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Intermediate transverse stiffeners in stiffened plate girders

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Abstract
Plate girders are usually stiffened with a set of longitudinal and transversal stiffeners to increase buckling resistance. EN 19931-5 gives provisions for the determination of internal forces in the stiffener due to deviation forces and due to tension field action. The tests and numerical simulations showed that the force due to tension field action is much smaller than provided by EN 1993-1-5. To simplify design rule and to evaluate actual action of tension field action on transverse stiffeners a numerical parametric study was performed. The idea is to simplify design of intermediate transverse stiffener only on stiffness requirement which is much more practical than checking the maximum stresses and out of plane displacement of the transverse stiffener due to effect of deviation forces and tension field action on geometrical nonlinear model. The parametric study that was performed takes into account all possible load situations such as: deviation forces only (only normal stresses in the web) , tension field action only (only shear stresses in the web) and interaction of both effects (normal stresses and shear stresses in the web plate).

1. Introduction
The transverse stiffeners in plated girders are usually designed as rigid, preventing any interaction between adjacent panels. To assure this the intermediate transverse stiffener must have sufficient rigidity to maintain zero lateral deflection along the line of the stiffener.

The main consequence is that the plate panel between adjacent rigid transverse stiffeners may be analyzed as an isolated panel with well defined boundaries. To be safe-sided the panel is assumed to be restrained for transverse movements and free to rotate along the edges. Also the buckling length of longitudinal stiffeners is well defined and can be assumed to be equal to the spacing of transverse stiffeners.

Transverse stiffeners at end and intermediate supports are subjected to large axial forces from support reactions. For this reason they are mostly designed as double-sided stiffeners and are not dealt with in this paper. Intermediate transverse stiffeners are installed to increase the strength and stiffness of the web panel and to prevent distortional effects on the plate girder cross-section. Normally they are designed as single-sided open stiffeners with different possible cross-sections. The most typical are flat stiffeners, L or T stiffeners.

In most cases intermediate transverse stiffeners do not carry large external forces. If they are subjected to large external forces, they have to be designed in a similar way as support stiffeners,

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taking account of any eccentricity if they are single-sided. In most cases intermediate transverse stiffeners are predominantly subjected to forces arising from the following two sources:

- Deviation forces from longitudinal stresses in the web panels adjacent to the stiffener that develops due to out-of-plane imperfect geometry of the stiffener. These deviation forces induce out-of-plane bending moments in the stiffener and are subjected to second order effects.
- Tension field action that develops in the post-buckling state in shear. It develops in the form of a diagonal tension band in the web plate and induces a compression axial force in the stiffener (truss analogy).

Both actions can appear individually or simultaneously. To resist these actions and to limit deformability, rigid transverse stiffeners should be in principle designed for strength and stiffness criteria at the ultimate limit state.

The first author that addressed the design issues of transverse stiffeners was Timoshenko (1936). The traces of his work can still be detected in current design rules for deviation forces as well as for shear buckling problems.

After 1950 many authors have dealt with transverse stiffeners, but mainly for the effects of the shear loading in the web panel: Stein&Fralich (1950), Basler et al. (1960), Rockey et al. (1971), Evans et al. [6], Höglund [7], etc. Two design rules were typically developed: the expression for calculating the minimum required second moment of area of the transverse stiffener and the expression for the axial force in the stiffener resulting from the tension field action in the web panel or as an alternative an expression for the minimum required cross-section area of the stiffener taking account of local buckling but usually ignoring overall flexural buckling of the stiffener.

Existing methods for design of intermediate transverse stiffeners vary widely in concept and in the resulting stiffener requirement. The AASHTO (1996) provisions for the design of transverse stiffeners were based on two criteria:

a) A moment of inertia requirement which ensure that the stiffener is able to maintain a line of near zero lateral deflection at the web shear buckling load. This requirement does not take into account the influence of postbuckling shear resistance.
b) Area requirement based on an estimate of the in-plane forces transmitted by the postbuckled web plate to the transverse stiffener.

