance for design by finite element analysis in daily engineering practice. The current paper gives an overview of the new code and accompanying Technical Report, as well as the development process and harmonisation within the current Eurocode 3 framework.

1. Introduction

The more widespread availability of digital tools and increasing computational power facilitates the ever-growing application of advanced analysis, also referred to as geometrically and materially non-linear analysis with imperfections (GMNIA) or second order inelastic analysis. While this is reflected in the worldwide research efforts and literature [1–7], there remains a disconnect with the established rules for design practice. Recent years have seen strong growth in the use of digital tools and advanced analysis in the design and assessment of structures, but supporting design guidance has thus far remained scarce. To date, comprehensive design rules for the finite element analysis-based design of steel structures have not been provided within the Eurocode 3 design framework. Existing guidance has been distributed throughout the different parts of the code (e.g. EN 1993-1-5 Annex C [8]; EN 1993-1-6 [9]) resulting in limitations in their scope and the potential for contradiction. Therefore, the vision of CEN/TC250/SC3 was that rules for finite element analysis-based design should be merged into one new comprehensive document based on the existing provisions and with extension where necessary to cover all fields of structural steel design. The scope of the new standard is to provide rules on the use of finite element analysis and other numerical methods for verifying ultimate limit states, serviceability limit states and fatigue. Within the development process, two documents have been prepared: (i) the code,

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https://doi.org/10.1016/j.istruc.2026.112810
Received 11 June 2026; Accepted 5 August 2026
Available online 25 August 2026

EN 1993-1-14 and (ii) the Technical Report, TR 1993-1-141. The Technical Report contains the background information and explanation of all aspects of the code including the analysis types, material and geometric modelling, model validation and verification and design checks. Additionally, it provides a series of benchmark cases and worked examples to support the correct interpretation.

The focus of this paper is on presenting an overview of the content and development process of the code and the Technical Report, as well as summarising some of the research that has underpinned the presented design rules. In particular, the paper highlights several new terms introduced and gives their definition and correct interpretation. To conclude, several ongoing research directions of WG22, the Working Group responsible for the preparation of EN 1993-1-14, are summarised, thus providing a starting point for further development.

2. Development process

The development of EN 1993-1-14 began when an Ad-Hoc Group (AHGFE) was established in October 2016 following Decision 23/2016 made by CEN/TC250/SC3, the subcommittee responsible for the Eurocode design of steel structures. The general scope of the AHGFE was to further develop Annex C of EN 1993-1-5 into a more general and comprehensive annex or an individual part on design assisted by finite element analysis. The main requirement was that this new document should cover the needs of all existing parts of Eurocode 3. Members of the Ad-Hoc Group were delegated by the Working Groups of SC3 (Design of Steel Structures), with one member additionally delegated by CEN/TC250/SC9 (Design of Aluminium Structures). This delegation process ensured that the AHGFE represented an internationally leading team with expertise covering the entire breadth of structural steel design. The AHGFE received a three-year mandate from SC3 to collect, harmonise and classify all existing design rules and guidance related to the finite element-based design of steel structures. The main development strategy approved by SC3 was to develop two documents: (i) a short code-like document and (ii) a longer Technical Report/background document summarising the background information behind the design rules and presenting further recommendations and guidelines to designers, as well as benchmark examples of verification and validation best practice.

When the mandate of the AHGFE terminated, a new Working Group (CEN/TC250/SC3/WG22: "EN 1993-1-14 - Design assisted by FEM") was established in 2019 and the development process continued. All contributing countries were able to delegate experts to the Working Group, and currently WG22 has 37 members from 17 countries. It is an active working group with two meetings each year.

The first objective of WG22 was to prepare the draft prEN 1993-1-14 code through collecting all the necessary design rules for FEA-based design of steel structures. This developed document was systematically reviewed in line with standard processes, and checked by SC3 and a wide range of experts in the relevant fields. Following each review, WG22 considered all the collected comments and remarks and amended the document accordingly. The technical approval of the document was made by SC3 in December 2021 confirming the technical adequacy of the document.

Alongside the code development, WG22 started to work on the Technical Report to support the application and interpretation of the new EN 1993-1-14 code. These two documents together are aimed to give a comprehensive framework for designers to apply numerical model-based design as a standardised design process. Both documents were submitted to the CEN Enquiry in September 2023 with national mirror committees asked for technical comments and suggestions for improvements. Consequently, a response to each comment was made with changes incorporated where deemed appropriate. With each change to the code affecting the Technical Report, a decision was made to stagger their finalisation. Thus, EN 1993-1-14 was published in 2025 [10], while the Technical Report is due to be presented to SC3 for formal vote in 2026 [11].

