

NUMERICAL SIMULATION OF THE STAINLESS STEEL RHS MEMBER UNDER CYCLIC LOADING, IDENTIFICATION OF MATERIAL MODEL PARAMETERS, AND COMPARISON WITH HSS STEELS

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ABSTRACT

This study examined the cyclic behavior of stainless steel through a combination of experimental tests and numerical simulations. The study began with a comprehensive analysis of material properties and experimental configurations, which provided a solid foundation for developing a robust finite element (FE) model.

A new simplified material model inspired by Ramberg-Osgood was developed for easy use in practical tasks. For example, the ANSYS software only offers the original Ramberg-Osgood model for monotonic loading and Chaboche model is not as easy to calibrate as the Ramberg-Osgood model which is defined by parameters which can be easily retrieved from coupon tests. The combination of the validation against experimental data and material model parameters identification using sensitivity analysis and mathematical metamodel confirmed that the model accurately reflects the material's performance under cyclic loading conditions.

Further comparisons with high strength steels (HSS) underscore the superior performance of stainless steel when subjected to cyclic loading. These findings underscore the advantages of stainless steel in structural applications requiring high ductility, strain hardening, and resistance to cyclic loading.

In conclusion, this research validates the effectiveness of the simplified material model and underlines the increasing use of stainless steel in contemporary structural engineering. Its distinct properties make it a valuable material, especially in many times repeated loading, where performance under cyclic loading is critical.

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1. Introduction

Carbon steel has been historically the most prevalent material used in civil engineering constructions. In recent decades, stainless steel has been increasingly employed in certain industries due to its much improved chemical and biological resistance, strength, and favorable mechanical features. Above all, stainless steel high ductility, strain hardening, and fire resistance all possess distinct benefits compared to common carbon steel. Consequently, stainless steel is becoming more and more a fitting construction material for such tasks as seismic engineering. [1], [2], [3]. In [4], Chen et al. performed a series of experiments and numerical simulations to verify the applicability of prEN 1993-1-4(EC3) [5] code relations for dynamically loaded stainless steel H cross-sections. As expected, the standard provides conservative values, while the methodology modified by the authors got on the dangerous side under certain circumstances.

While the monotonic loading behavior of stainless steel is well-documented, the investigation into its response under cyclic loading conditions is relatively recent but rapidly expanding [3], [6]. Research efforts have been directed toward understanding the performance of stainless steel grades (e.g., austenitic, duplex) under both axial [7] and bending [8] cyclic loads. Numerous experimental studies have been conducted on both material coupons and full-scale structural members to characterize their cyclic response. These experimental studies have been extensively complemented by numerical simulations utilizing the finite element (FE) method, which incorporates appropriate advanced material models (e.g., Chaboche, Armstrong-Frederick, two-surface plasticity models) to accurately predict behavior under complex cyclic loading conditions [9], [10].

Luo et al. in [11] conducted a series of experiments at medium and high levels of plastic stress on elements including the weld and the heat-affected region. Based on the results, they calibrated the Chaboche model. The authors stated that its accuracy is strongly influenced by the correspondence of the loading and simulated levels of plastic strain. The authors [12] approach the problem in a similar way, extending the study to a wide range of steel grades. On the contrary, the study [13] is very closely devoted to a detailed description of the differences in the response to cyclic loading based on the change in the chemical composition of stainless steels. By reducing the nickel content, the new QN1803 stainless steel has greater strength at a lower cost than the widely used S30408 stainless steels. The study notes a significantly better response to the cyclic loading of both stainless steels than conventional steels of comparable strength classes.

In [14], improved Voce-Chaboche constitutive relations are described. The added combination of isotropic and kinematic hardening schemes can better

describe the transition to the first plastic cycle.

The authors [15] also deal with the Chaboche model with a combined hardening surface. The authors describe a simplified procedure for calibrating the parameters. Using 171 response experimental curves, they designed a four-stage statistically based prediction method that should be able to replace classical calibration.

The thesis [16] deals with the revision of the Chaboche model. A viscous parameter is added, which is ignored in the classical model in order to better describe the variable plastic modulus in stress-controlled cycling and the continuously increasing strain in stress-controlled cycling. By adding parameters, it is possible to better describe the response, but at the cost of difficulty obtaining the supplied input parameters by means of non-standard tests. Parameters are also added in [17]. The described model does not consider some parameters, simplifies others – it introduces a linear relationship between the coefficient and the effective/equivalent stress.

In [18], Kaleva et al. perform an extensive comparison of the Ottosen-Stenström-Ristinmaa and Lemaitre-Chaboche models for application to the high-cycle fatigue model. They confirm that some parameters cannot be identified directly experimentally. Based on their observations, a high agreement in the response of both models was found.

A lot of attention is paid to the effort to streamline the finding of input parameters of material models. In [19], the method of modification of the cyclic experimental loading is used. Authors [20] and [21] follow the path of optimization and subsequent training of genetic algorithms that should generate input parameters of the material models.

Though these advancements have been achieved, uses of sophisticated material models in commercial FE softwares to continue to present difficulties for practical engineering use because they are too complex, expensive to calculate, and difficult to calibrate material model parameters. There is a fundamental need for material models that are sufficiently accurate but not too computationally expensive and simple to apply and used by engineers for design and analysis.

This research complements this gap by examining the use of a newly developed simplified material model specifically for use in engineering, designed to accurately model the response of cyclic loading on stainless-steel members. A compromise between accuracy and simplicity, which is typically not available in any current commercial analysis packages for cyclic loading analysis, the model is derived from the popular Ramberg-Osgood formulation. The outcomes thus obtained via this reduced material model are then precisely compared with comparative experimental loading test, thus providing validation.

The methodology begins with the creation of a numeric FE model, experimentally validated with the help of loading test [22]. For reliability

verification of the proposed material model, the numeric model is investigated through a serious sensitivity analysis. In the sensitivity analysis, the impact of the input parameters of the newly proposed material model on the overall numeric simulation response is investigated. These most sensitive parameters are then optimized to generate the best possible agreement between the experimental results and the model predictions.

Finally, to also highlight the actual benefits of stainless steel in safety-critical application, a comparison study is done. Numerical calculations with the simplified material model of stainless steel are compared with those of high strength steels (HSS), specifically in the case of cyclic loading cantilever beams. The distinguishing cyclic performance and structural response characteristics of these two materials are identified, noting the superior capacity of stainless steel to resist repeated loading. This contrast also indicates the increasing utility of stainless steel as a preferred material for structural applications involving high ductility, significant strain hardening, and improved resistance to cyclic loading and fatigue.

2. Experiment

The experiment was conducted at the University of Studi. A study of nine cold-formed rectangular stainless-steel members subjected to cyclic loading was carried out [22]. For purposes of this article, one test configuration was selected. The Cantilever beam is made from EN 1.4301 austenitic stainless steel, cold formed cross-section 120×80×6 mm with a total length of 1730 mm and effective length of 1650 mm, see Fig. 2 (a).

