# Determination of the load bearing capacity of thin gauged cold-formed sections with consideration of imperfections due to the production process

Albrecht Gehring, Helmut Saal

Versuchsanstalt für Stahl, Holz und Steine, Universität Karlsruhe (TH),

Karlsruhe, Deutschland

**Summary:**

The load bearing capacity of thin gauged cold-formed sections strongly depends on deviations from the nominal dimensions and the material properties. The former reduce the load bearing capacity. The latter enhance the load bearing capacity, because of work hardening during the manufacturing process. It is difficult to realistically account for both effects in a finite-element analysis of the load bearing capacity of thin gauged sections. Today, cost intensive testing is necessary, if a maximum utilization of the load bearing capacity is desired.
The properties of a product can be determined during the product development process with a new simulation strategy, which covers the production process as well as the state of servicabilty of a product. The roll forming process is simulated first. This is followed by a non-linear ultimate limit state analysis. The combination of both analysis steps gives the possibility to determine the load bearing capacity realistically as deviations from the nominal value of dimensions and material properties are included in the analysis. The new analysis strategy is demonstrated for a C-section. It is shown, that the new strategy leads to a realistic estimation of the load bearing capacity of thin gauged sections.

**Keywords:** Load bearing capacity, Imperfections, Cold-formed sections, Finite-element analysis, Product development

# 1 INTRODUCTION

The application of cold-formed sections in buildings is well established. The resistance of thin gauged sections can be determined with calculations based on the effective width approach according to international design codes, e.g. prEN 1993-1-3 [1]. The application of the design codes leads to conservative resistance values. The full benefit of the cross-sectional resistance can be achieved only by cost intensive experimental investigations, e.g. according to the guidelines given in prEN 1993-1-3 [1]. In this case a specific technical approval issued by the building authorities is required for the application in building.
Cold-formed sections are produced by roll forming and press braking. They compete with other building products, e.g. hot-rolled steel profiles, extruded aluminium profiles, structural timber members or composite components. The competitiveness of cold-formed sections can be improved on the one hand with new developments and improvements in tooling design [2] and on the other hand by an optimisation of the cross-section with regard to its resistance. The latter can be done by taking advantage of hidden resources of the product. A procedure to quantify these resources is presented in this paper. Thus, the effect of variations of product properties, e.g. material specification or geometry, on the performance in use can be quantified realistically.

# 2 ANALYSIS STRATEGY

## 2.1 State of art

In prEN 1993-1-5 [3], Annex C a guidance is given for the use of finite-element analysis for ultimate limit state verification for application in buildings, which includes appropriate assumptions for material models and imperfections. In the following, an analysis according to the guidance in prEN 1993-1-5 [3], Annex C is called conventional analysis strategy. A non-linear finite-element analysis is necessary for the determination of the ultimate limit state of thin gauged sections. Where the non-linearity takes into account geometric deviations as well as material aspects. The imperfections can be introduced by applying equivalent geometric imperfections defined in design codes, which are scaled eigenmodes obtained from buckling analysis. Usually the material properties are assumed to be distributed uniformly, which leads to a safe estimation of the failure loads. General considerations on the characterisation of imperfections in numerical analyses are given in [4]. Some researchers [5], [6] introduce an enhanced yield strength due to cold-working by partitioning a cross-section. However, the problem is the lack of knowledge about the initial state of cold-formed sections [4]. The effect of changes of product properties on the load bearing capacity of a cross-section can therefore only be determined qualitatively. Often the desired improvements in product performance are not arising in reality.

## 2.2 Advanced analysis strategy

The advanced strategy is divided into the following steps:

- Analysis of the manufacturing process
- Introduction of imperfections and change of material properties obtained by the analysis of the manufacturing process as initial state to the new model
- Non-linear ultimate limit state analysis
- Verification of results

This analysis strategy is important in product development as it gives possibilities for improvements in the manufacturing process as well as in product performance. This helps to minimize costs caused by necessary modifications during product development. Also, the strategy can be used as virtual test for achieving a technical approval [7] for building application. Thus, the amount of testing can be minimized as only some verification tests are necessary.
The advanced analysis strategy is demonstrated by the determination of the load bearing capacity of a C-section subjected to uniform compression load. Some general aspects of the strategy are shown with the example.