Neither of this requirements does not consider the effect of out-of-plane forces on transverse stiffeners which are caused by initial imperfections and postbuckling response of the web panel. In AASHTO (2007) only moment of inertia is required to assure full development of postcritical resistance of the plate, while the area requirement is no longer specified as many research studies have shown that transverse stiffeners in I-girders designed for tension-field action are loaded predominantly in bending due to the restraint they provide to lateral deflection of the plate.

According to Eurocode EN 1993-1-5 (2006) the intermediate transverse stiffener has to meet strength and strain requirement. This requirements needs to be fulfilled taking into account second order effects.

The common drawback of all mentioned design rules is that the axial force in the stiffener induced by the tension field action in the post-buckling state is overestimated to a large extent, as has been demonstrated by several authors (Lee et al. 2002, 2003, Presta 2007, Hendy et al. 2008, and will be demonstrated again later on in this paper. This will be done based on two tests performed on 1.5 m high plate girder and on the results of extensive numerical parametric study. The main aim is to find out if it is possible to cover all relevant design issues of rigid intermediate transverse stiffeners of plate girders by the stiffness approach alone – defining the minimum required second moment of area of the stiffener.

2. Design Provisions

2.1 AASHTO (2007)

In AASHTO (2007) the transverse stiffeners adjacent to web panels in which neither panel supports shear forces larger than the shear buckling resistance, the moment of inertia of the transverse stiffener shall satisfy the smaller of the following:

$$I_{st} \geq \min(a,\ h_w) \cdot t_w^3 \cdot \max\left(2.5 \cdot \left(\frac{h_w}{a / h_w}\right)^2 - 2.0,\ 0.5\right) \tag{1}$$

and

$$I_{st} \geq \frac{h_w^4 \cdot \rho_t^{1.3}}{40} \left(\frac{f_y}{E}\right)^{1.5} \tag{2},$$

where I_{st} is moment of inertia of the transverse stiffener taken about the edge in contact with the web, and ρ_t is ratio of yield stress of the stiffener to the local buckling stress of the stiffener:

$$\rho_t = \max\left(\frac{f_y}{F_{crs}},\ 1.0\right) \tag{3},$$

$$F_{crs} = \frac{0.31 \cdot E}{\left(b_{st} / t_{st}\right)^2} \leq f_y \tag{4},$$

where E is elastic modulus and f_y yield strength of the steel. For other notations see Fig. 1.

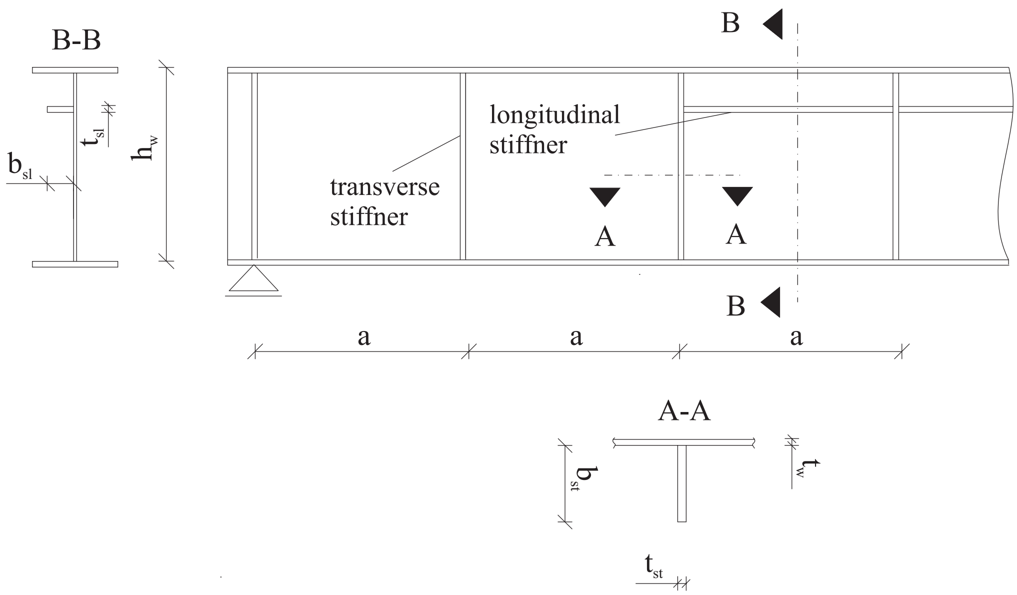


Figure 1: Notation of the stiffened panel

To develop the web shear postbuckling resistance associated with tension field action, the moment of inertia of the transverse stiffeners must satisfy Eq. 2.