2.1. Material properties

The mechanical properties of the material were further determined by experiments carried out at the Universitat Politècnica de Catalunya [23]. A series of tensile coupon tests were carried out on both the flat and the corner parts of the cross-sections to take into account the increased tensile strength of the corner parts due to the cold forming process. Obtained material parameters and stress-strain curves are shown in Table 1 and Fig. 1. E is the Young's modulus, $\sigma_{0.2}$ is the strength at the strain 0.2%, σ_u is the ultimate strength, ϵ_u is the strain at ultimate strength, n is strain hardening parameter, and m is second strain hardening parameter.

Table 1
Material parameters [23]

Parameter	Unit	Flat part	Corner part
E	MPa	185 778	185 360
$\sigma_{0.2}$	MPa	479	635
σ_u	MPa	679	840
ϵ_u	m/m	0.39	0.34
n	-	7.05	5.40
m	-	2.55	7.89

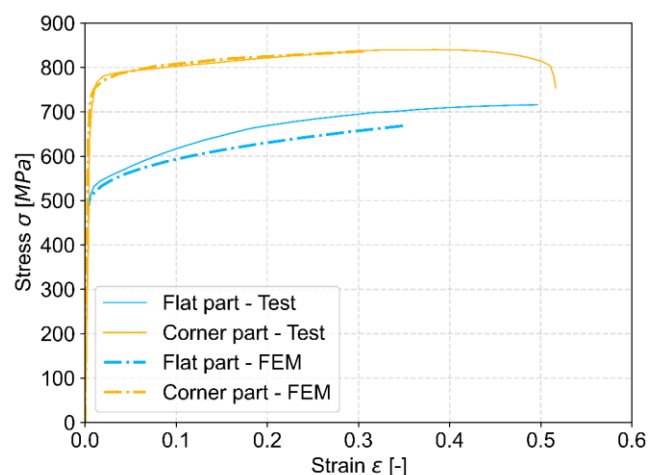


Fig. 1 Stress-strain diagram for flat and corner coupons (solid lines) and for the material model (dash dot)

2.2. Test configuration

The test configuration is shown in Fig. 2 (a). The beam was subjected to cyclic loading for testing bending around the major axis. The bottom end of the beam was embedded to the floor and the top end was loaded by a hydraulic actuator. The actuator is hinged on both sides to prevent bending moments and vertical forces. The bottom end was made from flange and stiffeners, which were welded to the beam. The flange is fixed to the ground by four bolts. Loading protocol is shown in Fig. 2 (b). The record of the load test is shown in Fig. 2 (c), where u is the displacement of the top of the beam where the actuator is hinged, and the force reaction is the force in the actuator.

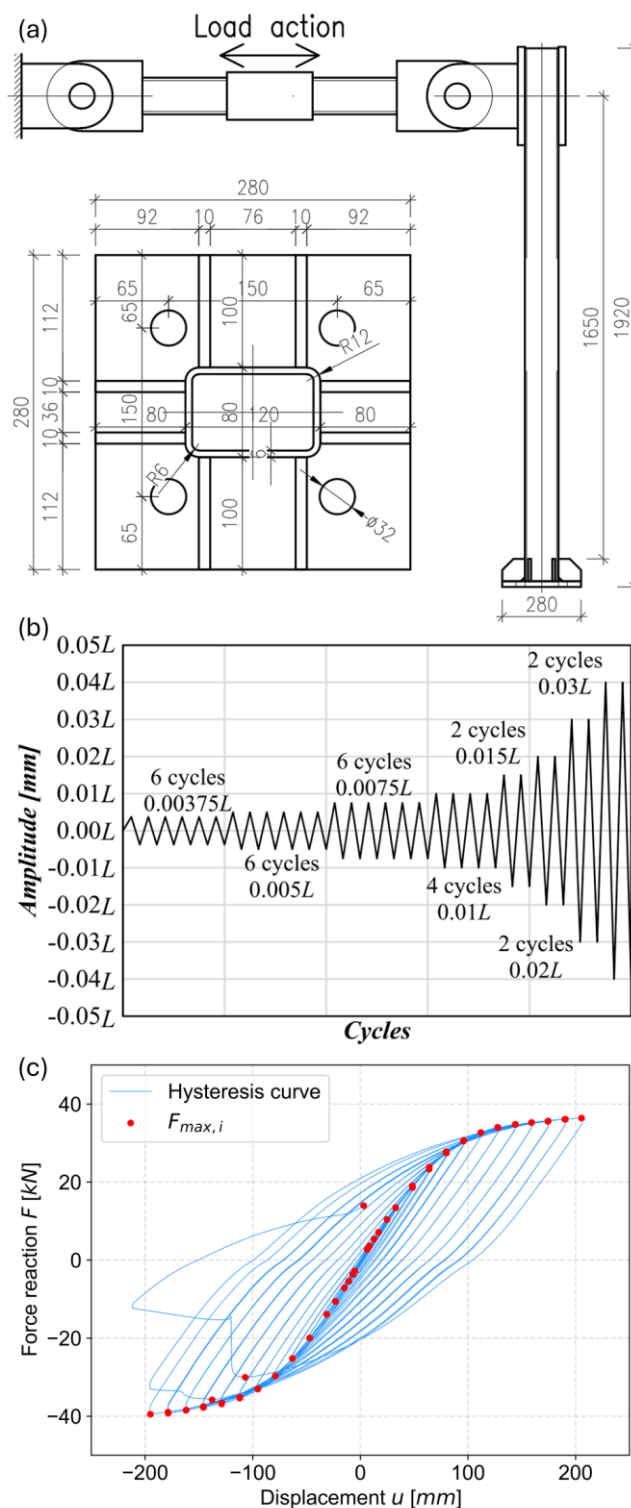


Fig. 2 (a) Experiment (loading test) configuration, (b) Loading protocol [4] and

(c) Record of the load test – Hysteresis curve

3. Numerical model

The Finite Element method was used for the numerical simulation of the loading test. To solve the static response, a 3D FE shell model was constructed with a nonlinear elastoplastic material model with kinematic hardening, which properly simulates the Bauschinger effect while cyclic loading [6], [7]. Detailed information about the material model and FE model is described in the subchapters below.

3.1. Material model

The nonlinear elastoplastic material model with kinematic hardening was used to describe the material behavior under cyclic loading. The material model is based on Nadai and Ramberg-Osgood theory [24]. This theory was many times modified e.g. [25]. For current work was used the material model defined by equations (1-5) with linear elastic branch and nonlinear plastic branch with linear unloading branch. Stress-strain diagram is shown in Fig. 3.

$$\varepsilon = \varepsilon_{el} + \varepsilon_{pl} \quad (1)$$

$$\varepsilon_{el} = \frac{\sigma}{E} \quad (2)$$

$$\varepsilon_{pl} = \frac{\sigma - \sigma_y}{E_y} + \varepsilon_u \left(\frac{\sigma - \sigma_y}{\sigma_u - \sigma_y} \right)^m, \quad \sigma > \sigma_y \quad (3)$$

$$\varepsilon = \begin{cases} \frac{\sigma}{E}, & \sigma \leq \sigma_y \\ \frac{\sigma}{E} + \frac{\sigma - \sigma_y}{E_y} + \varepsilon_u \left(\frac{\sigma - \sigma_y}{\sigma_u - \sigma_y} \right)^m, & \sigma > \sigma_y \end{cases} \quad (4)$$

$$E_y = \frac{E}{1 + 0.002n \frac{E}{\sigma_y}} \quad (5)$$

Where ε is total strain, ε_{el} is elastic strain, ε_{pl} plastic strain, σ actual stress, σ_y yield strength, σ_u ultimate strength, n strain hardening parameter, m second strain hardening parameter and E_y is a tangent modulus of the stress strain curve at the yield strength.