# 3 EXAMPLE

## 3.1 Advanced analysis strategy

The roll forming process of a C-section 10 / 35 / 100 / 35 / 10 x 1 is simulated. The applied inner bending radius is 4 mm. The C-section is obtained in 9 steps. First the edge stiffener of the C-section is formed with 4 roll stands in steps 20°/40°/60°/90°. Then the web is folded with 5 roll stands in steps

15°/35°/55°/75°/90°. All roll stands for the stiffener and the roll stands of the steps 15° and 35° are built with two tools. An additional side tool is applied in the roll stands of steps 55°, 75° and 90° respectively, see Figure 1. The inter-pass distance is set to 500 mm.
The forming process can be regarded as a quasi-static dynamic process. Thus an explicit solver is applicable. The explicit solver is advantageous for an analysis, where contact is involved [8]. The software package Abaqus [9] is used for the analysis. Due to symmetry one half of the system is modeled. The forming tools are represented as rigid bodies in the analysis. The sheet is meshed with the 4 node shell element S4R. In the bending area 7 integration points through thickness are used. In the other areas 5 integration points through thickness are used. An element size of 3.0 x 3.0 mm is adopted in the flange and in the web. The bending area is meshed with elements of size 1.5 x 3.0 mm. Fixed boundary conditions are applied to the forming tools, as friction is neglected. The ends of the sheet are constrained in rolling direction to simulate an endless sheet. Roll forming is done with a constant forming speed of 30 m/min. The analyses are executed parallel with the domain-level method. All analyses jobs are run on 8 cpus on the HP XC 6000 cluster [10]. The parallel performance has a speedup factor of approximately 5.5.

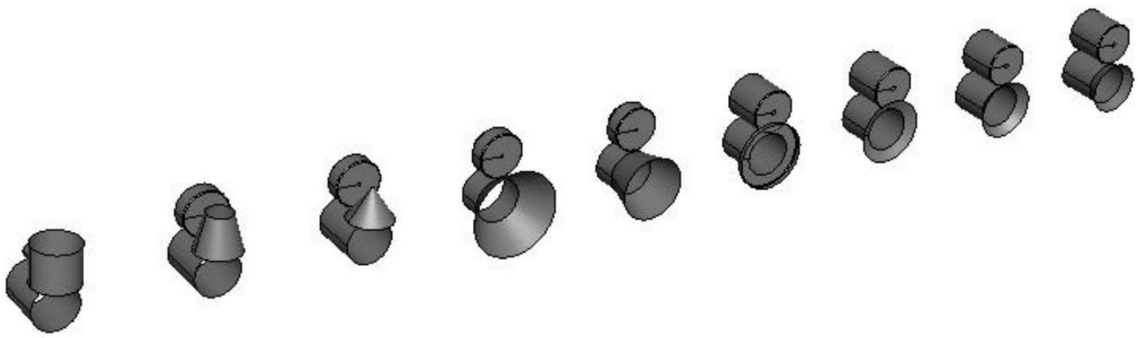


Fig. 1. Model of roll former with 9 roll stands (only half model due to symmetry)

A Young's Modulus of E = 210 GPa and a Poisson's ratio of $\nu$ = 0.3 define the elastic response in the analysis. The yield strength is $f_y$ = 320 MPa, the tensile strength is $f_u$ = 390 MPa and the uniform elongation is $\varepsilon_u$ = 0.12. These values comply with steel grade S320 according to EN 10326 [11]. The strain hardening behaviour is described by the modified Ludwik-Hollomon equation, which is usually applied in forming analysis. In this equation

$$\sigma_y(\varepsilon_p) = f_u \cdot \left(\frac{e}{n}\right)^n \cdot \varepsilon_p^n \qquad (1)$$