In parallel to the activities of WG22, TC250 also independently established an Ad-Hoc Group (CEN/TC250/SC10/WG3) to investigate numerically-based design rules. Consequently, CEN/TC250/SC10/WG3 is currently working on an informative Annex on numerical methods for EN 1990; due to close collaboration, the content is predominantly harmonised with the work of WG22 and with the normative EN 1993-1-14.

3. Scope of EN 1993-1-14 and Technical Report TR 1993-1-141

The scope of EN 1993-1-14 is to give rules on the use of finite element (FE) analysis and other numerical methods for verifying ultimate limit states, serviceability limit states and fatigue of steel structures. The scope of application is for all steel grades from S235 up to and including S700. It is intended to contain rules on the following topics:

a. the modelling of structural components and boundary conditions;
b. the use of imperfections (geometrical imperfections, residual stresses and equivalent geometric imperfections);
c. the modelling of material properties;
d. the modelling of loads;
e. types of analysis;
f. verification and validation of FE models;
g. modelling of limit state criteria;
h. the harmonisation of limit state criteria and the chosen modelling level and type of analysis;
i. the partial factors to be applied;
j. the choice of software and documentation.

The provisions of the new code consider the following design criteria:

a. plastic failure;
b. fracture;
c. buckling;
d. fatigue;
e. serviceability.

EN 1993-1-14 gives general design recommendations for a wide range of applications of numerical models used (i) in daily design practice and (ii) for product development purposes. The document covers the necessary rules for both applications. Additionally, the rules are intended to be software independent; however, a level of experience in the use of FEA is assumed.

The general development strategy was that EN 1993-1-14 should define the framework for finite element analysis-based design, providing general rules and modelling and analysis methodologies. However, additional more specific design rules, application specific design parameters and limiting values should continue to be defined within the relevant code parts. Therefore, detailed discussions with the WGs responsible for the other parts of EN 1993 took place during the development process of the EN 1993-1-14, to ensure that the codes were harmonised.

EN 1993-1-14 includes the provisions for a step change in design practice by enabling widespread use of finite element analysis-based design, ensuring the same level of safety as existing design practice according to the Eurocodes. Thus, to support this new standardisation and ensure understanding and correct application by designers, a background document (Technical Report – CEN/TR 1993-1-141: Background and explanations on EN 1993-1-14 Design assisted by finite element analysis) has also been prepared. The aim of the Technical Report is to give detailed background information and design guidance along with benchmark examples to the new design rules. In particular, the Technical Report contains guidelines and explanations for the numerical modelling, selection of analysis type, model validation and verification and design checks of steel structures using finite element analysis. It also summarises the key research that underpins the design rules and provides a starting point for further development. The content of TR 1993-1-141 mirrors that of the code, as summarised in Fig. 1, but with two additional annexes added to present a series of verification and validation (Annex D) and design (Annex E) examples. The validation examples are included to give background and support to the numerical model validation process, while the design examples support the correct application of the EN 1993-1-14 design provisions.

The assumed primary stakeholders of the document are designers. Other stakeholders are researchers and experts who are working on the further improvement of the existing design rules and the development of products and future codes.

4. General design rules – basis of design with numerical methods

There are different modelling levels and analysis types that can be used by designers during daily design practice and by research and development (R&D) engineers. The code reflects this, with the design rules separated into two tracks based on the analysis purpose: (1) numerical design calculations and (2) numerical simulations. Fig. 2 gives a general overview of these tracks and the key components of each. For the application of the design rules given in EN 1993-1-14, it is important to determine first which corresponding track is required for the FEA purpose.

The first track, numerical design calculations, covers practical design cases. This track has two sub-tracks: (1) analysis requiring subsequent design checks (design track 1–1) and (2) direct resistance checks (design track 1–2). Within the first sub-track, the numerical model is used to calculate system response quantities (e.g. internal forces, deformations, critical load factors, stresses, design factors, etc.) which are then used in the analytical design formulae given in the codes for the specific check. In this case, the resistance of the structure under investigation is not directly determined by the numerical model, with only the design parameters for further processing taken from the numerical model. Within design track 1–1, the following analysis types are commonly applied to determine the system response quantities: LA (linear analysis), LBA (linear bifurcation analysis), GNA (geometrically non-linear analysis), GNIA (geometrically non-linear analysis with imperfections), MNA (materially non-linear analysis). The second sub-track is the direct resistance check. In design track 1–2, the ultimate resistance of the structure is the direct result of the numerical simulation i.e. no additional analytical or empirical-based calculations are necessary. Consequently, a materially non-linear analysis must always be utilised - MNA, GMNA or GMNIA to determine the structural resistance. The choice of analysis is governed by whether second order effects and imperfections have an impact on the non-linear behaviour and resistance of the structure. These analysis types are not yet widely used in daily design

