# IMPERFECTION SENSITIVITY ANALYSIS OF LONGITUDINALLY STIFFENED PLATED GIRDERS SUBJECTED TO BENDING-SHEAR INTERACTION

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Abstract. This paper presents the study of imperfection sensitivity of longitudinally stiffened plated girders subjected to bending and shear load. For this purpose a finite element model is developed and verified against real tests. The geometrical imperfections are defined manually as general expected shapes and as buckling modes. For the study of structural imperfections, i.e. residual stresses, simplified stress field is used over the web and flanges.

### **1 INTRODUCTION**

The initial geometric imperfections are always present and have to be properly considered in geometrical and material nonlinear analysis. The imperfections, particularly for plated girders, are manly caused by steel plate rolling, cutting and welding. Since in a design procedure the real initial (geometrical and structural) imperfections are in general not known, the most unfavorable shape of the imperfections that can be realistically expected to appear should be taken into account.

The amplitudes of geometrical imperfections are limited with fabrication tolerances. Because the residual stresses are more difficult to model, the usual approach is to model geometrical and structural imperfections with equivalent geometrical imperfections.

In this paper, the influence of geometrical as well as structural imperfections on longitudinally stiffened plate girder resistance subjected to bending and shear is studied. The shapes of applied geometrical imperfections are defined in two ways: according to EN 1993-1-5 [1] and with buckling modes. The purpose is to find out which shapes are most critical for the stiffened panel resistance. The influence of simultaneously applied structural and geometrical imperfection are also studied and compared to the influence of equivalent imperfections.

The sensitivity analysis was carried out on symmetric and asymmetric cross sections. The parameters that were taken into account are: number of longitudinal stiffeners n (n = 1, 2), position of stiffeners, aspect ratio  $\alpha$  ( $\alpha$  = 1, 2), slenderness of the web  $h_w/t_w$  ( $h_w/t_w$  = 200, 250, and 300), stiffness of the longitudinal stiffener and type of stiffener cross-section (open T, closed trapezoidal). The analysis was performed for girder loaded with low bending – high shear, for girder loaded with high bending - high shear.

### **2** FINITE ELEMENT MODELING

The sensitivity analysis of stiffened plate girders was set up using software package ABAQUS. The basic girder layout is shown in Figure 1. This comprises an inverted simply supported beam with global panels of length a and height  $h_w$ . In the analysis symmetry of the girder is taken into account where only half of the girder with proper support conditions is modeled. Lateral torsional buckling was restrained by

providing adequate lateral restraint to the compression flanges. The structural steel S355 was modeled as elastic plastic with a linear strain hardening E/200.



Figure 1: Girder layout used in finite element modeling

To cover different levels of bending and shear load the panel length L of the girder was varied. Bending moment M and shear load V were calculated at a distance  $0.5 \times \max(b_i)$  from vertical stiffener. In Figure 2 the M-V interaction and typical lengths are shown. Models with length L4 were loaded with high shear – low bending, where shear failure mode with formation of tension field in the panel is expected. Models with lengths L1, L2, L3 were defined in the area of M-V interaction where mixed failure mode in the sense of tension field and plastic hinge formation is expected. In the last case the length of the girder L5 was designed to get only bending failure (formation of a plastic hinge). Lengths L2, L4 and L5 were defined with the following equations:

$$L2 = \frac{M_{f}}{V_{hw}}, \ L4 = \frac{M_{f}}{2 \cdot V_{hw}}, \ L5 = \frac{M_{el,eff}}{2 \cdot M_{f}},$$
(1)

where  $M_{el,eff}$  is elastic effective bending resistance of the plated girder,  $M_f$  is bending resistance of flanges only and  $V_{bw}$  is shear resistance of the web.