$\sigma_y$ is the true yield stress, n is a constant $\varepsilon_p$ is the true plastic strains and e is the Euler number. Equation 1 leads to a good estimation of the flow curve for low alloy steel and aluminium alloys [12], if the exponent n is related to the uniform elongation $\varepsilon_u$ in terms of

$$n = \ln(1 + \varepsilon_u) \qquad (2)$$

The second step of the analysis is to transfer the results of the preceding analysis as initial state into the new model. In this step the out-of-balance forces of the explicit analysis are removed and static equilibrium is achieved. This accounts for springback effects. Thus dimensional deviations and cold-working effects due to roll forming are considered in the initial state.
The failure load is calculated in the last step of the analysis. For this, the profile is divided into 6 specimen with a length of 250 mm each. This value is less than 20 times the radius of gyration and thus agrees with the length of stub column specimen recommended in prEN 1993-1-3 [1]. The virtual stub column tests are performed with the 4 specimen from the middle part of the profile. New boundary conditions are applied to the model. At one end of the sections all translation degrees of freedom are fixed and at the other end the out-of plane degrees of freedom are fixed. The sections are subjected to constant translation in longitudinal direction.

### 3.2 Conventional analysis strategy

For comparison, the ultimate limit state of the C-section is determined with the conventional analysis strategy. The eigenmode which corresponds to the lowest eigenvalue is used as imperfection. The amplitude of the eigenmode is scaled to a value of b/200 which complies with the value recommended in prEN 1993-1-5 [3], Annex C. The material properties are the same as defined above. These are assumed to be constant across the cross-section. The boundary conditions are defined as in the last step of the advanced analysis.

### 3.3 Evaluation procedure

The effective cross-sectional area $A_{eff}$ of the C-section is calculated in accordance with provisions given in prEN 1993-1-3 [1]. The characteristic resistance $N_{c,EC3}$ of the cross-section for uniform compression according to prEN 1993-1-3 [1] is

$$N_{c,EC3} = A_{eff} \cdot f_y \tag{3}$$

The failure load $N_u$ obtained from the finite-element analysis is calculated to

$$N_u = \sum_{i=1}^{k} n_{1,i} \tag{4}$$

where $n_{1,i}$ is the reaction force of the i-th node in loading direction and k is the number of nodes across the section.
In addition, the average yield strength $f_{ya}$ is determined from the results of the advanced analyses. Plastic flow occurs according to the von Mises criterion, if the equivalent yield stress attains the defined reference yield stress value. The size of the yield surface changes with the equivalent plastic strain $\varepsilon_{eppq}$. From this follows, that the yield stress $f_{y,fem}$ at any point of the profile can be expressed as

$$f_{y,fem}(\varepsilon_{eppq}) = f_u \cdot \left(\frac{e}{n}\right)^n \cdot \varepsilon_{eppq}^n \tag{5}$$

where the hardening behaviour according to Equation 1 is assumed. Then the average yield stress $f_{ya}$ becomes

$$f_{ya} = \frac{1}{l} \cdot \int_0^l f_{y,fem}(\varepsilon_{eppq})\, dl \tag{6}$$

where l is the developed length of the cross-section.
The variation of material properties and geometric imperfections due to the forming process (see Figure 4 and Figure 5) is taken into account in the determination of the load bearing capacity of the 4 individual specimen.

### 3.4 Results

The initial deformed shape for the conventional analysis and from the advanced analysis is shown in Figure 2. The deformed shape obtained from the advanced analysis exhibits typical geometric defects of roll formed sections, like the flare at the ends of the profile.
There are big differences between the initial deformed shapes. This is due to the discrepancies between the shape of the eigenmode and the measured geometric imperfections [13], which are usually not distributed periodically. The geometric imperfections obtained from the advanced analyses are shown in Figure 3, where the values are taken from a path along the arrows in Figure 2 respectively. The numbers in Figure 3 are referring to the specimen number for the virtual stub column tests. The maximum value of the geometric imperfection of the flange is approximately 0.4 mm and of the web approximately 0.5 mm. These values agree quantitatively with measured values of similar sections [13], [14].