EN 1993-1-14

0. Introduction
1. Scope
2. Normative references
3. Terms, definitions and symbols
4. Basis of design
5. Modelling
   5.1. Geometrical models
   5.2. Support and load models
   5.3. Material models
   5.4. Imperfections
   5.5. Imperfection combinations
6. Analysis
   6.1. Structural analysis
   6.2. Thermal analysis
7. Verification and validation
   7.1. General
   7.2. Verification
   7.3. Validation
8. Design methodology
   8.1. Ultimate limit state (excluding fatigue)
   8.2. Fatigue
   8.3. Serviceability limit state
9. Documentation

Annex A Calculation of model factor (γ_{FE})

Annex B Stress concentrations

Annex C Limits of maximum strains for beam finite elements

TR 1993-1-141

Literature

Annex D Verification and validation examples

Annex E Design examples

Fig. 1. Content of the code EN 1993-1-14 and Technical Report TR 1993-1-141.

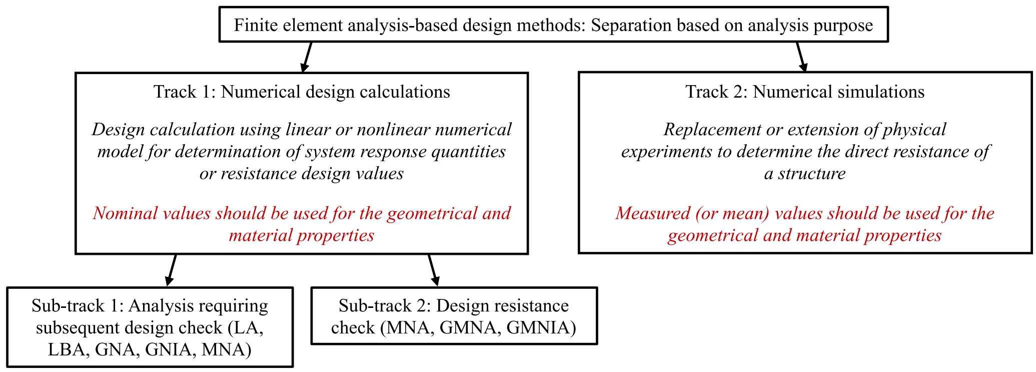


Fig. 2. Overview of the design tracks covered by EN 1993-1-14.

practice; however, the standardisation in EN 1993-1-14 will allow for further uptake of the advanced design options, ensuring all design provisions necessary for application by practicing engineers and research and development (R&D) designers.

The second track, numerical simulations, allows for supplementation of physical experiments and model validation. This option is covered by EN 1993-1-14 to allow for product development and R&D designers to extend experimental datasets through the use of accurate geometrically and materially non-linear numerical models. This is particularly useful for complex scenarios which are challenging to investigate fully with physical tests alone, such as in the case of cold-formed steel sections [12].

Fatigue design and modelling for fatigue assessment is considered slightly outside the previously described schematic separation; however, broadly speaking, fatigue design belongs to the analysis requiring subsequent design checks sub-track of the numerical design calculation track. Several design rules (e.g. meshing rules, validation and verification, mesh sensitivity study, stress concentration evaluation) do not apply for the numerical models if used for fatigue design checks, for which a linear analysis (LA) is performed. Thus, EN 1993-1-14 provides detailed design rules on numerical model-based fatigue design approaches (e.g. the hot-spot stress approach and the notch stress approach), as well as the creation of the numerical model, FE mesh and extrapolation of stresses. All fatigue resistance related design rules are given in EN 1993-1-9 [13], with the two codes fully harmonised.

The design provisions of EN 1993-1-14 do not change the safety level of structures. Thus, the reliability of structures designed by numerical model-based design methods should be the same as that required by EN 1990 [14] and all other EN 1993 parts. The design rules given in EN 1993-1-14 do not change the application manner of the partial factors and do not override or modify the values of the partial factors prescribed by the different EN 1993 parts for different structure types and failure modes. Only for specific cases, if the structural resistance is determined using the direct resistance check sub-track and the modelling uncertainties are not covered another way (e.g. by test-based buckling curves, application of analytical resistance models or performing statistical evaluation), the uncertainties of the numerical model should additionally be considered by a model factor γ_{FE}, as further described in Section 7.2.

Regarding the safety level harmonisation, EN 1993-1-14 also states that the application of finite element analysis-based design should not bring a significant resistance increase compared to well-established traditional design methods, unless shown to be reasonable through validation and verification of the employed finite element model covering all relevant failure modes. Thus, the general safety level required by EN 1990 should be maintained when applying the numerical model-based design. Consequently, significant resistance increases arising from the incorrect application of the numerical model, misinterpretation of the calculation results or black-box effects should be eliminated. If there are large differences (larger than 15–20%) between the utilisation ratio calculated by traditional and advanced numerical model-based design methods, the appropriateness of the numerical model should be proven; this can be done by an accurate verification and validation process. However, EN 1993-1-14 is also intended to support technical development and evolution. Therefore, results of a well-developed, accurate and validated numerical model should be accepted as the correct value, even if they are significantly larger or smaller than the predicted value given by the traditional design methods, provided the required safety level of the EN 1990 is demonstrated.

