IMPROVED DESIGN APPROACHES FOR THE LOAD BEARING CAPACITY OF WELDED I-PROFILES FROM HIGH STRENGTH STEEL CONSIDERING REALISTIC RESIDUAL STRESSES

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INTRODUCTION

The present work examines the comparison of recent standards and numerical load capacity calculation considering the effects of residual stresses. Therefore several simplified as well as measured residual stress distributions were used. Comparative analyses for high strength steel have partially shown deviations above 30 %, which underlines the importance of providing more realistic approaches for the future. In an ongoing research project different practical approaches are being developed using experimental and numerical parameter studies on welded I-profiles from S355J2+N and S690QL.

1 STATE OF ART

1.1 Load Capacity Calculation

For the prediction of load capacity the state after manufacture and assembly of the member has to be taken into account. The quality of results mainly depends on the assumptions made for the consideration of imperfections. In terms of welding process those are residual stresses and distortions. In practise, residual stresses are usually considered by definition of fictitious additional deformations. Its magnitude relates to the relevant buckling curve, which differs with respect to cross section, manufacturing process and failure mode. For several cases additional distinction was made dependent on the material grade. Yet especially for welded sections the consideration of the latter seems inappropriate, because the same values apply for all standardized material grades. The lack of an appropriate approach for welded sections leads to uneconomic results, especially as high strength steel is used. Currently an increased use of high strength fine-grained steels can be noted; the reduction in thickness and weight leads to significantly reduced manufacturing and welding costs [1].

The definition of equivalent imperfections mixes the effects from geometric and structural imperfections. Assumptions for the consideration of the residual stress state and its influence in terms of load capacity remain unknown for most engineers. Nevertheless, modern software codes allow separate consideration of various effects, and thus more realistic assessment of the structural behaviour. The flowchart shown in Fig.1 summarizes the most important aspects for the performance of such analysis.

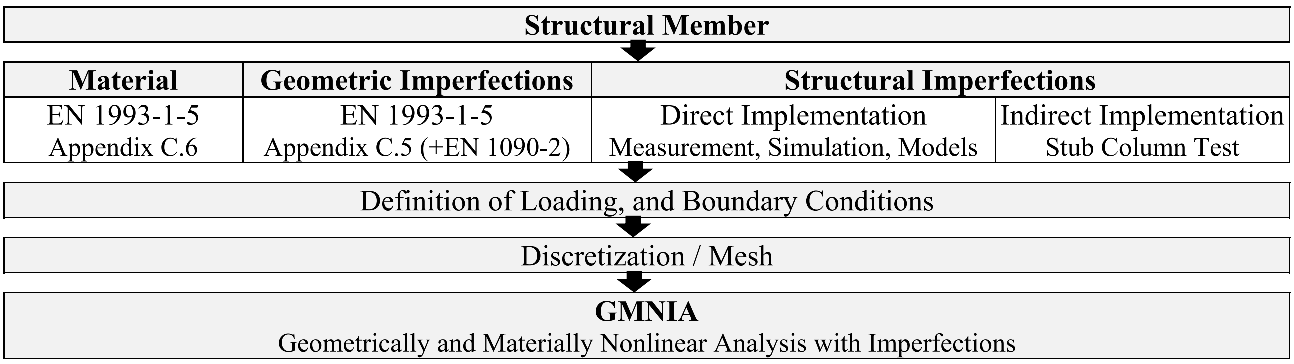


Fig. 1: Steps for Nonlinear Analysis

1.2 Residual Stress Field

Residual stresses are mainly caused by the welding process. Its magnitude varies systematically due to the applied manufacturing and boundary conditions as well as dependent on the material grade. Partly variation is also randomly, since particular conditions may vary for each case. However, only few approaches are available. Usually highly simplified approaches as displayed in Fig.2 are used. Their distribution is assumed to be trapezoidal, whilst boundaries are determined as function of geometry parameters. For both models the magnitude of tension residual stresses is expected to reach the yield strength, which applies for most normal strength steels. According to the approach, the width of tension zone may vary to a certain extent. The magnitude of compression residual stresses results from equilibrium conditions. For previous studies it could be noticed that the approach provided by [3] usually leads to better results [4].