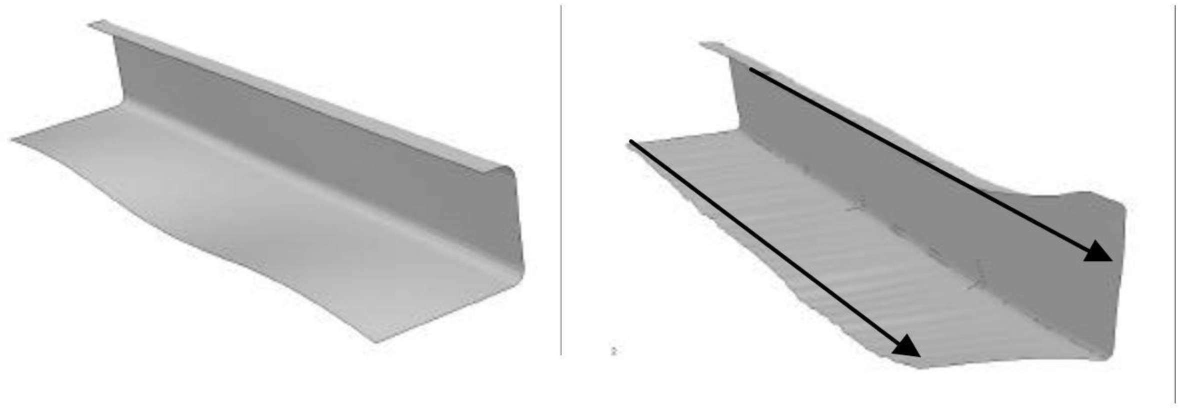


Fig. 2. Initial deformed shape from conventional analysis - length of specimen 250 mm (left), deformed shape from advanced analysis - total length of specimen 1500 mm (4 stub columns with 250 mm length plus 250 mm at each end of profile) (right) - scale factor 5

Also residual stresses and cold-working effects due to roll forming are considered in the initial state. The distribution of the yield stress after roll forming is shown in Figure 4. The distribution obtained from the advanced analyses agrees with the hardness distribution determined experimentally at similar C-sections, see Figure 4.