Figure 2: M-V interaction according to EN 1993-1-5 and denoted length of analyzed girders

In the parametric study the stiffness of the longitudinal stiffener was defined as a ratio of  $\gamma/\gamma^*$ , where  $\gamma$  is relative bending stiffness of the stiffener defined with:

$$\gamma = \frac{12 \cdot (1 - \nu^2) \cdot I_{sl}}{h_w \cdot t_w^3}, \qquad (2)$$

and  $\gamma^*$  is stiffness of the stiffner needed to prevent global shear buckling over the whole panel. The stiffness  $\gamma/\gamma^*$  was varied from 0.3 up to 28.

### 2.1 Geometrical imperfections

The initial geometrical imperfections were defined "manually" and as buckling modes. Numerical model for buckling analysis was modified to get buckling modes only in the analyzed panel. In Figure 3 the first five positive buckling modes, which were later used as initial geometrical imperfection are shown. The shapes of manually defined imperfections (see Figure 4) were modeled according to EN 1993-1-5:

- global stiffener deflection in half-sine wave out of the web plane (imperfection mode 1), with opposite direction in neighboring panel,
- as imperfection mode 1, with waves turned to the same direction (imperfection mode 2),
- local subpanel imperfection in half-sin wave out of the web plane, where longitudinal stiffener remains straight and waves in the subpanel are turned to the opposite direction (imperfection mode 3),
- the same as imperfection mode 3 with waves turned to the same side of the panel (imperfection mode 4)



Figure 3: Positive buckling modes for girder  $h_w / t_w = 2000/8$  mm,  $b_f / t_f = 500/30$  mm,  $\alpha = 1$ , T stiffener  $(b_{st} / h_{st} / t_{st} = 44/40/4$  mm,  $\gamma/\gamma^* = 1$ ), buckling model IMP 3



Figure 4: Manually defined initial geometrical imperfections

### 2.2 Residual stresses

The presence of residual stresses in stiffened plates is mainly attributable to the welding of plates. The residual stresses in the vicinity of the weld are close to the yield limit. Some examples of real distribution of the residual stresses can be found in [2, 3] for longitudinally unstiffened girder or in [4] for longitudinally stiffened plates. Because the real distribution of residual stresses in our case is not exactly known, simplification according to Figure 5b is proposed and used in numerical models. Simplification is as follows: in the vicinity ( $x_f$ ,  $x_w$ ) of the web – flange welds the web is in tension up to the yield limit, while the other parts of the web, including welded area in the vicinity of longitudinal stiffener, are in compression.

To investigate the effect of residual stresses on the girder resistance, the level of compression was varied from  $0.05 \times f_y$  to  $0.20 \times f_y$  (see Table 1). The area of the tension zone  $x_f$ ,  $x_w$ , depends on the level of assumed compression stresses  $k_f$ ,  $k_w$  and is given with equations in Figure 5. Residual stresses were investigated in combination with geometrical imperfections with amplitudes equal to 80% of fabrication tolerances according to EN 1090-2 [5].



Figure 5: Residual stresses in longitudinally stiffened plated girders with a slender web

MODEL	k <sub>w</sub>	k <sub>f</sub>	MODEL	k <sub>w</sub>	k <sub>f</sub>
RA005	0.05	0.20	RB005	0.05	0.05
RA010	0.10		RB010		0.10
RA015	0.15		RB015		0.15
RA020	0.20		RB020		0.20

Table 1: Considered level of residual stresses in stiffened girder

#### 2.3 Equivalent geometrical imperfections

To simplify the modeling of initial imperfections, i.e. geometrical and structural imperfections, the geometrical imperfections are enlarged to cover also the influence of residual stresses. Equivalent geometric imperfections that were considered in this study are determined according to EN 1993-1-5:

- EG1: global buckling of the stiffener with length a and amplitude of  $\pm \min(a/400, b/400)$
- EG2: local buckling of subpanel with short span a or  $b_i$  and amplitude of  $\pm \min (a/200, b_i/200)$
- EG3: local stiffener subjected to twist with amplitude of  $\pm 1/50$



Figure 6: Equivalent geometric imperfection

These imperfections were superimposed with respect to the imperfection direction and the selection of leading and accompanying imperfections. The amplitude of leading imperfection was taken as 100% and for all accompanying imperfections as 70%.