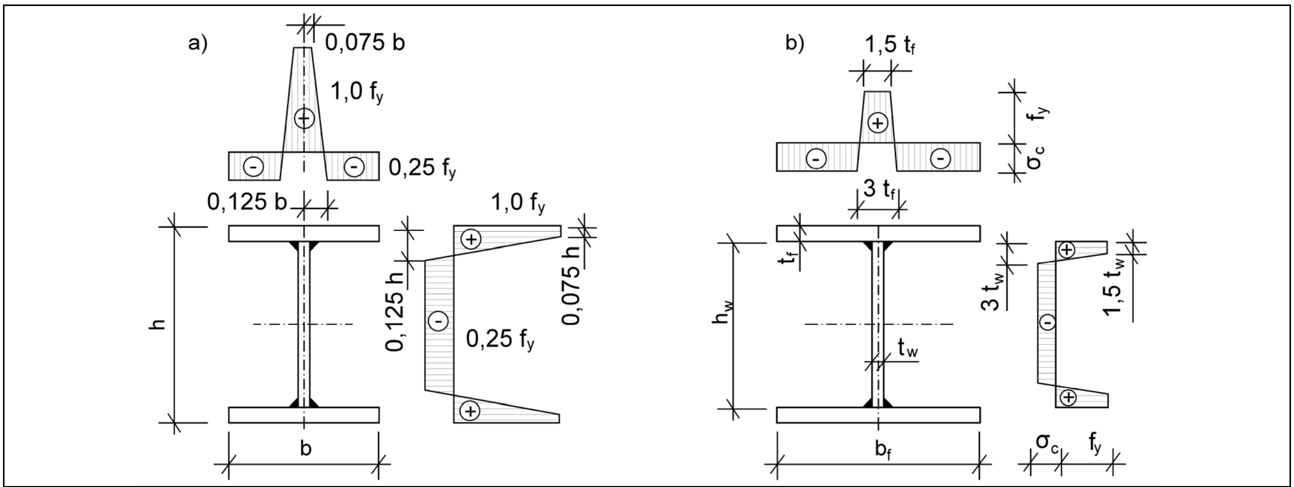


Fig. 2: Simplified Residual Stress Distribution by a) [2] and b) [3]

In practise values may differ significantly dependent on the particular manufacturing and boundary conditions, such as heat input, fixing or welding sequence [5]. Because the field of application stays unknown for both models, their accuracy may differ from sufficient to inappropriate. In general deviations will increase with the material grade assuming that other parameters stay unchanged. The reason is related to the complex interaction of phenomena responsible for the formation of residual stresses. Generally shrinkage and transformation stresses are distinguished. The former develops during the cooling process due to locally restrained shrinkage. Unless no further stress components act, their magnitude usually equals the yield stress of the material. It can be noticed, that the width of tension zone usually decreases with an increase in yield strength [6]. Transformation stress occurs, if areas within the heat affected zone are subjected to phase transformations during cooling. The transformation from austenite to ferrite/pearlite, bainite or martensite is coupled with an increase in volume; as a result compressive stresses are built up in the respective area. Depending on the temperature range for transformation as well as the yield strength at elevated temperatures, different interaction with shrinkage stresses is noticed [7].

The transformation from austenite to ferrite/perlite takes place at high temperatures. As the yield strength remains low at this temperature level, resultant stresses are comparatively small. After complete cooling the stress magnitude will reach the yield strength; no significant influence from phase transformations can be noted. In contrast, the transformation from austenite to bainite and/or martensite is initiated at a much lower temperature level. Therefore the formation of stresses from phase transformation will have noticeable effect on the final stress state. The extent depends on several factors such as heat control and the material grade. Especially for high strength steels effects of phase transformation are elementary for realistic approximation of the residual stress state [7]. The neglect of manufacturing and material influence during welding leads to wrong approximation of the residual stress state; often width and magnitude of the tension zone are overestimated. At the same time the level of compressive stress is increased, which may have considerable influence on the load capacity.