The rules of EN 1993-1-14 are intended to be independent of the software used. The code gives all necessary requirements for the numerical model, analysis type and design check. However, there are no guidance, limitations, or restrictions on the tools used, or how to develop the correct numerical model and process the design checks. The capabilities of the chosen software should be checked by the designer, and it should be confirmed that the software is applicable for the limit state check being used. The capabilities of the FEA program should correspond with the studied physical phenomena and the limit state criteria. The applicability of the chosen FEA program and the developed numerical model suitable for the task can be demonstrated by verification and validation.

The design rules given in EN 1993-1-14 are not only applicable for finite element analysis (FEA), but also for other numerical tools (e.g. finite strip method (FSM) and generalised beam theory (GBT) [15,16]). However, the limitation of these tools, particularly in terms of the types of analysis that can be performed, and their impact on the numerical model and its results should be checked by the designer. For example, the finite strip method is currently mainly used for the determination of the critical load factor using a linear bifurcation analysis (LBA).

National choice is allowed at a number of places in the code where the design rules affect the safety level of the structure and where different regulatory requirements arose during the development process of the code. Nationally determined parameters (NDPs) give all countries the opportunity to regulate the application and the safety level of numerical model-based design in their own countries via the National Annexes.

5. Modelling and analysis

EN 1993-1-14 provides detailed provisions and rules for the modelling of structural geometry, support and load arrangements, material behaviour, imperfections and the types of analysis to be used. Where appropriate, the standard distinguishes between modelling requirements based on the type of finite element used, i.e. beam, shell, solid, or multi-level and combined models, reflecting the varying levels of detail and capability associated with each. The guidance supports both simplified and advanced modelling strategies, allowing engineers to tailor their approach to the complexity and criticality of the structure under consideration. These modelling provisions are grounded in state-of-the-art research and reflect the most widely adopted modelling approaches in design by FEA. Importantly, the features of the model (e.g. element type, discretisation, imperfections modelled) should be harmonised with the modelling purpose and the limit criteria to be checked.

Key to any numerical model are the modelling input parameters, which govern the accuracy and reliability of the analysis. EN 1993-1-14 includes full range stress-strain curves for hot-rolled steels with a sharply defined yield point [17,18], and hot-rolled steels with a rounded stress-strain curve [18], cold-formed steel [19] and stainless steel [20]. Rules for imperfections are provided in terms of both the shape and magnitude for the direct modelling of geometric imperfections and residual stresses [21–23], or combined equivalent geometric imperfections [24,25]. Different types of analysis may be used depending on the relevant limit state criteria. For each analysis type (increasing in complexity from LA to GMNIA), guidance is provided on the required nonlinearities to be modelled.

6. Verification and validation

EN 1993-1-14 gives a clear definition of the verification and validation process required for design assisted by finite element analysis. Verification and validation should demonstrate that the numerical model is appropriate and fit for purpose.

Verification demonstrates that the numerical solution is a good approximation of the exact mathematical solution and the numerical model is properly implemented, understood and used. Verification should check the model sensitivity to discretisation and demonstrate the appropriate application of the numerical model and analysis. The primary sources of errors to be checked in the verification process are:

a. errors in the input data,
b. computer round-off,
c. inappropriate discretisation (mesh size),
d. inappropriate selection of the chosen finite element,
e. inappropriate loading and supporting conditions,
f. inappropriate imperfections,
g. inappropriate load (time) discretisation,
h. inappropriate solver settings,
i. computer programming errors

Validation is the comparison of the numerical results to experimental data, or known accurate solutions, to demonstrate that the model correctly or conservatively captures the physical phenomena to be modelled. The numerical model should be validated for each phenomenon to be analysed. Two examples of numerical model validation against experimental data are presented in Fig. 3 [26,27].

Verification and validation are generally complex and time-consuming processes and are not always required to be executed fully for each numerical model used in daily design practice. EN 1993-1-14 states that if the numerical model is used for numerical design calculations and direct resistance checks for standard design cases or analysis requiring subsequent design checks, the validation and verification process may be made based on previous experience on similar models. Consequently, if designers are using the same or similar (from a design point of view, e.g. investigating the same failure mode, using similar meshes) numerical models repeatedly, the model validation should be made once at the first application and then the numerical model can be accepted as validated. A new term is also introduced: standard design case. This means a numerical model-based checking of failure modes with an existing Eurocode-based design resistance model. In this case, the designer could have sufficient background for comparison or previous experience on the analysed failure mode and the resistance to be obtained. Therefore, large differences, unexpected mistakes and unreasonably large resistances coming from the numerical model can be discerned and eliminated by the designer. Practically speaking, where mainly numerical design calculations are performed and standard design cases are checked, the validation and verification should be