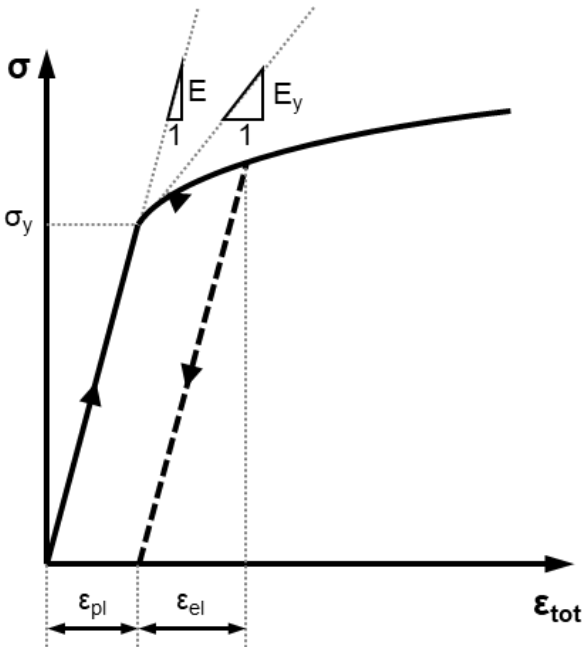


Fig. 3 Nonlinear elastoplastic stress-strain diagram of the simplified material model

Input of the stress-strain relationship is carried out using the true stress. The relationships between the engineering stresses obtained from the experiment and the true stresses used in numerical simulations are shown in the equations (6-7).

$$\sigma_{TRUE} = \sigma_{ENG}(1 + \varepsilon) \quad (6)$$

$$\varepsilon_{TRUE} = \ln(1 + \varepsilon) \quad (7)$$

The use of a linear elastic branch is a simplification in compared to [24] and the stress-strain relationship specified in EN 1993-1-4, which consider a nonlinear elastic branch and the plastic strains formation at stresses under proof stress. The stress-strain relationship according to Annex C of EN 1993-1-4 and prEN 1993-1-14 [26] is defined by equations (5, 8-11), this stress strain diagram was also used by [27] in case of stainless steel CHS members.

$$\varepsilon = \begin{cases} \frac{\sigma}{E} + 0.002 \left(\frac{\sigma}{f_y} \right)^n, & \sigma \leq f_y \\ 0.002 + \frac{f_y}{E} + \frac{\sigma - f_y}{E_y} + \varepsilon_u \left(\frac{\sigma - f_y}{f_u - f_y} \right)^m, & \sigma > f_y \end{cases} \quad (8)$$

$$n = \frac{\ln(20)}{\ln\left(\frac{f_y}{R_{p0.01}}\right)} \quad (9)$$

$$\varepsilon_u = 1 - \frac{f_y}{f_u} \quad (10)$$

$$m = 1 + 3.5 \frac{f_y}{f_u} \quad (11)$$

Where ε is total strain, σ actual stress, f_y yield strength, f_u ultimate strength, ε_u strain at ultimate strength, n strain hardening parameter, m second strain hardening and $R_{p0.01}$ is stress at plastic strain 0.01%.

Simplification has been used for ease of use in practical problems, both in specifying the material model and in evaluating stresses and clearly identifying elastic and plastic deformations.

3.2. Numerical FE model

The FE model was modelling using linear shell elements with six degrees of freedom at each node. The SHELL181 element type is suitable for thin shell structures, large strain nonlinear applications, and change in shell thickness. Element formulation is based on logarithmic strain and true stress measures. [12]

The finite element mesh is mostly composed of 4-node finite elements and combination of 4-node and 3-node elements in the regions of mesh refinement. The spatial regions are formed by a mapped mesh of 4-node elements. In the region of high stress gradient, the finite element mesh is condensed to a finite element size of 5 mm. Above this part, the transition region consists of a combination of 4-node and 3-node elements. The remainder of the beam is made up of a mapped mesh of element size 20 mm. The finite element mesh of the stiffeners and flanges is made up of a free mesh of sizes in the approximate range of 5-25 mm.

The model was supported at nodes in the center of the holes in the flange. The bolts were replaced by boundary conditions that constrain the node displacement in all directions with free rotational degrees of freedom. These nodes were coupled to the holes edge by contact pair elements CONTA177 + TARGET170 using the MPC (Multi-point constraint) algorithm. [12]

The displacement of the top of the beam is realized by a node at the end position of the actuator. This node is also coupled to the beam by the contact pair elements CONTA174 + TARGET170 using the MPC algorithm. The boundary condition of this node is only a constrained (prescribed) displacement in the loading direction (x direction – about the major axis of the cross-section), other degrees of freedom are free.