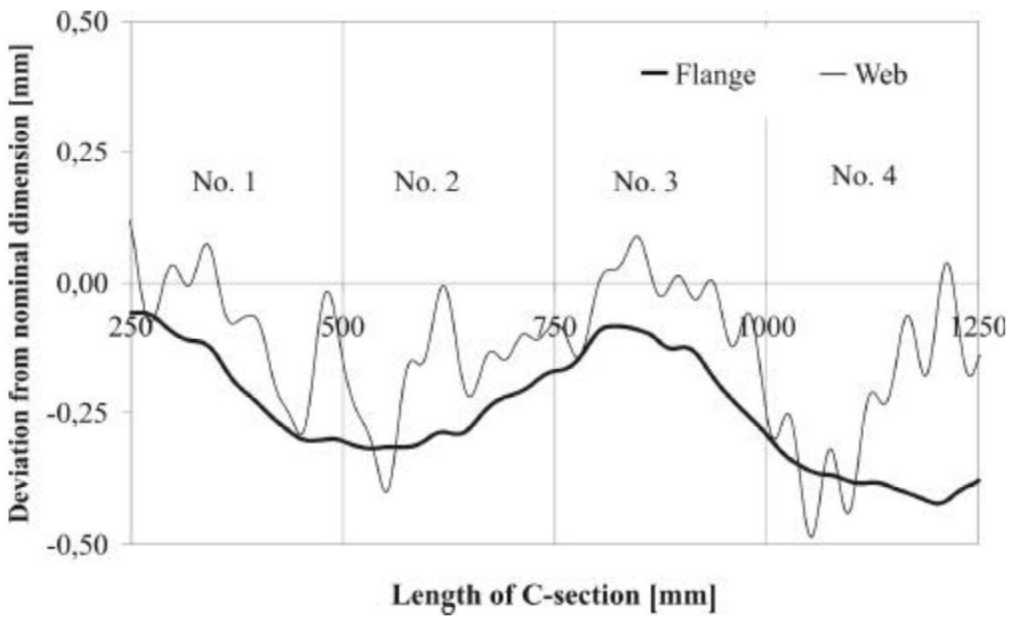



Fig. 3. Distribution of geometric imperfection

The load displacement curves obtained from the finite-element analysis are shown in Figure 5. The load displacement curves show a distinct linear range. There are only slight differences between the curves obtained form conventional and advanced analysis respectively. The deviations in the elastic range are caused by the differences in the geometric imperfections. The increase of the failure loads is caused by the increase of the yield strength. The distinctive drop in the load displacement curves is characteristic for thin gauged sections.

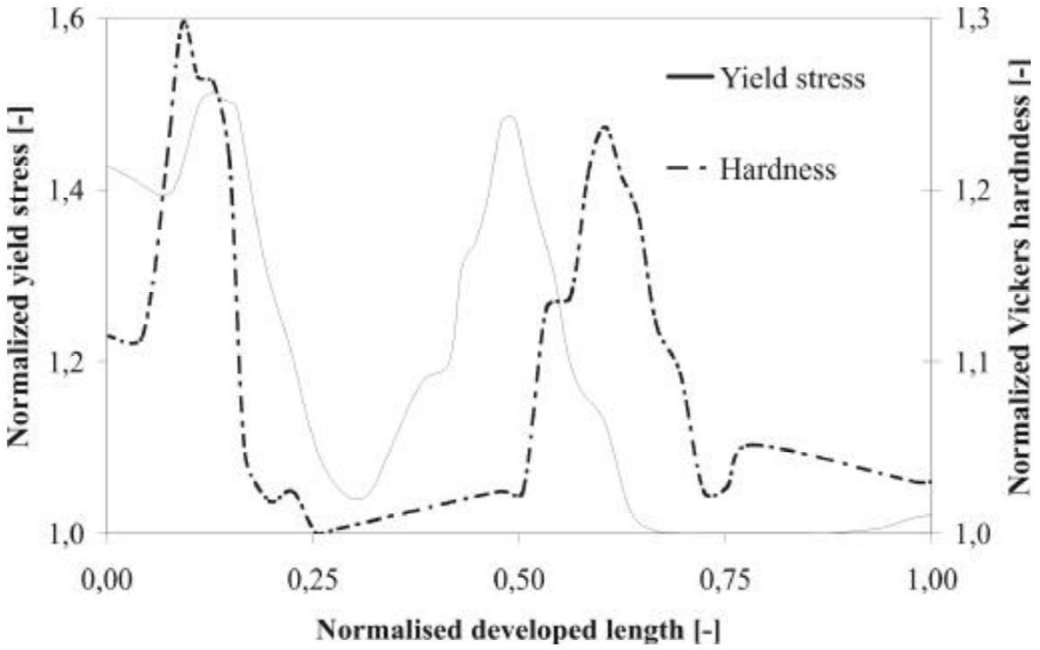



Fig. 4. Yield stress and hardness distribution in section after roll forming (half section)