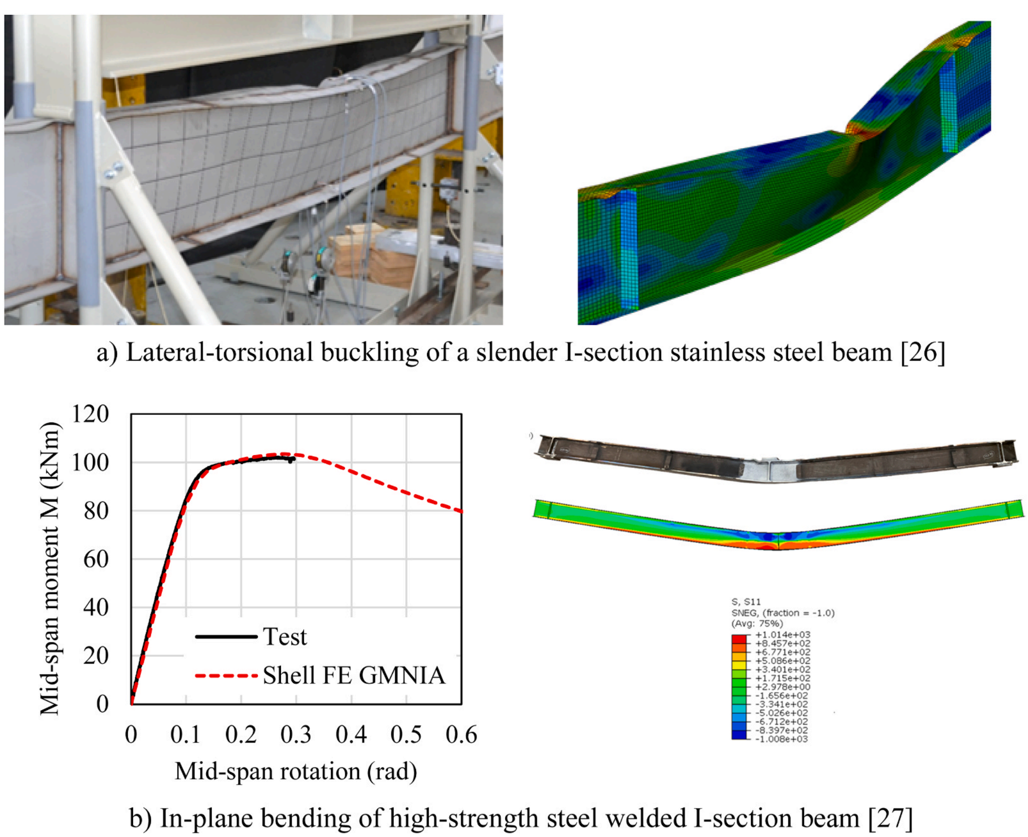


Fig. 3. Example validation comparisons of experimental versus numerical results.

executed for each designer at the time of the first application of their numerical model. If similar problems are solved repeatedly, the verification and validation process need not be repeated to ensure efficient model application and design processes.

7. Design methodology

7.1. General

EN 1993-1-14 contains definitions of the analysis types and the different numerical model-based design methods to determine the characteristic values of resistances calculated by numerical analysis. Design rules are included for the elastic, plastic and buckling resistance design checks of steel structures.

Special attention is given to the harmonisation of the (i) numerical model level, (ii) analysis type, and (iii) applied design methods. As such, it is important to recognise that the design checks vary depending on the limit state criteria. An example of the necessary harmonisation of design rules is in the consideration of stress concentration zones. In the case of numerical design calculations using analysis requiring subsequent design checks, stress concentrations can be neglected in the elastic stress check or in the determination of stresses or internal forces used for further evaluation in elastic or plastic strength checks or in stability checks. However, stress concentrations cannot be neglected if fatigue or fracture limits states are being checked. In advanced numerical models, refinement of the model can result in stress concentrations at the location of joints, connected elements, cross-section changes and/or positions of load introduction and support locations. Stress concentrations are expected in steel structures; however, they only occur in the numerical models if shell or solid element are utilised, and not in beam element models. EN 1993-1-14 gives application rules for the accurate and safe consideration of stress concentration zones.

7.2. Model uncertainty

EN 1993-1-14 states, except where a more advanced method is performed, in which input parameters are treated as stochastic variables, the reliability of the numerical model should additionally be checked by using the model factor γ_{FE}. The model factor covers the uncertainties of the numerical model and the executed analysis type [28]. However, it does not override the application of any other partial factors given in EN 1993 (all parts). Additionally, in the case of fatigue design or if an MNA is applied for the plastic reference load calculation for shell structures, the model factor γ_{FE} should not be applied. The application of the model factor is also linked to the analysis purpose, as summarised in Fig. 4.