According to experimental investigations published in [8], the magnitude of residual compressive stress for high strength steel varies between 0.10...0.20·f_y. For normal strength steel usually a value of 0.20...0.30·f_y applies. Furthermore it was noticed, that stresses introduced by previous production steps such as cutting influence the formation of the final stress state after welding. In construction industry the major part of cutting is realized by flame or plasma cutting. The cut results in local tension stresses, comparable with those around the weld center. The superposition with welding stresses leads to a reduction or reversal of residual compressive stresses at the flange edges, which may have positive influence depending on the failure mode.

2 NONLINEAR ANALYSIS CONSIDERING RESIDUAL STRESSES

2.1 Approach for Residual Stress Field

By the use of simplified models the actual load capacity is often underestimated, in particular for high strength steels. To illustrate the potential coupled with the implementation of more realistic distributions, several finite element calculations based on measurements, simplified models and recent standards have been carried out. The experimental part refers to a compilation of measurements presented in [8]. Fig.3 shows two representative measurements taken for high strength steel S690. For further calculation steps the stress field was approximated by trapezoidal distribution, as the level of compressive stress remains nearly constant. Considerable variation through the thickness is only noted for the tension zone around the weld, and is therefore neglected. Further distinction is made for specimens with and without stress relief heat treatment prior to assembly. In case of untreated specimens an additional block at the each edge was defined. For comparison distributions are superposed in Fig.3.