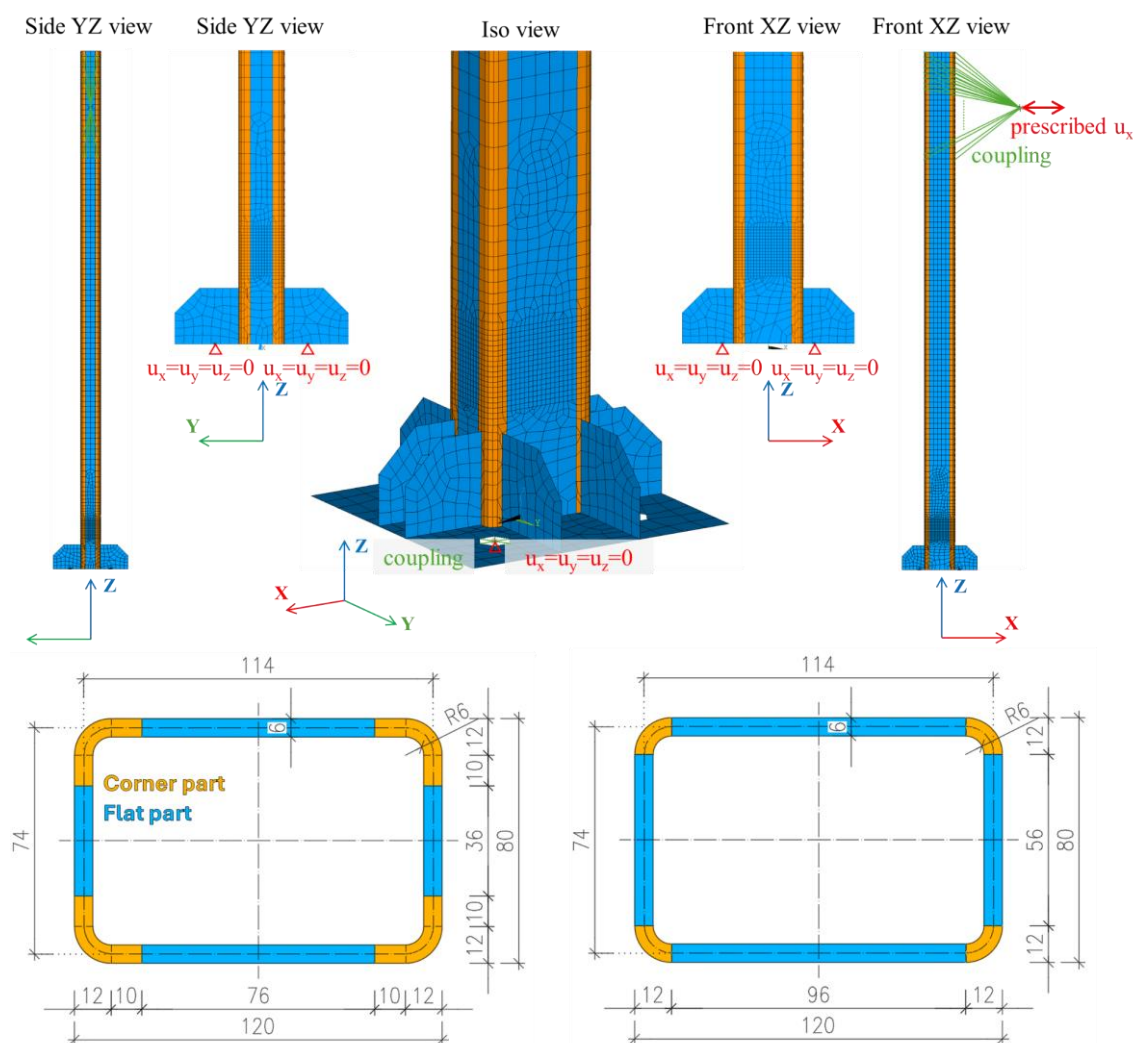


Fig. 4 FE mesh, boundary conditions, material model assignment and cross-section with and without corner area extension

The material model assignment to the finite elements is shown in Fig. 4. The material model for the corner part is assigned to the extended corner part of the section according to the cold forming process of the RHS section manufacture. The distance of the extension is chosen according to previous research. Values of the extension range from the thickness t up to $2t$ [25], for this work was used extension of $0.5\pi r_i$ [28], where r_i is the inner radius. The extension of 10 mm is shown in Fig. 4.

The initial material model input parameters were retrieved by fitting the stress-strain diagrams from coupon tests [23]. The initial material model input parameters are given in Table 1 and the fitted stress-strain diagrams are plotted and compared with measured stress-strain curves in Fig. 1.

The numerical model was subjected to a sensitivity study of model to verify

the model and check various influences on the results. In the study, the influence of support stiffness (rigid/deformable), finite element mesh size (2 times finer), corner extension (see Fig. 4), finite element integration method (full/reduced) and finite element type (linear/quadratic) were investigated.

This verification was carried out for the monotonic loading test. An overview of the test study is given in Table 2. A comparison of the results is shown in Fig. 5. From the load-displacement curves it can be seen that the stiffness of the support, the mesh element size, the integration method and the element type have an insignificant effect. The effect of the corner extension will be investigated further in subsequent chapters by optimizing the material parameters.

Table 2
Optimized values of the material model parameters.

Model	Supports	Mesh	Corners	FE integration	Element type
00 – Reference	Rigid	Ref.	No extended	Full	Linear (SHELL181)
01 – Support stiffness	Deformable	Ref.	No extended	Full	Linear (SHELL181)
02 – Mesh size	Rigid	Finer	No extended	Full	Linear (SHELL181)
03 – Corner extension	Rigid	Ref.	Extended	Full	Linear (SHELL181)
04 – Integration method	Rigid	Ref.	No extended	Reduced	Linear (SHELL181)
05 – Element type	Rigid	Ref.	No extended	Full	Quadratic (SHELL281)

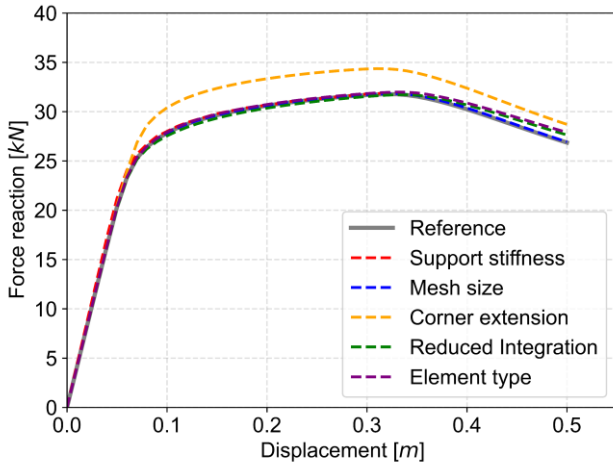


Fig. 5 Load-displacement curves of the influence study

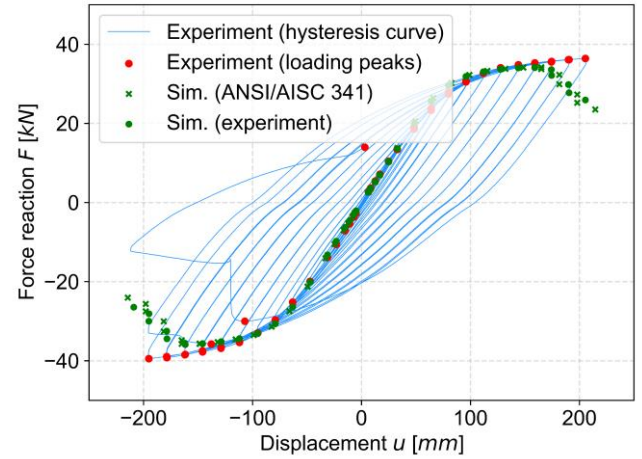


Fig. 6 Comparison of the load steps

3.3. Numerical simulation and results

The numerical simulations were controlled by the prescribed displacement of the node replacing the actuator, see Fig. 2 (a) and Fig. 4.

The beam was cyclically loaded according to ANSI/AISC 341 [14] in relation to the experimental load test [4], where the prescribed displacements weren't exactly achieved. The record of the experimental loading test is shown in Fig. 6 with a comparison of the load stepping according to ANSI/AISC 341. In the simulation test, the beam was loaded for a total of 96 cycles.

The calculation was carried out for two variants. One variant without extended corners and one variant with extended corners, see Fig. 4. The input material model parameters were used as described in Table 1. The results of these two numerical simulations are shown using load-displacement hysteresis curves in Fig. 7 (a, b). The hysteresis curve is the record of the displacement and force at the node, which replaces the actuator in the numerical simulation. For a clearer view, the results are also shown using the peak values where the load changes the direction, see Fig. 7 (c, d). From the result can be seen, that a better response is obtained using the FE model with an extended corner part. This model was further used for sensitivity analysis and optimization of material model input parameters to achieve a more accurate response to cyclic loading.