If the finite element model is applied for numerical design calculations using an analysis requiring subsequent design checks, the model uncertainty of the structural resistance is covered by the partial factor according to EN 1990 and all parts of EN 1993 and the model factor should not be applied. If the numerical model is applied for numerical design calculations with direct resistance checks, the uncertainty of the design should be evaluated based on a combination of the partial factors according to all parts of EN 1993 and the model factor. Finally, if the numerical model is applied for numerical simulations, and statistical evaluation according to EN 1990 is performed to determine equivalent test-based design resistance (i.e. the required partial factor for use in design is calculated [29]), the model factor should not be applied. The uncertainty of design by numerical simulation is treated in the same way as physical experiments according to EN 1990.

7.3. Evaluation method for analysis with material non-linearity

For design tracks 1–2 and 2 (see Section 4), guidance is given on the determination of the structural resistance R_{comp} (for example equal to R_{GMNIA}, depending on the analysis type) from the non-linear load-deformation path based on two criteria, as shown in Fig. 5. The C1 criterion is based on the maximum load level of the load-deformation path, i.e. a strength criterion, while C2 gives a deformation limit, i.e. a strain criterion, to prevent excessive plastic deformations or, in the case of beam finite elements, to control cross-section resistance.

If the material model does not contain a damage criterion (which is the most standard situation), the C2 criterion is the only limitation on the plastic deformations, and thus its consideration is highly important

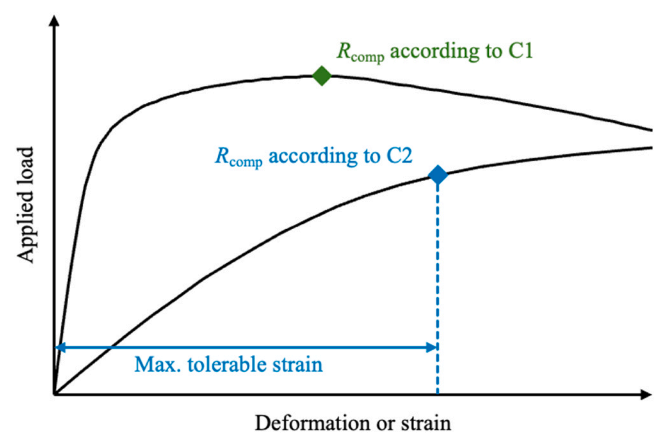


Fig. 5. Determination of structural resistance R_{comp} according to criteria C1 and C2.

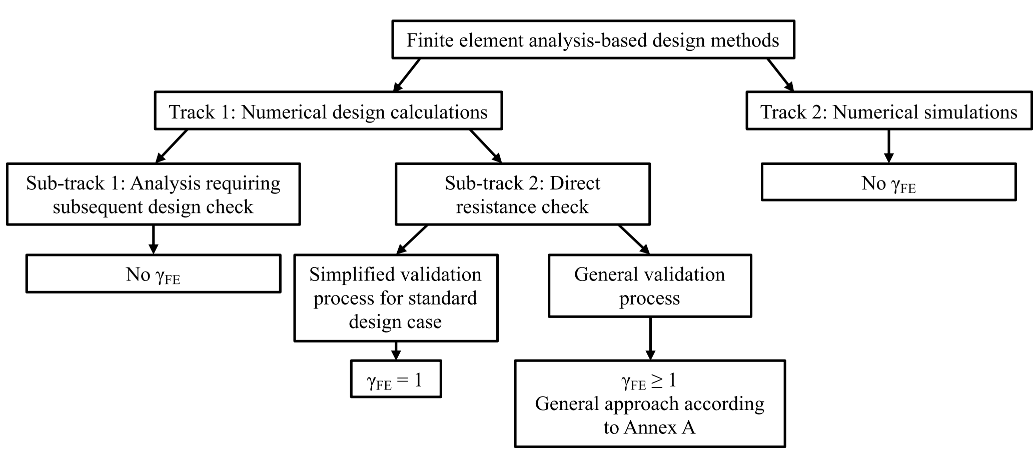
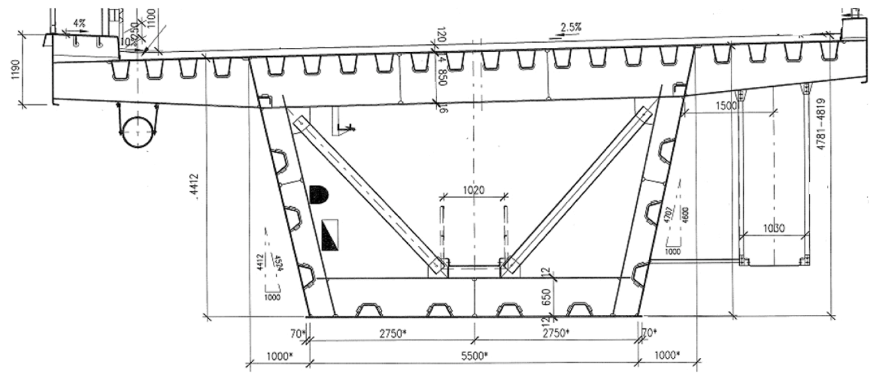
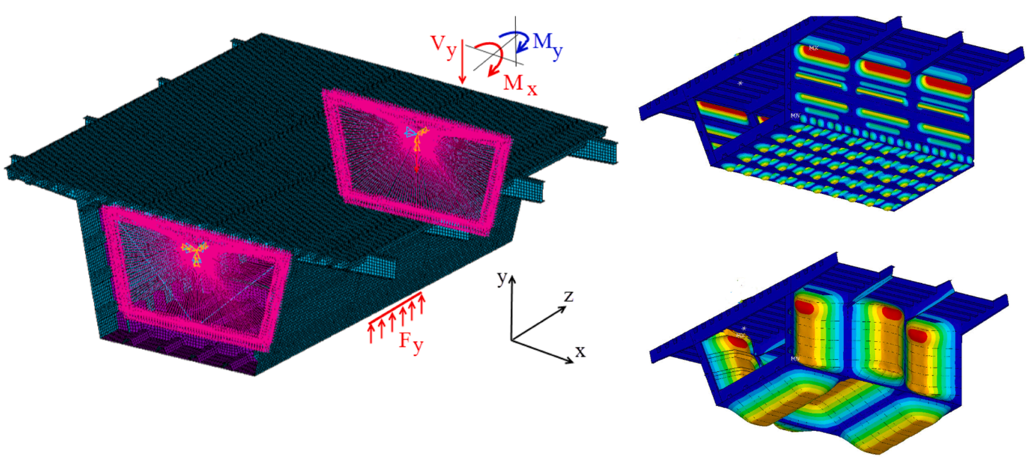