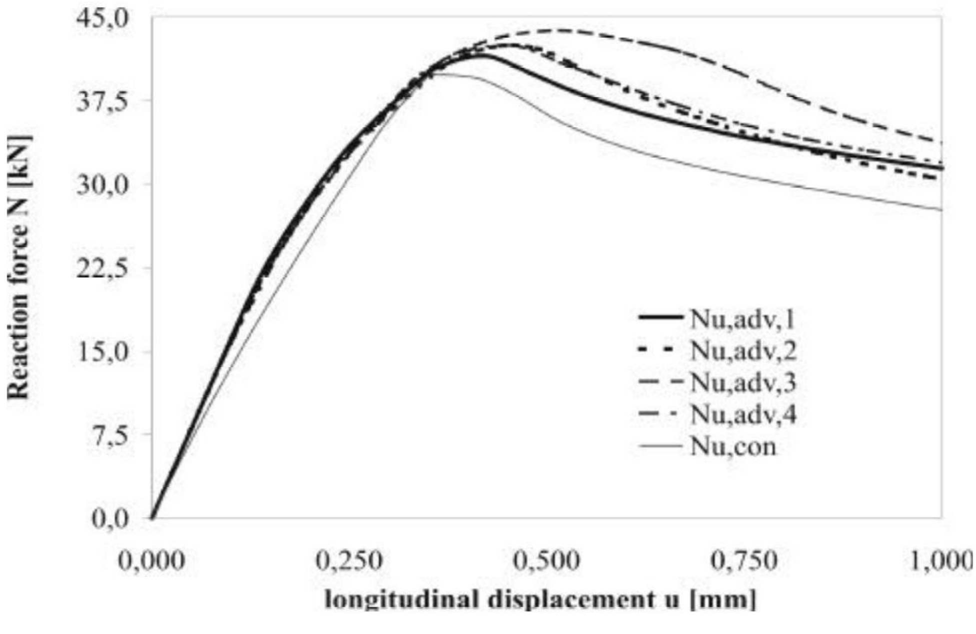


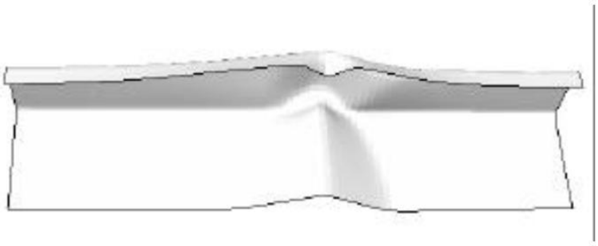

Fig. 5. Load-displacement curves

The deformed C-sections after failure are shown in Figure 6. The failure modes deviate from each other, because the applied imperfections are different. In the conventional analysis, the wave length of the edge stiffener is longer than in the advanced analysis. It is obvious from Figure 6, that the advanced analysis includes different imperfection modes and thus reveals different failure loads for each virtual test. The failure loads determined with finite-element analyses are given in Table 1. The subscripts con and adv refer to the conventional and advanced analysis respectively. The characteristic resistance according to prEN 1993-1-3 [1] is $N_{c,EC3}$ = 37,0 kN.

The higher failure loads are due to the increased yield strength and the smaller geometric imperfections with the advanced analysis strategy. The average yield strength $f_{ya}$ is 18 % higher than the yield strength $f_y$ of the virgin material.

no. 0

no. 1



no. 2

no. 3

no. 4

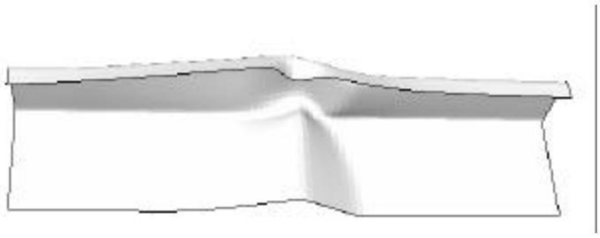


Fig. 6. Failed specimen from conventional analysis (no. 0) and advanced analysis (from no. 1 to 4)

The highest failue loads are obtained from the advanced analysis strategy. These are approximately 4 % to 10 % higher than the failure load obtained from the conventional analysis strategy and approximately 11 % to 18 % higher than characteristic resistance Nc,EC3 according to prEN 1993-1-3 [1].