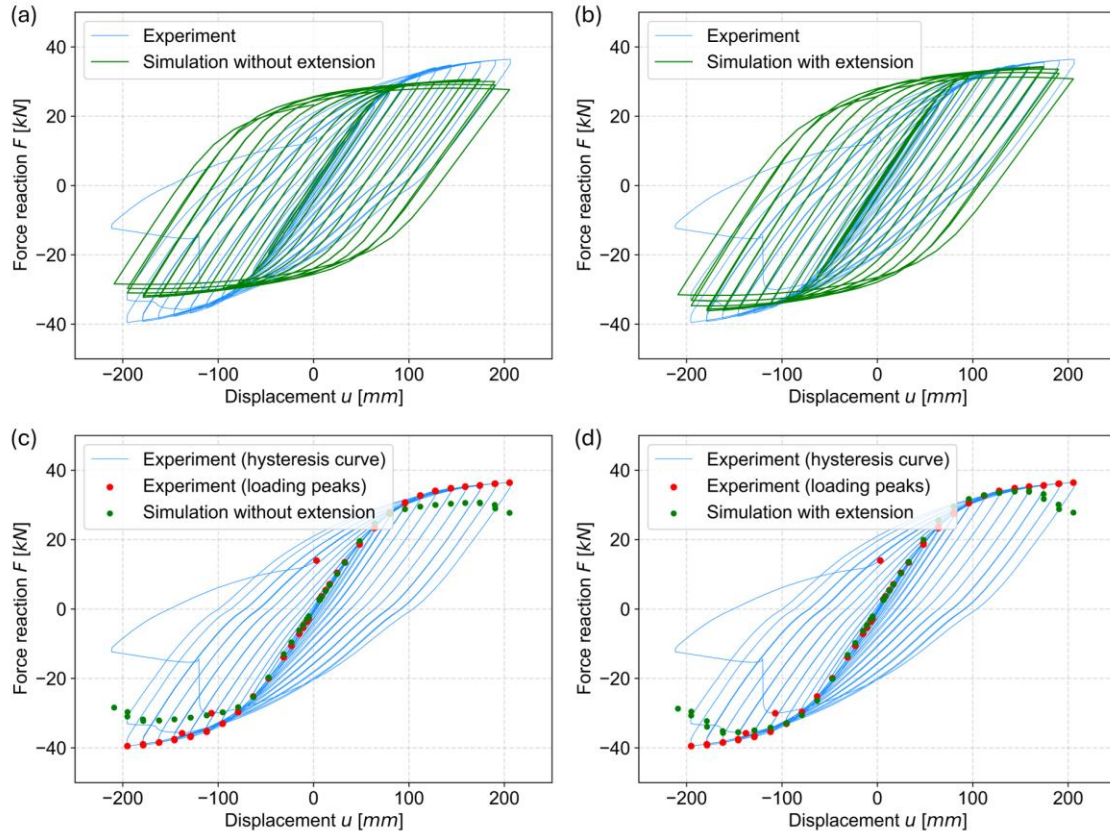


Fig. 7 Load-displacement hysteresis curves with original material model parameters (a), (c) for model without cross-section corner extension and (b), (d) for model with cross-section corner extension

4. Sensitivity analysis and optimization of the material model parameters

Optimization was carried out to achieve a more accurate response from the numerical model. The optimization was performed for the input parameters of the material model.

To save computational time, the optimization was performed using a surrogate mathematical metamodel – MOP (Metamodel of Optimal Prognosis) that was constructed using approximations of the responses of the set of numerical simulations [29]. The mathematical model approximates and replaces the numerical model for pre-selected responses that it can be predicted based on

the input parameters.

4.1. Mathematical metamodel and sensitivity analysis

The mathematical metamodel was created by combining several approximation models for individual responses. Possible approximation models were Linear Regression, Moving Least Squares, and Isotropic Kriging [30]. The choice of the approximation model depended on the value of the *CoP* (Coefficient of optimal prognosis), which quantifies the quality of the approximation by the equation (12) as follow:

$$CoP = 1 - \frac{SS_E^{Prediction}}{SS_T} \quad (12)$$

where $SS_E^{Prediction}$ is the sum of the squared prediction errors and SS_T is equivalent to the total variation. The value of this coefficient ranges from 0 to 1.0, with 1.0 representing a perfect approximation. A further description can be found in [30].

The metamodel contains 12 input parameters, which are the input parameters of the material model for the flat and corner parts of the cross-section. The input parameters are given in Table 3 with the initial values and upper and lower bounds. The responses of the metamodel were the load forces at the end of the selected load steps during the numerical simulation of the load test.

To create the metamodel, 150 numerical simulations of the load test were performed at first step. The input parameters of these simulations were generated using Advanced Latin Hypercube Sampling. At the second step, the AMOP (Adaptive Metamodel of Optimal Prognosis) was performed to achieve higher values of the *CoP*. There were made 650 simulations at all to create the MOP.

An overview of the MOP is provided by the *CoP* matrix shown in Fig. 9 (a, b), where the *CoP* values of each response approximation are shown in the right

column. The remaining columns show the sensitivities of the input parameters to each response. A clearer representation of some selected responses and sensitivities is shown in Fig. 9 (c–h). The *CoP* matrix clearly shows the high sensitivity (high importance) of the elastic modulus in the early stages of the loading. At later stages, the sensitivity of the elastic modulus decreases, and the sensitivity of the yield and ultimate stresses increases. The parameters of the corner parts are more sensitive than those of the flat part. The sensitivities of the parameters n_1 and n_2 are small, and the sensitivities of the eps_u_1 and eps_u_2 are unimportant within the given sensitivity analysis boundaries (see Table 2). To validate the unimportant parameters, two further analyses were performed, and the results confirmed their unimportance, see load displacement diagram in Fig. 8. With increasing plastic strains, minor differences occur at later stages, but these are negligible for current analysis. If loading were to continue to later stages, the influence of the eps_u parameters would be greater.