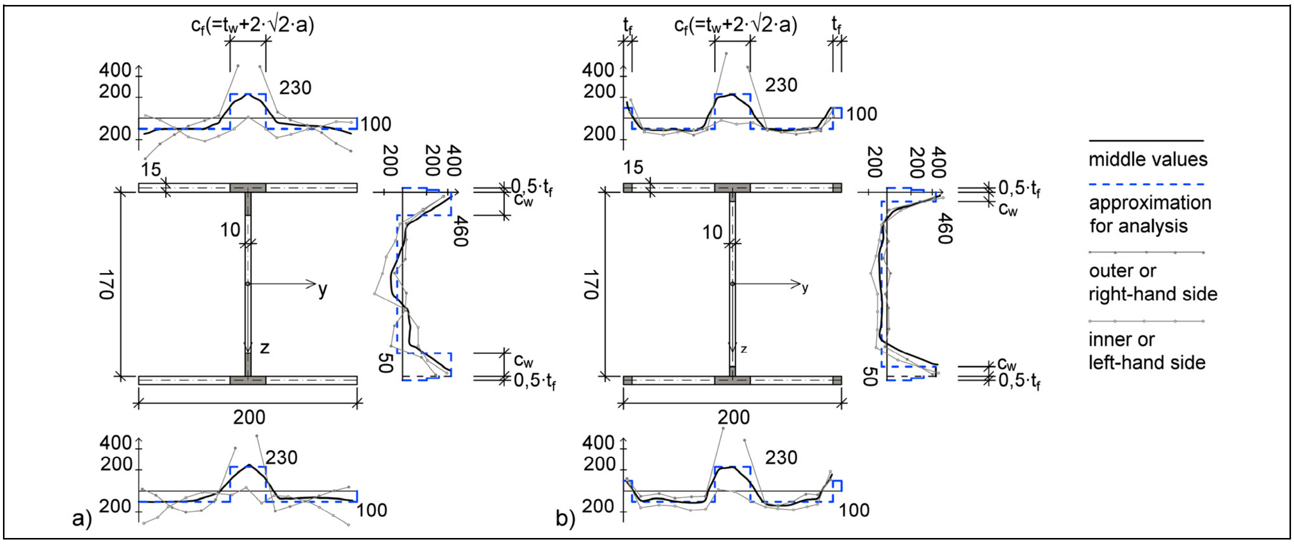
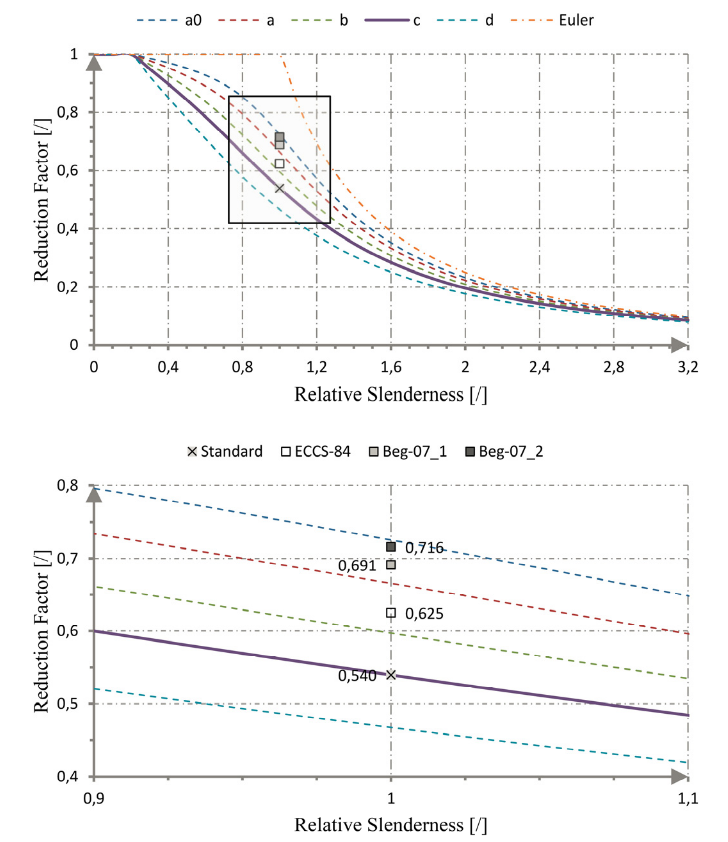


Fig. 3: Residual Stress Profile for St E 690 (EN: S690Q), from [8]; a) with and b) without Stress Relief Treatment prior to Welding

2.2 Numerical Model

A geometrically and physically nonlinear analysis is most suitable for describing the actual load bearing behaviour. The failure mode examined shall be flexural buckling of a simply supported beam under pure compression. The section geometry refers to the specimens presented in 2.1, cross section class is 2. The geometric imperfection is included using the shape of the relevant eigenmode obtained from a previously run buckling analysis. The scale factor equals 80% of the permitted geometric tolerance given by DIN EN 1090-2. Usually a center distance of L/1000 (=0.8·L/750) is applied. The material behaviour is simplified using bilinear ideal elastic-ideal plastic stress-strain curve. To avoid numerical problems pseudo-hardening with a slope of E/10000 is used for the plastic range. The residual stress field is considered as initial stress state. For comparative purpose, calculations are carried out both using simplified approach and experimental approximation. All calculations were done using commercial finite element software (Abaqus, V.11-3).

In order to evaluate results, load capacity is referred in terms of the reduction factor ($\chi = N_R/N_{Pl}$). The relative slenderness was chosen as $\bar{\lambda} = 1.0$ for all calculations, which equals typical conditions for slenderness. Previous studies have shown that effects from the residual stress state have particularly large influence in the medium slenderness range. The evaluation of results is shown in Fig.4.