Fig. 4. Application of the model factor γ_{FE}.

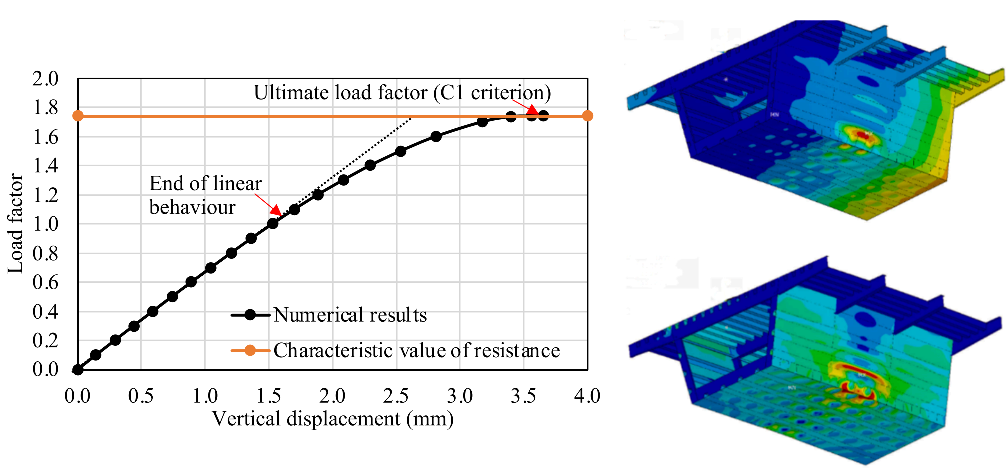
for plastic design. EN 1993-1-14 gives generally applicable strain limits but reference should also be made to other EN 1993 parts for particular cases. Further research is ongoing to give more refined rules e.g. based on damage theory. Additionally, the provisions are only valid for base material, and not for connections which might need more specific requirements; an Ad-Hoc-Group in SC3/WG8 is currently developing such criteria for connections. For frame structures modelled using beam finite elements, maximum strain limits [30,31], defined based on the Continuous Strength Method [32], are set out in Annex C.



a) Full geometric details provided for the design example to allow for full reproducibility (dimensions in mm)



b) Finite element model including boundary conditions, applied loading, and the local and global imperfections introduced.



c) Result evaluation and calculation of design resistance

Fig. 6. Example information provided for Annex E1 Example 1 [11] which presents the application of the direct resistance check method using GMNIA to a complex structural system.

8. Validation and design examples

The Technical Report includes a selection of examples supporting the application of the code rules. There are two types of examples: (i) validation examples and (ii) design examples.