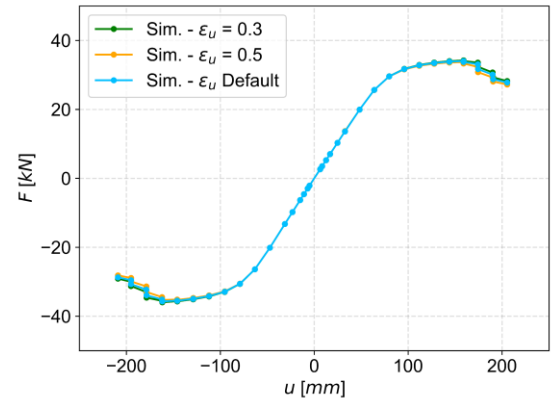


Fig. 8 Load-displacement diagram of eps_u influence study

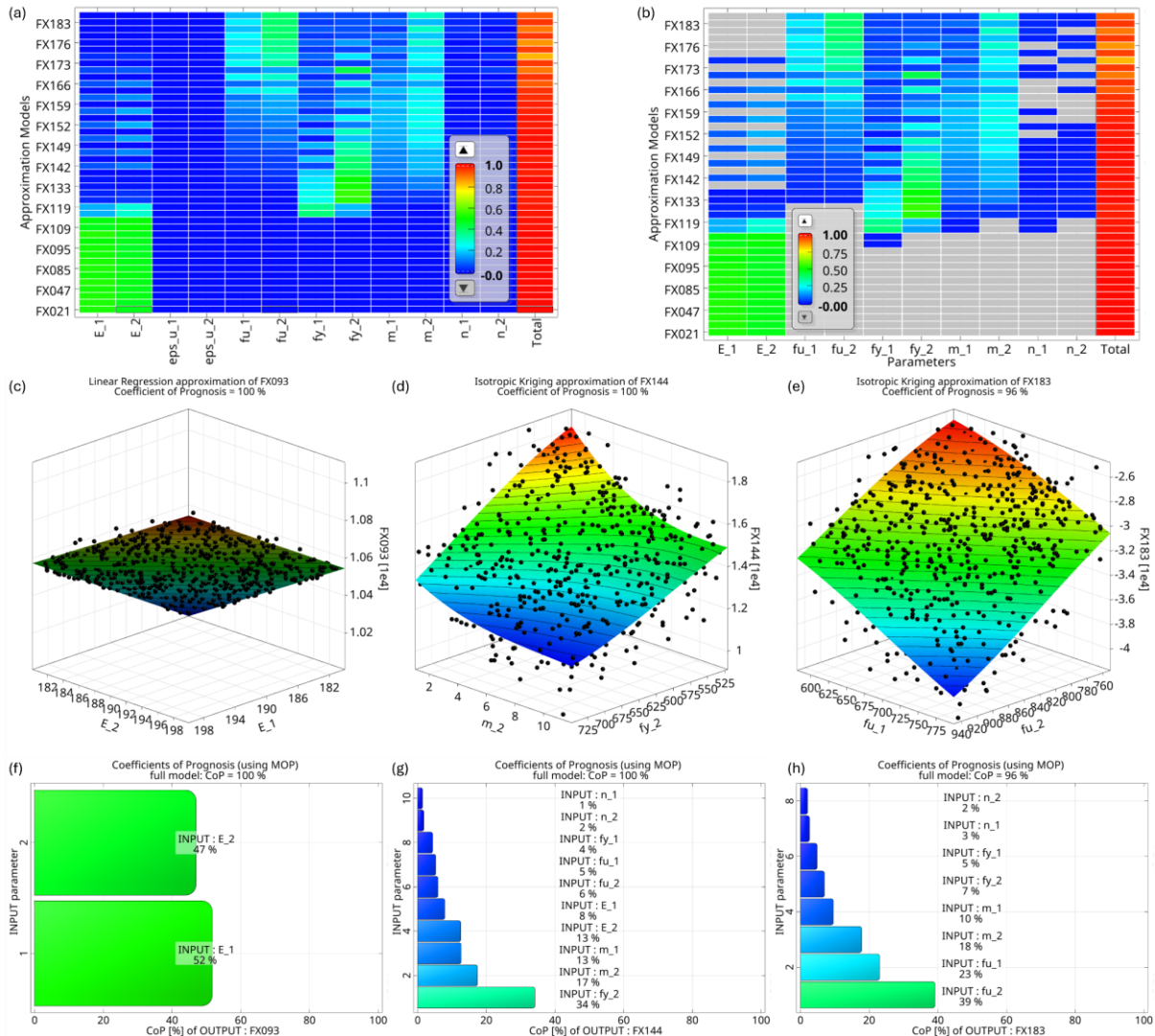


Fig. 9 (a) Full *CoP* Matrix, (b) Filtered *CoP* Matrix, (c–h) *CoP* of the selected responses and sensitivity of its input parameters

4.2. Optimization

The optimization was performed by minimizing the objective function. The objective function was the sum of the differences in the measured forces at the selected load levels between the experiment and the mathematical metamodel prediction. See equation (13).

$$f_{obj} = \sum_{k=1}^n \Delta_k = \sum_{k=1}^n |F_{k,exp} - F_{k,pred}|, \quad (13)$$

where $F_{k,exp}$ are the measured forces from the experiment and $F_{k,pred}$ are the predicted forces by the mathematical metamodel.

The advantage of using the mathematical metamodel is low computational

cost and therefore the possibility of using more optimization methods. At this work, optimization was performed using the Non-Linear Programming by Quadratic Lagrangian (NLPQL), the Adaptive Response Surface Method (ARSM), and the Evolutionary Algorithms (EA) which are suitable for optimization with one objective function [30].

Optimization was performed with all input parameters except the eps_u_1 and eps_u_2 , which were determined as unimportant by the sensitivity analysis, see Fig. 9 (a). The upper and lower bounds of the parameters value range remain the same as for the mathematical metamodel, see Table 3.

Optimized values of the material model input parameters converge to similar values. Optimized values from optimization using ARSM are listed in Table 3 and the stress-strain diagrams of the material model is plotted in Fig. 10.

Table 3

Optimized values of the material model parameters.

Input parameters		Unit	Lower bound	Upper bound	Ref. value	Optimized
E	E_1	GPa	180	200	185.8	180
$\sigma_{0.2}$	f_y_1	MPa	400	560	479	440
σ_u	f_u_1	MPa	650	800	679	750
ε_u	eps_u_1	m/m	0.3	0.5	0.39	-
n	n_1	-	1	16	7.05	7.2
m	m_1	-	1	16	2.55	10.6
E	E_2	GPa	180	200	185.4	180
$\sigma_{0.2}$	f_y_2	MPa	520	750	635	550
σ_u	f_u_2	MPa	750	950	840	900
ε_u	eps_u_2	m/m	0.25	0.45	0.34	-
n	n_2	-	1	16	5.4	3.0
m	m_2	-	1	16	7.89	12.1

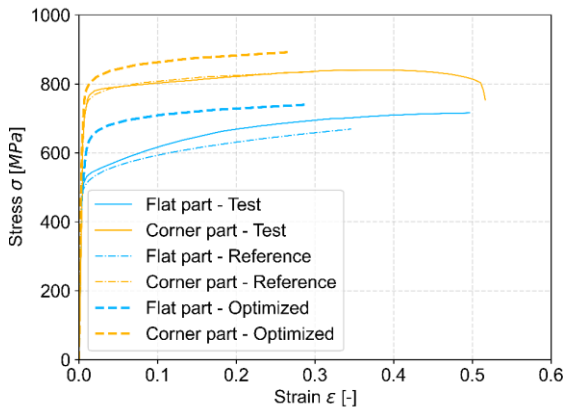


Fig. 10 Stress-strain diagram of the material with the optimized values

4.3. Verification of the metamodel

The verification was performed to check the quality of the mathematical metamodel. The numerical simulation results were compared with the prediction of the mathematical metamodel. The calculations and predictions were performed with the optimal input parameters of the material model listed in Table 3. The comparison of the numerical simulation and the experimental measurements is shown in Fig. 11 (a). The comparison with the mathematical metamodel is shown in Fig. 11 (b).

