SHS and RHS stainless steel slender members loaded by compression and bending interaction

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Abstract. Behaviour of stainless steel slender members loaded by interaction of axial compressive force and bending moment is investigated in this research. Square hollow sections (SHS) made of austenitic stainless steel grade are considered. An initial numerical parametric study in FE software Abaqus is given and its results are compared to the existing design procedures and design standard rules. The investigated parameters are mainly the column slenderness, section slenderness, ratio between the applied bending moment and axial compressive force and the moment distribution along the member. The necessity of having additional design rules for stainless steels is firstly demonstrated on the values of interaction factors ky which are significantly higher for stainless steel members due to the material non-linearity with decreased stiffness even at lower stress levels. As an alternative, the General Method is used for comparison to the Abaqus GMNIA model results. The limitation of the method when used for members of non-linear material behaviour is shown and a safe modification of design procedure is suggested.

1. Introduction

Stainless steel alloys utilization as a structural elements increased, mostly due to their corrosion resistance, mechanical properties, aesthetic appearance and easy maintenance, in the last few decades. Nevertheless, it is still restrained by the high initial investment which is, partially, caused by the insufficient background of stainless steel structures behaviour. Design procedure of stainless steel members loaded by the interaction of compressive force and bending moment provided by stainless steel code EN 1993-1-4 [1] is mostly based on the carbon steel code 1993-1-1 [2]. That leads to some inaccuracies. Many researches tried to develop this procedure to be more accurate and efficient in the last years. 1993-1-1 [2] providing another design approach called General method applicable for beam-columns. The procedure is not commented in [1] and therefore there is no limitation regarding to material behaviour. This paper is primarily focused on the evaluation of the General Method for stainless steel square hollow section (SHS) members and some improvement is suggested. Further, new design approach developed by Ou Zhao [3] and current design approach provided by stainless steel [1] are evaluated too.

2. Investigated members

As was mentioned before, only SHS member research is presented in this paper. Cross-sections 80x3 and 80x5 mm were considered. Member lengths are various between 1000 mm and 7000 mm. The same cross-section members also being tested and will be presented on the conference as well. The
austenitic stainless steel grade 1.4404 was selected. The material properties were obtained through the tensile tests recently. Due to high strains occurred in the cross-section corner parts during cold-working, tensile tests were performed for corner and flat coupons separately. Location of the test coupons providing Figure 1.

![Figure 1. Location of flat and corner coupons.](image)

MTS Qtest 100 kN electromechanical testing machine with all data recorded at 5 HZ using the SPIDER data acquisition system with CATMAN32 data acquisition software was used to all coupon tensile tests. The tests were controlled by the strain. To obtain smooth stress-strain diagram curve, the accepted strain rate for testing up to 1.5 % strain was 0.007 % per second, followed by 0.2 % per second until fracture. In the research, flat coupon behaviour was considered for the whole cross-section. Effect of the corner region different properties was shown as negligible on the interaction in [4]. Member lengths and slenderness information are summarised in Table 1. Table 2 providing material properties information. Where $E_0$ is the initial young modulus of elasticity, $\sigma_{0.2}$ is the 0.2% proof stress, $\sigma_{1.0}$ is the 1.0% proof stress and $\sigma_u$ is the ultimate stress.

| Section | $L$ [mm] | 1000 | 1500 | 2000 | 2300 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 6000 | 7000 |
|---------|-----------|------|------|------|------|------|------|------|------|------|------|------|------|
| 80x3    | $\lambda$ | 0.64 | 0.76 | 1.01 | 1.16 | 1.26 | 1.51 | 1.77 | 2.02 | 2.27 | 2.52 | 3.02 | 3.53 |
| 80x5    | $\lambda$ | 0.58 | 0.87 | 1.15 | 1.32 | 1.44 | 1.73 | 2.01 | 2.30 | 2.58 | 2.87 | 3.44 | 4.02 |

Table 2. Material properties.

| Section | $E_0$ [MPa] | $\sigma_{0.2}$ [MPa] | $\sigma_{1.0}$ [MPa] | $\sigma_u$ [MPa] |
|---------|-------------|----------------------|---------------------|-----------------|
| 80x3    | 183200      | 397.1                | 465.3               | 627.6           |
| 80x5    | 190500      | 448.1                | 516.2               | 627.4           |

3. Numerical modelling

In order to obtain the real member behaviour, 3D model using GMNIA, geometrically and materially non-linear analysis with imperfections, was created in software Abaqus. The model will be validated soon on the planned tests. The same model was successfully validated in [4].