For longitudinally stiffened girders Eq. (2) can be used to determine the transverse stiffener area with h_w equal to the whole girder depth, if the tension field over the whole web is developed and with h_w equal to maximum subpanel depth, when tension fields in each subpanel are independently developed. Additionally, the transverse stiffener used in the longitudinally stiffened web panels shall also satisfy:

$$I_{st} \geq \left(\frac{b_{st}}{t_{st}}\right)\left(\frac{h_w}{3 \cdot a}\right) \cdot I_{sl} \tag{5}$$

where I_{sl} denotes the second moment of area of the longitudinal stiffener including an effective width of the web equal to $18t_w$ and calculated for the neutral axis of the combined section, b_{st} and t_{st} are shown in Fig. 1.

2.1 EN 1993-1-5

According to Eurocode EN 1993-1-5 specifications the stiffener has to meet strength and stiffness criteria given as:

- Maximum stress in the stiffener should not exceed the yield strength:
  $\sigma_{\max} \leq \frac{f_y}{\gamma_{M1}}$.
- Additional lateral deflection should not exceed:
  $w_{\max} \leq \frac{h_w}{300}$.

When transversally stiffened plate is loaded only with pure shear, the transverse stiffener has to fulfill minimum stiffness criteria:

$$I_{st} \geq \frac{1.5 \cdot h_w^3 \cdot t_w^3}{a^2} \quad \text{for } \alpha = \frac{a}{h_w} \leq \sqrt{2}$$
$$I_{st} \geq 0.75 \cdot h_w \cdot t_w^3 \quad \text{for } \alpha = \frac{a}{h_w} > \sqrt{2} \tag{6}$$

This is in analogy with stiffness requirement given with AASHTO (1996). Due to tension field action in the web plate and truss analogy the stiffener is subjected to axial force defined as:

$$N_{st,ten} = V_{Ed} - \frac{1}{\overline{\lambda}_w^2} \cdot h_w \cdot t_w \cdot \frac{f_y}{\sqrt{3} \cdot \gamma_{M1}} \tag{7},$$

where V_{Ed} is a design shear force and $\overline{\lambda}_w$ is a slenderness of the web panel adjacent to the stiffener. Double sided stiffeners may be simply designed as concentrically compressed columns. In case of single sided stiffeners the stiffener should be verified for the axial force and for bending moments coming from the eccentricity of the axial force. Local buckling of open stiffeners is closely linked to the torsional buckling mode and in EN 1993-1-5 local buckling is prevented with the following expression:

$$\sigma_{cr} \geq \theta \cdot f_y \tag{8},$$

where σ_{cr} is the elastic critical stress for torsional buckling of the stiffener and θ is a parameter that is linked to the stiffener cross-section shape (2 for flat stiffeners, 6 for stiffeners that possess warping torsional stiffness).

Longitudinal compression stresses in the web plate and in longitudinal stiffeners coming from bending moments and axial forces induce transverse deviation forces. The magnitude of these deviation forces q_{dev} is related to the stiffener imperfection amplitude w_0 and is subjected to the second order effects. The corresponding calculation model adopted in EC 1993-1-5 is shown in Fig. 2. The minimum required second moment of area to resist deviation forces according to the mechanical model presented in Fig. 2 is given with the following expression:

$$I_{st} \geq \frac{\sigma_m}{E}\left(\frac{h_w}{\pi}\right)^4 \left(1 + w_0 \frac{300}{h_w} u\right) \tag{9},$$

where

$$\sigma_m = \frac{\sigma_{cr,c}}{\sigma_{cr,p}} \frac{N_{Ed}}{b}\left(\frac{2}{a}\right),$$

$$u = \frac{\pi^2 \cdot E \cdot e_{\max}}{f_y \cdot 300 \cdot b / \gamma_{M1}} \geq 1.0\,,$$

$$w_0 = \min\left(\frac{h_w}{300}, \frac{a}{300}\right),$$

N_{Ed} is the maximum compressive force of both adjacent panels, e_{max} is the maximum distance from the edge of the stiffener to the centroid of the stiffener, $\sigma_{cr,c}$ and $\sigma_{cr,p}$ are elastic critical stresses for column- and plate-like buckling.