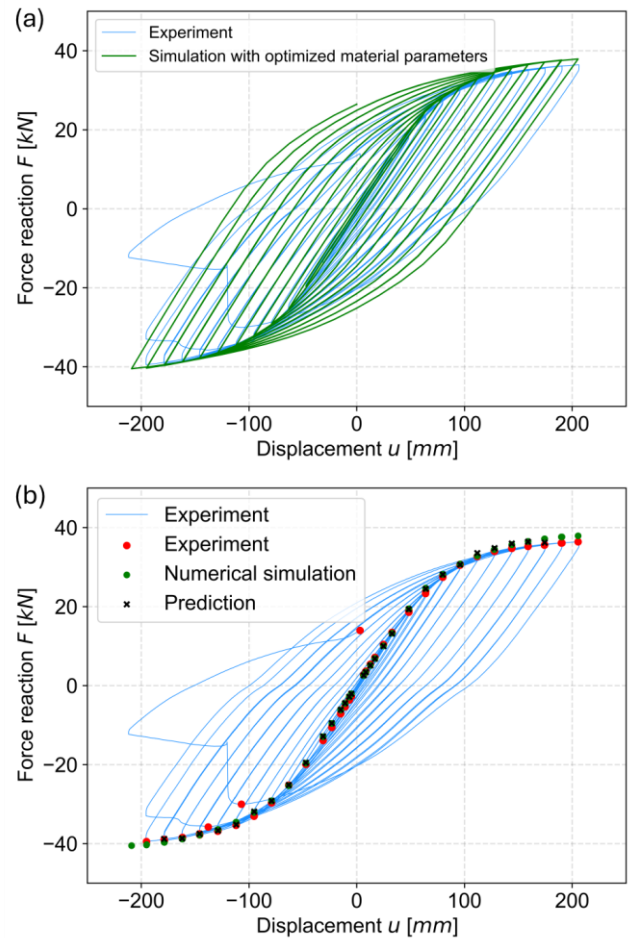


Fig. 11 (a) Numerical simulation with optimized input parameters of the material model

(b) Comparison of the experiment, metamodel prediction, and numerical simulation

5. Comparison with HSS steels

To compare the response under cyclic loading between carbon and stainless steels, a series of numerical simulations were carried out using high strength constructional steel, see Table 4 for material parameters and Fig. 12 with plotted stress-strain diagrams in true stress. The ultimate strain is determined by the equation (14).

Table 4

Nominal values of yield and tensile strengths and minimum percentage elongation after fracture of High strength steels according to EN 10025-6 [31].

Type	f_y N/mm ²	f_u N/mm ²	A %
S460	460	550	17
S500	500	590	17
S550	550	640	16
S620	620	700	15
S690	690	770	14
S890	890	940	11

$$\varepsilon_u = \left(1 - \frac{f_y}{f_u}\right) A \quad (14)$$

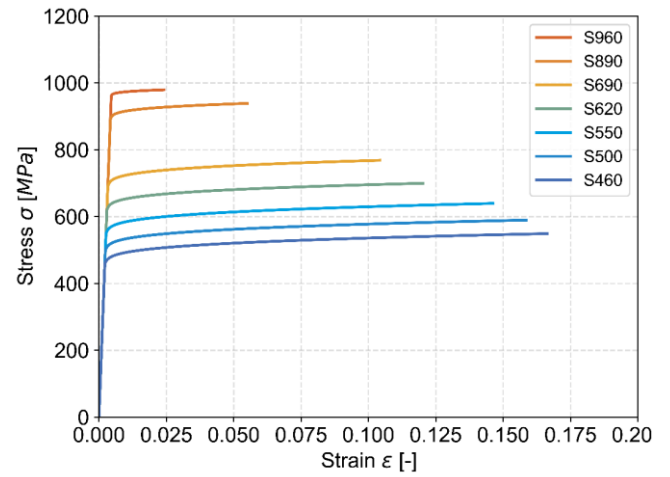


Fig. 12 Stress-strain diagram (true stress) according to EN 10025-6 and prEN 1993-1-14

The comparison is made using several methods. Load-displacement curves are shown in Fig. 13 (a). The results with HSS are directly compared with stainless steel represented by load test results and numerical simulation with optimized material model parameters. The comparison in the Fig. 13 (b) is made by directly normalizing the load-displacement curve by yield strength. Both comparisons show a non-decreasing curve of stainless steels compared to high strength steels. In addition, stainless steel shows a much higher F/f_y ratio

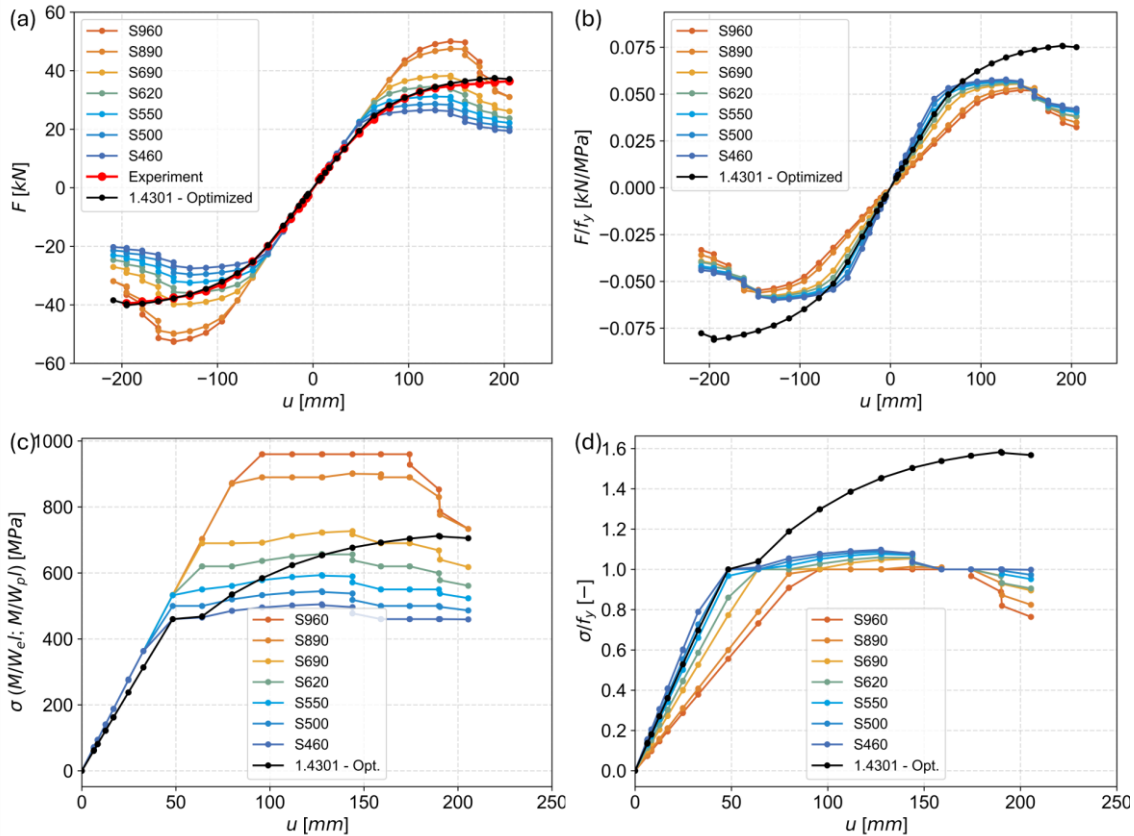


Fig. 13 Simulations results with the HSS in compare with the numerical simulation with optimized material model parameters. (a) Load-displacement curve, (b) Load displacement curve normalized by the yield strength, (c) Normal stresses at critical section (at embedment) calculated using equation (15), (d) Normalized normal stresses at critical section (at embedment) calculated using equation (16)