### 2.4 Model verification

The non-linear numerical model was verified with the test performed by Pavlovčič [6] and with the test executed in the framework of the COMBRI [7] project. The test of Pavlovčič was designed to get more or less pure shear resistance of the longitudinally stiffened girder. The longitudinally stiffened girder performed in the COMBRI project was intended to get information on the M-V interaction in the area of high bending moment and shear force. The results show good agreement in the sense of failure mode as well as in girder capacity.

### **3 INFLUENCE OF INITIAL IMPERFECTION – NUMERICAL STUDY**

### 3.1 Imperfection shapes

Figure 7 shows the influence of initial imperfections and initial amplitudes on girder resistance loaded with high bending-shear load (L1). The amplitudes of all investigated imperfections were  $+h_w/400 = 5 \text{ mm}, \pm h_w/200 = 10 \text{ mm}$  and  $\pm h_w/100 = 20 \text{ mm}$ . The shapes of imperfections were defined "manually" and as buckling modes. The results show that one general imperfection shape which leads to the minimum resistance of the plated girder is very difficult to obtain in this way. By increasing the amplitude of initial imperfection the capacity decrease is not always the case (see Figure 7a, imperfection 4, 5). In this case the imperfection amplitude direction is found as unimportant. The main reason for this is that local buckling prevails, especially in case when girder is stiffened with stronger longitudinal stiffeners.



Figure 7: Imperfection study on girder L1:  $h_w / t_w = 2000/8 \text{ mm}, b_f / t_f = 500/30 \text{ mm}, \alpha = 1, \text{ T stiffener } (b_{st} / h_{st} / t_{st} = 44/40/4 \text{ mm}, \gamma/\gamma^* = 1)$ 

Further results of imperfection influence are compared between the maximum and the minimum capacity calculated with different imperfection shapes (defined as first ten positive buckling modes). Figure 8 shows the normalized difference between the maximum and the minimum capacity and standard deviation for all analyzed initial imperfections with amplitude  $+h_w/200$ . The analysis was performed on girders:

- Ni ... symmetric girder with one open stiffener in compression zone,
- NiZ ... symmetric girder with one closed stiffener in compression zone,
- Ni-20 ... symmetric girder with two open stiffeners in compression zone,
- Ni-2OS ... symmetric girder with two open stiffeners in tension and compression,
- Ni-NP ... unsymmetrical girder with one open stiffener in compression zone,

where i indicates integers 1 to 4 and describes the stiffness of the stiffner mentioned in Section 2. Among all analyzed imperfections the difference between the maximum and the minimum value for



symmetric girder under high bending – high shear load (model L1) is up to 3.02% and up to 3.40% for asymmetric girders.

Figure 8: Imperfection study on girder L1 in relation to stiffness of the longitudinal stiffener

### 3.2 Influence of slenderness, panel aspect ratio and stress state in the panel

In Figure 9a-b the effect of geometrical imperfections on girder resistance against different slenderness of the web and panel aspect ratio is shown. At the change of web slenderness girders show very small change in imperfection sensitivity. This is found for all girder configurations. By increasing the panel aspect ratio  $\alpha$ , the sensitivity of girder resistance decreases for girders L4 which are loaded in high shear – low bending and girders L5, loaded in high bending – low shear. For girders L1 loaded in high shear – high bending the effect of geometrical imperfections on girder resistance remains more or less the same.



Figure 9: Sensitivity analysis on girders with different slenderness of the web (a) and different panel aspect ratio (b)

Finally, the imperfection sensitivity for different stress states in the panel is presented in Figure 10. For all studied girders with different stiffness of longitudinal stiffener N1-N4 the same behavior is found. Sensitivity of girder resistance decreases with increasing bending moment in the panel. This can be

clearly seen from Figure 10 where at the beginning (L4 to L2) considerable drop is observed. Furthermore, the effect on girder resistance remains more or less the same as long as the bending moment is the same as or higher than the bending capacity of flanges.