| $N_{u,con}$ kN | $N_{u,adv,1}$ kN | $N_{u,adv,2}$ kN | $N_{u,adv,3}$ kN | $N_{u,adv,4}$ kN |
|---|---|---|---|---|
| 39,8 | 41,4 | 42,4 | 43,7 | 42,4 |

Table 1: Ultimate loads

### 3.5 Discussion of the results

The example shows, that the advanced analysis strategy gives the opportunity to simulate the structural performance of cold-formed sections realistically. This is due to the fact, that deviations from the nominal dimensions and material properties are taken into account. The results are reasonable and within the expected range. With this model, the effect of slight modifications of, e.g. material specification, tool design, on the failure load, can be determined easily.
However, in any case the results have to be verified with some tests before introducing them as characteristic resistance values in design of cold-formed sections.

## 4 CONCLUSIONS

The new analysis strategy for determination of the ultimate failure load of cold-formed sections shows:

- Deviation from the nominal dimensions and material properties are estimated realistically.
- The obtained failure loads are reasonable compared to the values according to design standards.
- The characteristic resistance obtained from this process oriented analysis is higher than the characteristic values for general use in design standards.
- The analysis strategy gives the chance to optimize the dimensions, the material specification and the manufacturing process of a section without a cost intensive experimental trial and error procedure.

It has to be kept in mind that the advanced analysis strategy will only lead to safe results if they are based on a profound knowledge of the manufacturing process and the structural behaviour of the component (load transfer and possible failure modes). This demands substantial experience with experimental and numerical analysis of the object.

## 5 REFERENCES


[1] prEN 1993-1-3:2006, Eurocode 3 - Design of steel structures - Part 1-3: General rules - Supplementary rules for cold-formed members and sheeting, Brussels, 2006

[2] Groche, P., von Breitenbach, G., Jöckel, M., Zettler, A., New tooling concepts for future roll forming applications, Proceedings of ICIT conference, Bled, Yugoslavia, 2003

[3] prEN 1993-1-5:2004, Eurocode 3 - Design of steel structures - Part 1-5: General rules - Supplementary rules for cold-formed members and sheeting, Annex C

[4] Schafer, B. W., Peköz, T., Computational modeling of cold-formed steel: characterizing geometric imperfections and residual stresses, Journal of constructional steel research 47 (1998), 193 – 210

[5] Garnder, L., Nethercot, D.A., Numerical modelling of stainless steel in structural components – a consistent approach, Journal of structural engineering 130 (2004), 1586 – 1601

[6] Lecce, M., Rasmussen, K., Distortional buckling of cold-formed stainless steel sections: finite-element modelling and design, Journal of structural engineering 132 (2006), 505 – 512

[7] Gemeinsame Erklärung des CSTB und DIBt zur technischen Bewertung von Bauprodukten auf Grundlage virtueller Versuche mit dem Ziel der Kostenreduzierung im Bauwesen, In: DIBt Mitteilungen 35 (2004), Heft Nr. 5, S. 146

[8] ABAQUS Documentation – Version 6.6.1, Copyright 2006, ABAQUS, Inc.

[9] ABAQUS (Explicit & Standard); Version 6.6.1, Copyright 2006, ABAQUS, Inc.

[10] http://www.rz.uni-karlsruhe.de/ssc/hpxc

[11] EN 10326:2004, Continuously hot-dip coated strip and sheet of structural steels - Technical delivery conditions

[12] Lange, K., Hrsg., Umformtechnik – Handbuch für Industrie und Wissenschaft, Band 1: Grundlagen, 2. Auflage, Springer Verlag, Berlin, 1984

[13] Lecce, M., Rasmussen, K., Experimental investigations of the distortional buckling of cold-formed stainless steel sections, Research report No. 844, University of Sydney, Sydney, 2005

[14] Gehring, A., Bericht Nr. 064052, Versuchsanstalt für Stahl, Holz und Steine, Universität Karlsruhe (TH), Karlsruhe, 2006, unpublished