Approach	χ [/]	[%]
Standard, EN 1993-1-1, curve c	0,540	100,0
Simplified Approach, due to [2]	0,625	115,7
Measurement, due to [8], with treatment	0,691	128,0
Measurement, due to [8], untreated	0,716	132,6

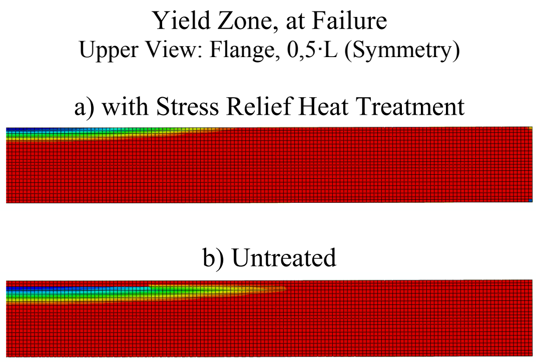


Fig. 4: Evaluation of Results (GMNIA), left side: Flexural Buckling (z-z), right side: Table, Yield Zone

Especially as high strength steel is being used, the implementation of the simplified distribution leads to considerable deviations in terms of load capacity. For the examined failure mode values differ by about 15 %. Similar trend can be noted for buckling about the strong axis. For the untreated specimens including the effect of flame cutting additional increase in load capacity can be seen (> 5 %). This can be explained by different yield zone patterns at the state of failure. Related to the relevant buckling curve stated by the standard deviations exceed 30 %. For normal strength steels deviations usually remain below 10%, assuming that the simplified distribution matches the actual stress state.

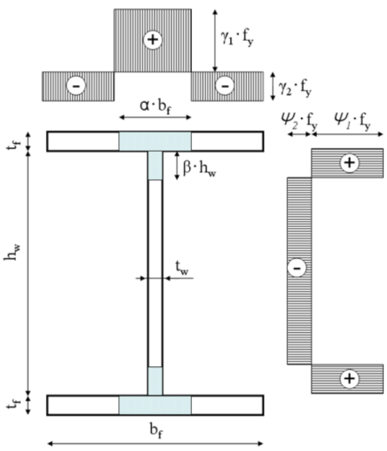
To improve the quality of results, models considering relevant manufacturing and boundary conditions have to be provided. Further distinction is necessary in particular for the material grade, as shown in the paper. However, at the same time models should stay practicable. Although experimental and numerical methods for the development of such models are available, yet systematic study was not carried out.

3 DEVELOPMENT OF REALISTIC APPROACHES CONSIDERING EFFECTS FROM WELDING

For calculations of complex structures practical models should be applied. Using the models described in 1.2 manufacturing and boundary conditions as well as characteristics related to the material grade cannot be taken into account. Usually this leads to an underestimation of load capacity, which in particular shows for high strength steels. Furthermore it is assumed that members are free from residual stresses at the state of welding. As shown in 2.1 previous production steps such as cutting may affect the final stress state.

It is the intention of the authors to develop several realistic as well as practicable models for the prediction of welding imperfections, in particular the residual stress state. This allows users more accurate calculation of load capacity, as far as nonlinear finite element analysis is applied. At the same time the basis for the adjustment of recently valid standards is given. Especially in case of welded sections existing specifications seem inappropriate.
Alternate and more realistic models basically exist. However, their applicability to real components is doubted, because experiences are mainly limited to small specimens. The variety of models and its modifications lead to a state of confusion, which is why models still remain unknown to the building sector. A proposal for different approaches is given in Fig.5.