In most practical design cases the web plate is subjected to combination of shear and normal longitudinal stresses. The stiffener is subjected to axial load $N_{st,ten}$ due to tension field action and to deviation forces q_{dev} due to normal stresses acting on initially imperfect stiffener. For these load combinations the stiffener should be designed taking into account second order effects and both strength and stiffness criteria should be met. EN 1993-1-5 does not give explicitly the design checks for this general case, which is critical especially for single-sided stiffeners because the overestimated axial force from the tension field action is acting eccentrically on the stiffener.
A relatively simple design check that covers strength and stiffness criteria including second order effects is given in Beg et al. (2010) or Johansson et al. (2007).

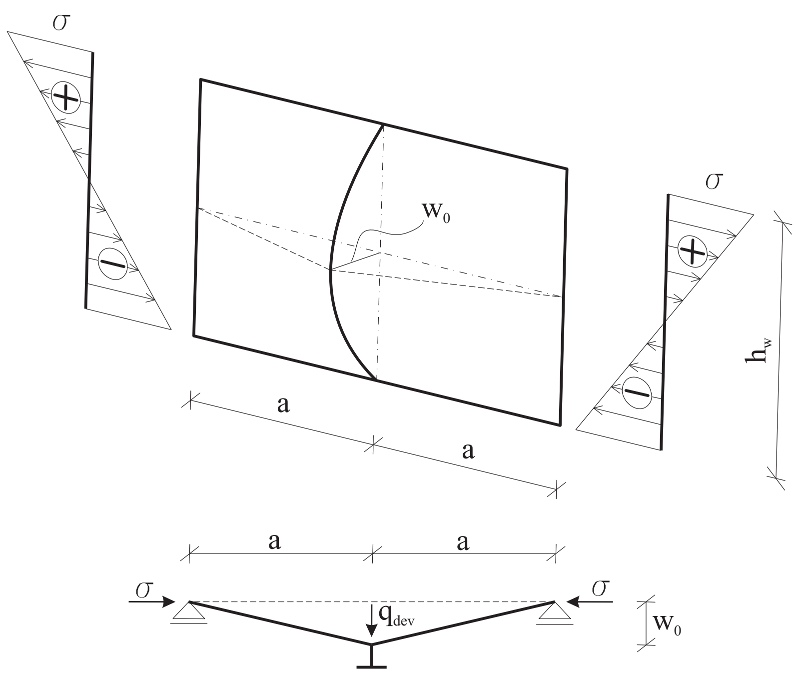


Figure 2: Calculation model for deviation forces in EN 1993-1-5

3. Experimental work

Two tests on intermediate transverse stiffener were performed. The layout of the tested girder and the load positions for tests S1 and S2 are shown in Fig. 3. The dimensions of the girder cross-sections are gathered in Table 1. The intermediate transverse stiffeners were designed for the effect of deviation forces and for the effect of tension field action. The deviation forces were calculated from the stress distribution due to pure bending resistance of the plate. Only half of the axial force due to tension field action, calculated according to (7), was considered in the design. In both studied cases the dimension of transverse stiffener was finally set to $b_{st} \times t_{st} = 120 \times 15$ mm.