In Fig. 13 (c), the comparison is made using the normal stress in the critical section above the embedment. The stress is determined by an approximate method by considering a linear elastic-perfect plastic stress distribution in the plane of the section. The stress calculation is given by the equation (15). Next comparison (Fig. 13 (d)) is made using normalized values of previously calculated normal stresses which are normalized by yield strength and ultimate

strength. The calculation of the normalized values is shown in the equation (16). However, the plotted stresses are not real stresses, but a quantifier/indicator of section utilization. At the same time, there is no real stress drop, which can be seen in Fig. 13 (b), it is the loss of section bearing capacity due to local buckling of the cross-section above the embedment shown in Fig. 14.

$$\sigma = \begin{cases} \frac{M}{W_{el}}, & \frac{M}{W_{el}} \leq f_y \\ f_y, & \frac{M}{W_{pl}} \leq f_y \\ \frac{M}{W_{pl}}, & \frac{M}{W_{pl}} \leq f_u \\ \frac{M}{W_{pl}}, & \frac{M}{W_{pl}} > f_u \end{cases} \quad (15)$$

$$\sigma/f_y = \begin{cases} \frac{M}{W_{el}}/f_y, & \frac{M}{W_{el}} \leq f_y \\ \frac{f_y}{f_y} = 1, & \frac{M}{W_{pl}} \leq f_y \\ \frac{M}{W_{pl}}/f_u, & \frac{M}{W_{pl}} \leq f_u \\ \frac{M}{W_{pl}}/f_u, & \frac{M}{W_{pl}} > f_u \end{cases} \quad (16)$$

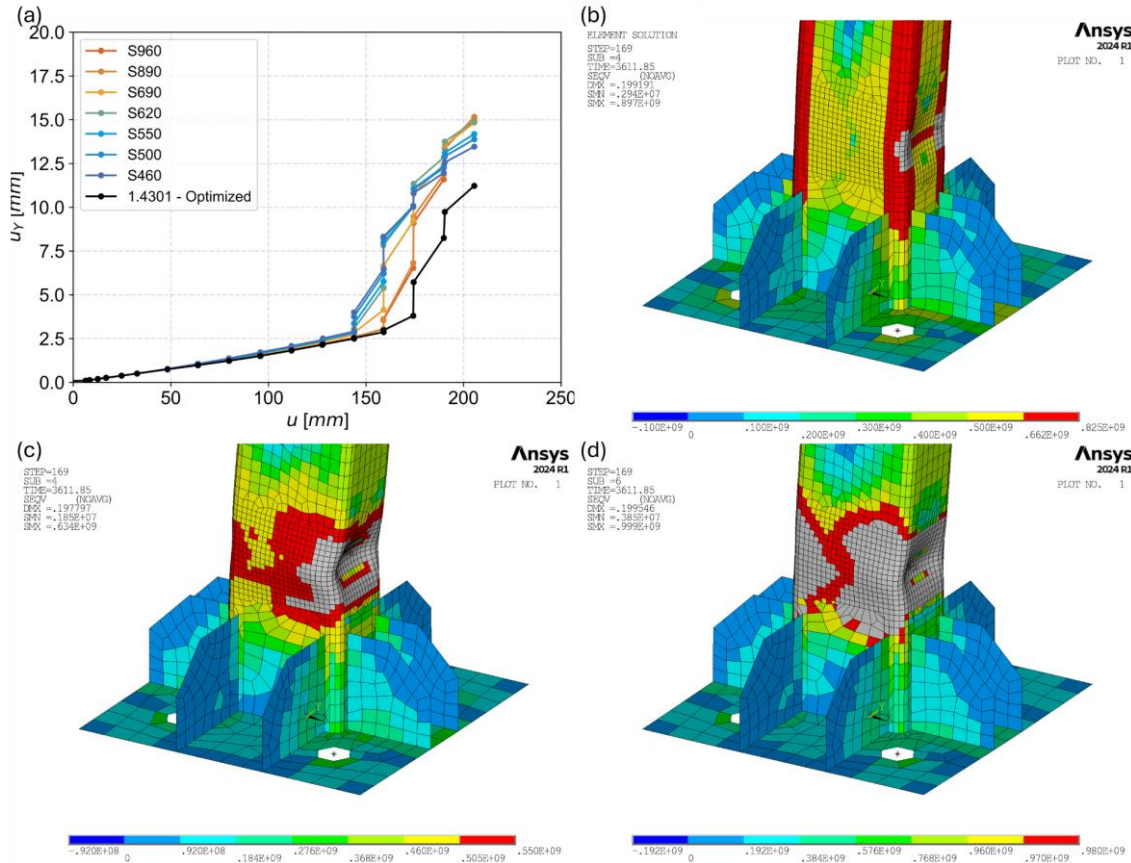


Fig. 14 (a) Transverse deformation of the cross-section. Equivalent stress above embedment. Step 169 at top displacement 175 mm. (b) 1.4301 – Opt., (c) S460, and (d) S980

The final comparison is the transverse deformation of the section above the embedment during loading, see Fig. 14 (a). Stainless steel exhibits lower transverse deformations at higher loads, while at lower loads the transverse deformations are comparable. The transverse deformation and local buckling above the embedment are shown in Fig. 14 (b–d).

6. Discussion

The superior performance of stainless steel compared to high strength steels (HSS) under cyclic loading conditions has notable implications for structural design, particularly under many times repeated loading. The ability of stainless steel to maintain its strength and ductility under repeated loading makes it a viable option for structures where resilience and durability are critical. This study supports the use of stainless steel in applications where materials are subjected to high cyclic loads, such as in bridges, high-rise buildings, and infrastructure in earthquake-prone areas.

7. Conclusion

This study systematically investigated the cyclic behavior of stainless steel through both experimental and numerical approaches, offering insights into the material's performance under cyclic loading conditions. The research began with a detailed examination of the material properties and experimental setup, laying the groundwork for developing a robust numerical FE model.

The simplified material model was developed, and its material model parameters were optimized using sensitivity analysis and MOP. The material model was validated against experimental data and was found to be effective in predicting the response of stainless steel under cyclic loading. The numerical model with the simplified material model qualitatively simulated the experiment

and proved to be an appropriate choice for modelling the cyclic behavior of stainless steel, whereas ANSYS only offers the Ramberg-Osgood model for monotonic loading.

Moreover, the simplified model appears to be a very good alternative to the Chaboche model because it is defined by fewer input parameters that can be more intuitively determined and identified from laboratory tests. The yield strength, ultimate strength and ultimate strain are clearly given and then it is practically sufficient to identify the strain hardening parameters m and n . Therefore, this simplified model is very suitable for practical use in nonlinear calculations of the steel structures under cyclic or repetitive loading.

Additionally, the study extended the comparison to high strength steels (HSS), demonstrating that stainless steel exhibits superior effectiveness in scenarios involving cyclic loading. The findings underscore the potential of stainless steel as a preferred material in structural applications where ductility, strain hardening, and resistance to cyclic loading are required.

In conclusion, this research not only validates the effectiveness of the simplified material model but also reinforces the growing importance of stainless steel in modern structural engineering, particularly in dynamic and seismic environments.

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