The aim of the validation examples is to give background and support for designers within the validation process. The examples illustrate how a numerical model should be validated for each phenomenon analysed and are thus prepared to cover a range of application fields and failure modes, which can be referred to by designers in practice. The descriptions contain all necessary details of the executed laboratory test and the developed numerical model. Relevant comparisons between the results are presented. These benchmark cases also demonstrate good practice for numerical model development and illustrate the accuracy that can be achieved by a detailed and accurate numerical model. The main output data are provided for comparison purposes. In parallel, a number of the examples [33,34] have also been further developed as part of a special issue of the Data in Brief journal on 'GMNIA Validation in Computational Structural Engineering' [35].

The aim of the design examples is to support designers with the application of the design rules. These design examples cover specific design situations taken from practice and show the correct application of the new code provisions. The examples have been chosen to highlight different aspects of the code, as well as a range of structural design cases. In all cases, sufficient detail has been presented to allow for full reproducibility.

As an example, Fig. 6 illustrates the information provided for Annex E1 Example 1 which presents the application of the direct resistance check method using GMNIA to a complex structural system. In this example, the buckling resistance of a box-section bridge subjected to combined bending, shear and local transverse forces is determined using a numerical model-based design process.

9. Conclusions and ongoing research activities

EN 1993-1-14 introduces the first standardised framework for finite element analysis-based structural design and presents an exciting advance in the context of the second generation of the Eurocodes for facilitating the wider use of finite element analysis in the future design of steel structures. Recognising the novelty in many of the design provisions to the general practicing engineer, a companion Technical Report has been developed in parallel with the code. This background document, with comprehensive descriptions and supporting worked examples, will be crucial in supporting the translation of this design framework into practice.

The publication of this new code represents a turning point for the industry to be able to embrace the latest analysis and design techniques; however, there remains considerable scope for future refinement and expansion. As with the other Eurocode working groups, WG22 has the responsibility of continuing to improve and drive the state-of-the-art development and design provisions of design assisted by finite element analysis. Some of the current research interests of the Committee include:

Rules on imperfections. The correct definition of the shape and magnitude of geometric imperfections is of great importance in the stability design of steel structures. Two research areas of current interest are determining: (1) accurate amplitudes for GMNIA [36,37] and (2) appropriate imperfection combination rules to ensure their suitable introduction at the local [38], member and system levels [36].

Consideration of stress concentration zones. Stress concentrations always exist in steel structures; however, their consideration in design is not comprehensively covered across the design approaches. Therefore, current investigations are focused on the development of general design rules for stress concentration zones considering different failure modes and limit state criteria.

Maximum allowed plastic deformations. For some design scenarios (e.g. connection design), the maximum allowable plastic strain is a key parameter. Advanced material models that incorporate fracture criteria can be applied in the numerical models, or the maximum plastic strains can be checked within the calculation process. Current research activities are ongoing to define accurate values for different material grades and application purposes.

Application method and value of the model factor. The model factor is a newly introduced factor that covers the uncertainties of the numerical model [28]. However, its definition is outside the general determination method for the Eurocode partial factors, where the material and the modelling uncertainties are incorporated into the γ_M value. For the correct determination of the model factor γ_{FE}, the material and the model uncertainties should be separated, and conversion should be made to the new terminology.

Looking ahead, the continued development and application of EN 1993-1-14 and advanced finite element modelling are expected to drive further standardisation in the assessment of existing structures, as well as in emerging fields such as hybrid construction, additively manufactured steel structures [39–41], and the integration of artificial intelligence [42,43] and digital twin technologies.

In conclusion, the development of the new EN 1993-1-14 presents a step change for the future design of steel structures and will support and facilitate the wider use of finite element analysis in practice. With an increased international understanding on the importance and need for efficient material usage in the built environment, this code presents a huge opportunity for enabling more streamlined and efficient structural design.

CRediT authorship contribution statement

Andreas Taras: Writing – review & editing. **Fiona Walport:** Writing – original draft, Visualization, Data curation, Writing – review & editing. **Mohammed Al-Emrani:** Writing – review & editing. **Leroy Gardner:** Conceptualization, Writing – original draft, Writing – review & editing. **Balázs Kövesdi:** Writing – original draft, Visualization, Data curation, Writing – review & editing. **László Dunai:** Writing – original draft, Writing – review & editing, Conceptualization. **Ulrike Kuhlmann:** Writing – review & editing. **Michal Jandera:** Writing – review & editing. **Herve Degée:** Writing – review & editing. **Miquel Casafont:** Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Leroy Gardner is Editor-in-Chief of Structures and Leroy Gardner, László Dunai, Balázs Kövesdi and Fiona Walport are guest editors of the special issue "Advanced FEM-based design of steel structures according to EN 1993–1–14".

Acknowledgements

The authors would like to express special thanks for all the WG22 members who actively supported the development process of EN 1993–1–14 and the Technical Report. Special thanks is also given to all SC3 members, who initiated the work of the AHGFE and later supported the establishment of the new WG22.

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