Empirical

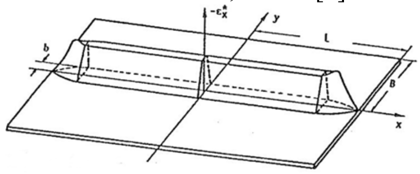


b_f x t_f x h_w x t_w						
Steel grade	α	β	γ_1	γ_2	ψ_1	ψ_2
S235	x	x	x	x	x	x
S275	x	x	x	x	x	x
S355	x	x	x	x	x	x
S420	x	x	x	x	x	x
S460	x	x	x	x	x	x
S690	x	x	x	x	x	x

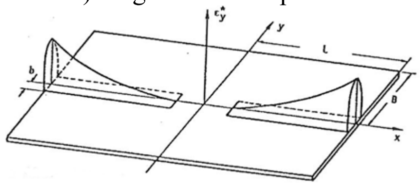
Factors (α, β, γ_1, γ_2, ψ_1, ψ_2)

Mechanical (Inherent Strain Method)

Inherent Strain, due to [9]:



a) longitudinal component

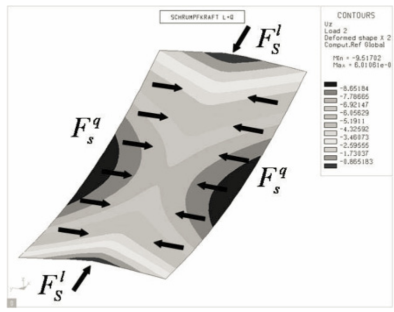


b) transverse component

Definition of Inherent Strain in Finite Element Model

$$\varepsilon^* = \sum \varepsilon - \varepsilon^{elastic}$$

Problem:
Distribution of Inherent Strain?



Example for Calculation of Distortion, from [10]

Equivalent Load
(Shrinkage Force)

$$f = \int E \cdot \varepsilon^* dA$$

Calculation by (Semi)Analytical Procedue

Inherent Strain
(Modification of Strain Distribution)

Fig. 5: Proposal for the Prediction of Welding Imperfections, Residual Stress State (and Distortions)

For practical calculations or fast evaluations empirical models may be favourable, as shown on principle in Fig.5. Therefore the authors propose the definition of factors, related to the shape and magnitude of the residual stress distribution. The development and calibration of such values can be realized by systematic experimental and numerical calculations. The calculation of factors controls the complexity of the model, and hence can be variable. The magnitude of each factor is a function of manufacturing and boundary conditions, such as heat control, fixing of plates, welding sequence and geometric parameters.
The principle of the second approach shown in Fig.5 is based on the Inherent Strain Method, introduced by [9]. Inherent strain is considered as plastic strain remaining after the welding heat cycle. In general, six components may be considered, however in practise only two components (ε_x, ε_y) are relevant. One is ε_x, which causes longitudinal shrinkage and bending. The other is ε_y, which causes transverse shrinkage and angular distortion. For load capacity analysis and the superposition with longitudinal stresses only ε_x may have influence. Their distribution is shown in principle in Fig.5. By integration of the inherent strain equivalent forces can be calculated. Their introduction to the model is comparable with the prestressing of tendons. Because its formation is based on the longitudinal and transverse shrinkage during cooling, this is often referred as shrinkage force. It

should be mentioned that the shrinkage force is an imaginary force; its application to the model is appropriate as far as only distortion may be calculated. For the calculation of the residual stress field inherent strain has to be applied directly to the structure. Nowadays most commercial software codes allow the definition of initial strain as input parameter. Alternate implementation may be realized by definition of fictitious temperature state.
The accuracy of results is dependent on the approach used for the approximation of size and distribution of inherent strain. The difficulty is the prediction of such values, which can only be checked by experimental and/or numerical investigations. An alternate (semi)analytical-numerical approach is provided by [10]. For the calculation of the longitudinal shrinkage force the following equation is given:

$$F_x = \left(0{,}335 \cdot q_s \cdot \frac{\alpha}{\rho \cdot c} \cdot E\right) \cdot K_{\text{mod}} \quad (1)$$

where F_x [N], q_s [J/mm], α [1/K], ρ [g/mm³], c [J/(g·K)], E [N/mm²], K_{mod} [/], see [10]

For practical calculations, in particular related to civil engineering, those models are mainly unknown. In addition only few comparisons for the residual stress state are available. Especially for high strength steels results may be inappropriate, since phase transformations can have considerable effect on the residual stress state. In the ongoing project the application and calibration of such models is carried out.