3.1. Considered loading

The research is focused on the compressive and bending interaction. Only uniform moment distribution along the member length was considered. The loading values are based on the axial
compressive force $N_{Ed}$ and member column resistance $N_{b,Rd}$ ratio labelled as $n_b$. Values of $n_b$ are shown in Table 3.

| $n_b$ | 0  | 0.3 | 0.5 | 0.7 | 0.8 | 1.0 |
|-------|----|-----|-----|-----|-----|-----|

For the initial prediction of the bending moment, the interaction formula provided in [3] was used. The bending and column resistances were obtained from Abaqus. The interaction formula is given by equation (1) and the interaction factor formula according to [3] by equation (2).

$$\frac{N_{Ed}}{N_{b,Rd}} + k_{cs} \frac{M_{Ed}}{M_{b,Rd}} = 1$$

$$k_{cs} = 1 + D_1 (\bar{\lambda} - D_2)n_b \leq 1 + D_1 (D_3 - D_2)n_b$$

where $N_{Ed}$ is the design compressive force, 
$M_{Ed}$ is the design bending moment, 
$N_{b,Rd}$ is the buckling resistance, 
$M_{b,Rd}$ is the bending resistance, 
$n_b$ is the $N_{Ed}$ to $N_{b,Rd}$ ratio, 
$k_{cs}$ is the interaction factor according to [3], 
$\bar{\lambda}$ is the non-dimensional slenderness, 
$D_i$ are the constants according to stainless steel grade and they are given by Table 4.

| Grade  | $D_1$ | $D_2$ | $D_3$ |
|--------|-------|-------|-------|
| Austenitic | 2.0   | 0.30  | 1.3   |
| Duplex  | 1.5   | 0.40  | 1.4   |
| Ferritic| 1.3   | 0.45  | 1.6   |

3.2. GMNIA model

The numerical model was created in software Abaqus. Four-noded shell element with reduced integration S4R was used. Two Reference Points situated on each member end in the centroid, rigidly coupled to the shell edged, ensured pin-ended boundary conditions.

To obtain the critical load with the corresponding eigenmodes the linear buckling analysis was made firstly. The first buckling mode was a flexural buckling mode as the sections are quite stocky. Local buckling mode was always some higher mode. Both local and global modes were used for the imperfection shape definition in the following calculation. The global imperfection amplitude was considered as $L/1000$ whereas the local imperfection amplitude was calculated according to Dawson and Walker [4] formula given by equation (3).

$$\omega_0 = \gamma \left( \frac{\sigma_{0.2}}{\sigma_{cr}} \right) t$$

where $\gamma$ is the material constant, for stainless steel is equal to 0.023, 
$\sigma_{0.2}$ is the 0.2% proof stress, 
$\sigma_{cr}$ is the cross-section critical stress, 
$t$ is the thickness of the structural element.
Separate model was used to section compression resistance \( N_{Rd} \) calculation. The same model was equipped by the additional supports in the middle of flat parts of the cross-section along the whole member. That prevent the local buckling phenomena. Only local imperfection was considered.

3.3. GNIA model
The General Method is based on the geometrically non-linear analysis of the structure with member imperfection (GNIA). Therefore, simplified 2D model, using B21 beam element, was created in software Abaqus. SHS cross-sections were simplified into the box cross-sections with modified wall thickness in order to keeping the same moment of inertia. The model was considered elastic using the elasticity modulus given in Table 2. The section resistance according to General Method is given by equation (4).

\[
\frac{N_{Ed}}{N_{Rd}} + \frac{M_{Ed}^u}{M_{Rd}^u} \leq 1
\]  

(4)

where \( N_{Rd} \) is the section compressive resistance, \( M_{Rd}^u \) is the maximum of the bending moment along the beam calculated by GNIA.

For the section resistance in compression and bending, values from the 3D GMNIA model were used. The member imperfection differs from those in chapter 3.2 as it should cover also the effect of material non-linearity. The initial geometric imperfection \( e_0 \) was calculated by equation (5).

\[
e_0 = \alpha (\bar{\lambda} - \bar{\lambda}_0) \frac{M_{Rd}}{N_{Rd}}
\]  

(5)

where \( \bar{\lambda} \) is the non-dimensional slenderness, \( \bar{\lambda}_0 \) is the plateau length, \( \alpha \) is the characteristic of the buckling curve.

4. Evaluation

4.1. Ou Zhao
Evaluation of the Ou Zhao method [3] is presented in this chapter. Assessment is focused on the interaction factor \( k \) calculated by [3] and obtained from the numerical GMNIA model. The comparison is shown in Figure 2 for SHS 80x3 mm and in Figure 3 for SHS 80x5 mm. Curves represent interaction factor according to [3] and dots are values obtained from numerical study.