Figure 10: Sensitivity analysis on girders with different stress state

#### 4 INFLUENCE OF RESIDUAL STRESSES – NUMERICAL STUDY

The residual stresses were calculated in combination with geometrical imperfections. Geometrical imperfections were defined according to EN 1993-1-5. The amplitude of the leading imperfection was taken as 80% and the accompanying imperfection as  $0.7 \times 80\%$  of those according to EN1090-2. Figure 11b shows the influence of residual stresses in the girder. Curve RSF represents the influence of the level of compression stresses  $a_f \times f_y$  ( $a_f = 0.05$ , 0.10, 0.15, 0.20) in the flanges, while the compression stresses in the web remain the same  $a_w \times f_y$  ( $a_w = 0.05$ ). By increasing the level of compression stresses in the flanges, the girder capacity decreases, however only to a certain level. The RSW curve presents the influence of level of compression stresses  $a_w \times f_y$  ( $a_w = 0.05$ , 0.10, 0.15, 0.20) in the web, at constant compression stresses  $a_f \times f_y$  ( $a_f = 0.20$ ) in the flanges. Already at the minimum applied residual stresses ( $a_w = 0.05$ ) in the web, significant drop in girder capacity can be found. Additional increase of residual stresses ( $a_w = 0.10$ , 0.15, 0.20) does not additionally influence girder resistance. However, comparing capacity to the one of the perfect girder, 2.5% decrease is found at most.



Figure 11: Influence of residual stresses on girder (N1-L1) resistance

### 5 EQIVALENT IMPERFECTIONS

When the influences of equivalent geometrical imperfections were taken into account, different combinations (see Figure 12) of basic imperfection shapes were analyzed to obtain the lowest resistance of the girder. In Figure 12 the normalized resistance for girder considering equivalent geometrical imperfections (I1-I4), geometrical imperfections (I5) and residual stress in combination with geometrical imperfections (I6) are presented. It can be seen that equivalent geometrical imperfections decrease the girder resistance only by 0.5% compared to the perfect girder, while the explicit consideration of residual stresses in combination with geometrical imperfection leads to decrease of girder resistance by 1.9%. In

this case equivalent geometrical imperfections do not reflect the influence of residual stresses present in the cross section.



I0: perfect girder I1: EG1+0.7×(EG2+EG3) I2: -EG1-0.7×(EG2+EG3) I3: 0.7×(EG1+EG3)+EG2 I4: EG1+0.7×(EG2+EG3) I5: I1 with amplitudes according to fabrication tolerances I6: I5 + considered residual stress acc. to model RA005

Figure 12: Influence of equivalent geometrical (I1-I4), geometrical imperfections (I5) and residual stresses (I6) on girder resistance

# 6 CONCLUSION

In this paper the effect of geometrical and structural imperfections of girder web panel is studied. Geometrical and structural imperfections are implemented in a nonlinear FEM analysis. Girders with different types and stiffnesses of longitudinal stiffeners subjected to bending and shear are considered. The main conclusions can be summarized as follows:

- Girders subjected to bending moment higher than bending capacity of flanges shows very little reduction in capacity when different initial geometrical imperfections and amplitudes are applied. The maximum reduction of 3.5% for amplitude of h<sub>w</sub>/100 is found.
- Higher geometrical imperfection sensitivity can be observed for girders loaded dominantly in shear (L4). In the worst case the maximum deviation of 7.5% is noted.
- The residual stresses do not influence so much the girder resistance (up to 1.5% for analyzed girder) as they influence the load-displacement response and failure mode which can differ in case of high compression stresses in the flanges.
- The main conclusion seems to be that girder web panels under high bending and shear are not as sensitive to the shape and expected amplitude of initial imperfection as girder web panels dominantly loaded in shear.

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