4 ACKNOWLEDGMENT

The authors would like to thank the German Federation of Industrial Research Associations (AiF) for its financial support on the research project IGF-Nr. 18104 BG. This project is carried out under the auspices of AiF and financed within the budget of the Federal Ministry of Economics and Technology (BMWi) as part of the program to support Industrial Community Research and Development (IGF).

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KEYWORDS: Nonlinear Analysis, Residual Stress State, High Strength Steel, Design Approach

ABSTRACT

The present work examines the effects of the residual stress distribution on the load capacity of welded sections, especially for high strength steel. Currently an increased use of high strength fine-grained steels can be noted; the reduction in thickness and weight leads to significantly reduced manufacturing and welding costs [1].
Usually highly simplified approaches are used [2]. Especially for high strength steels effects of phase transformation are elementary for realistic approximation of the residual stress state [3]. The neglect of manufacturing and material influence during welding leads to wrong approximation of the residual stress state; often width and magnitude of the tension zone are overestimated. At the same time the level of compressive stress is increased. In addition, previous productions steps such as cutting may have influence on the stress state after welding [4].
By the use of simplified models the actual load capacity is often underestimated, in particular for high strength steels. As an example, several finite element calculations based on measurements, simplified models and recent standards have been carried out. Fig.1 shows representative measurements for structural steel S690 from [4] and their approximation. The evaluation of results is shown exemplary for flexural buckling in Fig.2. In comparison to the relevant buckling curve deviations partially exceed 30 %.
To improve the quality of results, models considering relevant manufacturing and boundary conditions have to be provided. Further distinction is necessary in particular for the material grade. Although experimental and numerical methods for the development of such models are available, yet systematic study was not carried out.