![Figure 2. Results for SHS 80x3 according to Zhao and numerical model.](image)
In the comparison to the numerical model, the initial part of the formula seems to be conservative for \( \bar{\lambda} \leq 1.7 \) but the upper bound of the factor is unsafe, especially in the cases of dominant compressive force. That could be caused by a different cross-section used (in [3] RHS members were used) or more probably, by different material behaviour of the considered austenitic stainless steel.

### 4.2. **EN 1993-1-4**

Design procedure provided by Eurocode [1] is evaluated in this section. The interaction factor is calculated by equation (6). The comparison is shown in Figure 4 for SHS 80x3 mm and in Figure 5 for SHS 80x5 mm. Curves represent again the formula of the interaction factor \( k [1] \) and dots are values obtained from the numerical study.

\[
1,2 \leq k_y = 1 + 2(\bar{\lambda} - 0.5)\frac{N_{Ed}}{N_{b,Rd}} \leq 1,2 + 2 \frac{N_{Ed}}{N_{b,Rd}} \tag{6}
\]

**Figure 3.** Results for SHS 80x5 according to Zhao and numerical model.

**Figure 4.** Results for SHS 80x3 according to EN 1993-1-4 and numerical model.
This approach is mostly safe for $\bar{\lambda} \leq 2.0$. However, the method has quite good results in the case of uniform bending moment along the member, which is this case. For other moment distribution, it becomes too conservative as there is no factor considering the moment distribution along the member.

4.3. General Method
Evaluation of the General method is conducted through the ratio of compressive force $N_{Ed,ABQ}$ obtained from GMNIA shell model and $N_{Ed,GNIA}$ obtained from equation (4) based on the GNIA beam model. Because both SHS 80x3 mm and SHS 80x5 mm indicates similar results, the assessment is shown together in Figure 6. Values greater than one indicate safe results.

Almost all results are on the unsafe side, except members with very low slenderness. The unsafe results are probably caused by the simplification of the material behavior, which is considered in the General Method. That could leads to the neglecting of second order effect resulting from the material non-linearity, especially for very slender members and significant contribution of bending moment loading to high stress level.

Therefore, a modification was suggested. Initial young modulus of elasticity $E_0$ has been replaced by the secant modulus of elasticity for stress level equal to the yield strength $E_{s,0.2}$. Equation (7) was used to calculation of $E_{s,0.2}$. Results of this modification are shown in Figure 7.
\[ E_{s,0.2} = \frac{\sigma_{0.2}}{E_0 + 0.002} \]  

(7)

Figure 7. Comparison of the General Method \( E_{s,0.2} \) modification.

For each \( n_b \) line of results, SHS 80x3 mm is represented by the upper row of points and SHS 80x5 mm by the lower row of points. The results are mostly on safe side, except very slender members loaded mostly by bending moment. However, in the case of dominant compressive force the results are very conservative.

In order to eliminate over-conservative results, another modification was suggested. The secant modulus \( E_{s,M} \) was calculated based on the stress caused by the bending moment. The evaluation is presented only for SHS 80x3 mm through the Figure 8.

Figure 8. Comparison of the General Method \( E_{s,M} \) modification.

As could be seen, all results are on the unsafe side again. So, the calculation with the secant modulus equal to the yield stress level is the most suitable modification, currently.

5. Conclusions
The main objective of this research is to study behaviour of stainless steel slender members loaded by the compressive and bending interaction. The General Method provided by EN 1993-1-1 [2] evaluation is presented in this paper, mainly. Otherwise, design approach provided by stainless steel code EN 1993-1-4 [1] and approach developed by Ou Zhao [3] are compared too.
3D shell element numerical model using GMNIA was created in software Abaqus to obtain realistic members behaviour. Then, simplified 2D beam model using GNIA was made in order to produce the General Method results.

The design procedure developed by Ou Zhao [3] provide safe results for members with low non-dimensional slenderness. The method become very unsafe with increasing non-dimensional slenderness, especially in the cases of dominant compressive force. That could be caused by different cross-section type considered in [3] but most likely by different stainless steel material. EN 1993-1-4 [1] results are very similar with unsafe results as well.

The General Method evaluation shown very unsafe results, therefore it is not suitable for materials with non-linear behavior in the current form. Two modifications of this method were demonstrated. Replacement of the initial modulus of elasticity $E_0$ in the global analysis by the secant modulus of elasticity equal to the yield strength $E_{s,0.2}$. That leads to safe, usually very conservative results, except for very slender members loaded mostly by bending moment. In order to eliminate over-conservative results, second modification considering secant modulus of elasticity calculated through the stress caused by bending moment $E_{s,M}$ was presented. The results are very unsafe again, so this modification is useless. Further investigation of this method is under way to obtain more accurate results.

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