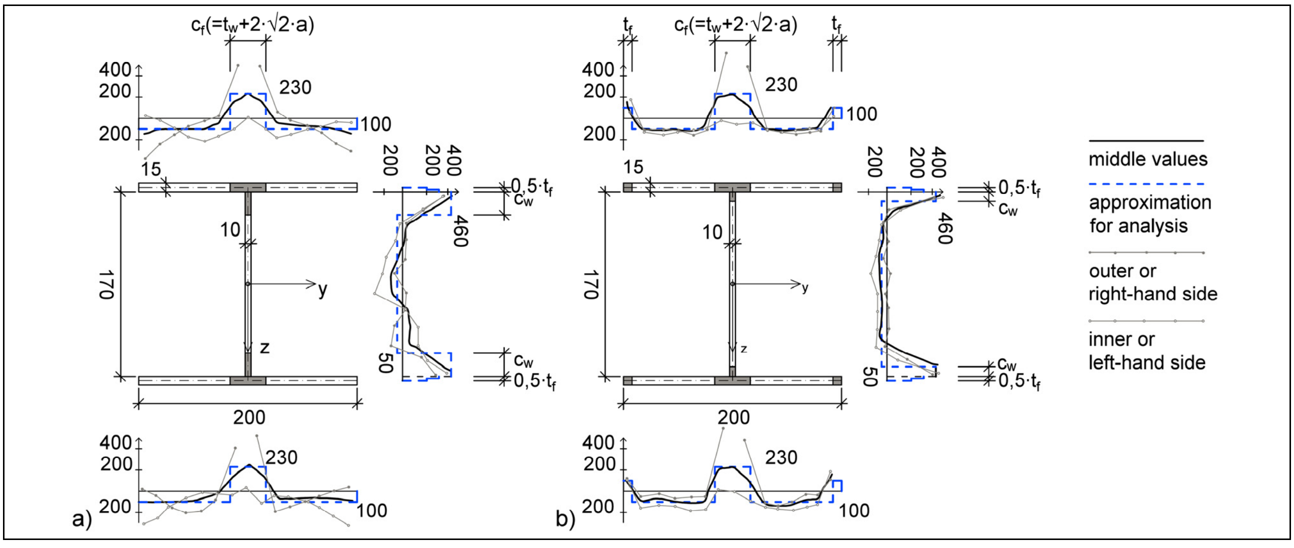
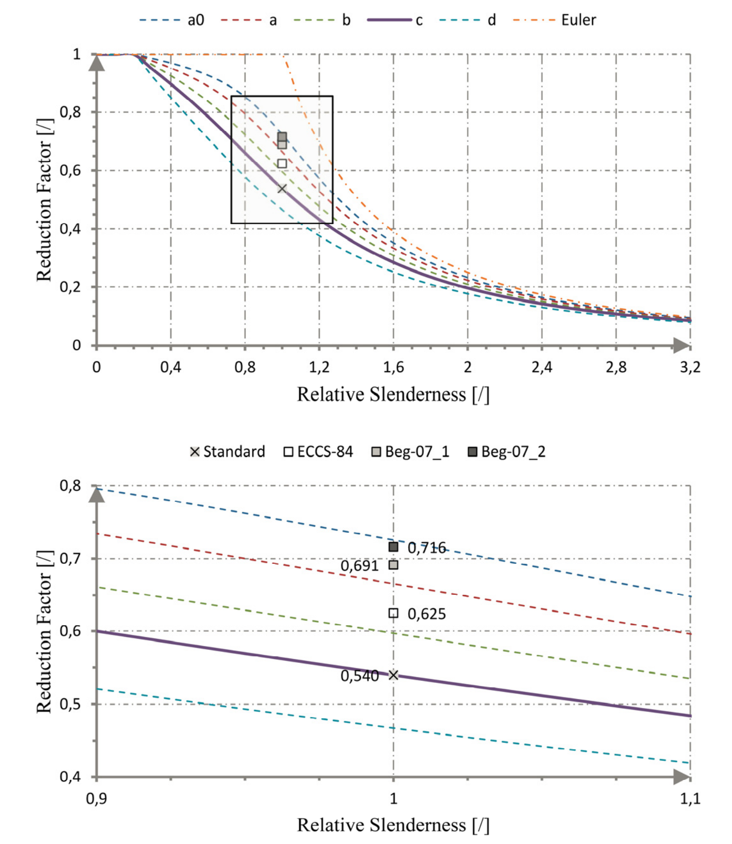


Fig. 1: Residual Stress Profile for St E 690 (EN: S690Q), from [4]; a) with and b) without Stress Relief Treatment prior to Welding



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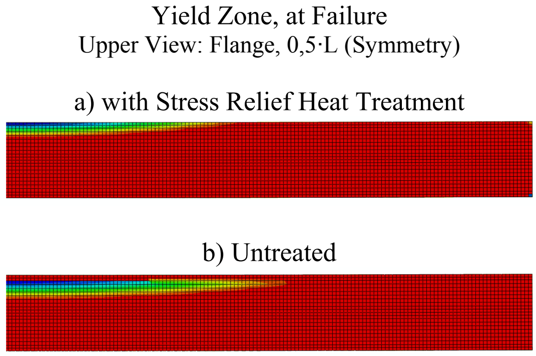

Fig. 2: Evaluation of Results (GMNIA), left side: Flexural Buckling (z-z), right side: Table, Yield Zone

CONCLUSIONS

It is the intention of the authors to develop several realistic as well as practicable models for the prediction of welding imperfections, in particular the residual stress state. This allows users more accurate calculation of load capacity, as far as nonlinear finite element analysis is applied. At the same time the basis for the adjustment of recently valid standards is given. Especially in case of welded sections existing specifications seem inappropriate.

Alternate models basically exist. However, only few comparisons for the residual stress state are available. In terms of high strength steels results may be inappropriate, since phase transformations can have considerable effect on the residual stress state. In the ongoing project the application and calibration of such models is carried out.

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