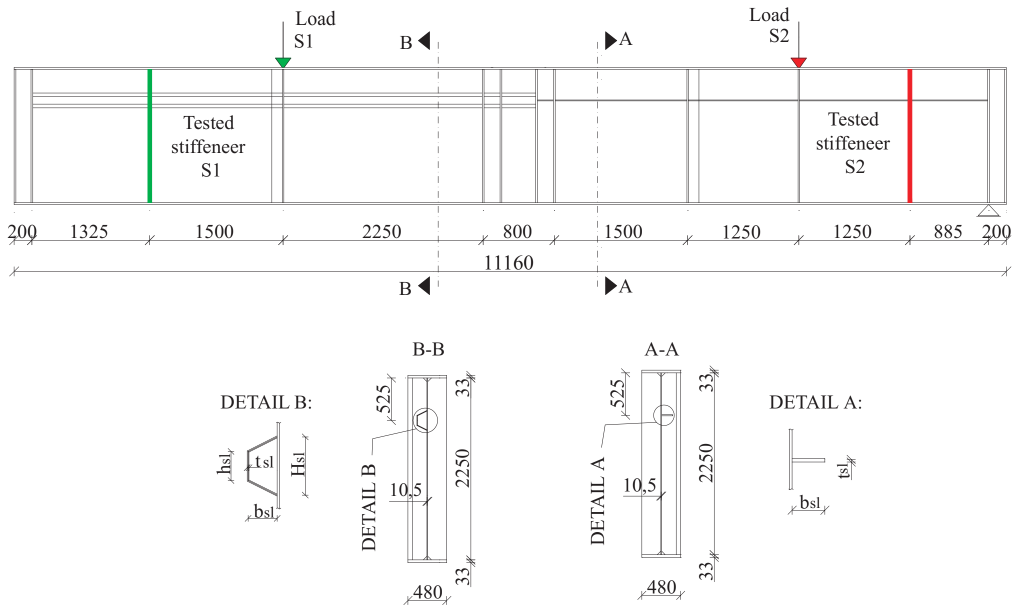


Figure 3: Layout of the tested girder and loading positions for tests S1 and S2

Table 1: Geometry of the tested steel plate girders

Specimen	Web			Upper flange		Bottom flange		Longitudinal stiffener			
	h_w [mm]	t_w [mm]	a [mm]	b_{f1} [mm]	t_{f1} [mm]	b_{f2} [mm]	t_{f2} [mm]	H_{sl} [mm]	h_{sl} [mm]	b_{sl} [mm]	t_{sl} [mm]
S2	1500	7	1500	320	22	320	22	/	/	90	10
S1	1500	7	2250	320	22	320	22	160	80	80	5

The out-of-plane displacements in the panel as well as in the investigated transverse stiffener were measured in discrete points by displacement transducers. Besides displacements also strains in the transverse stiffener and in the web plate in the vicinity of the stiffener were measured, as shown in Fig. 4. The strain gauges were positioned on each side of the stiffener and of the web plate.

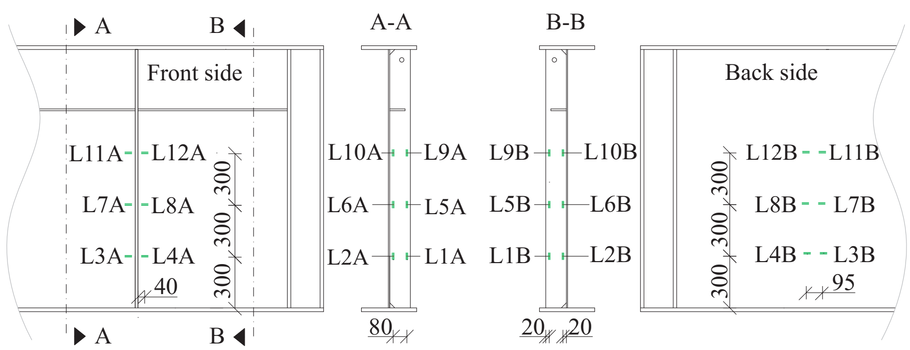


Figure 4: Position of applied strain gauges in the stiffener and in the web

The initial geometrical imperfection of the transverse stiffener was measured and in both cases bow imperfection in direction of the intermediate transverse stiffener was detected with maximum amplitude of 4.7 mm for stiffener S1 and 3.7 mm for stiffener S2.

3.1 Test results

In Fig. 5 the load-deflection curves are plotted for both tests. In the first test S1 the load was increased up to the value of 2572 kN. The test was stopped just before the maximum capacity of the girder was reached. In the second test S2 the test specimen was loaded up to the maximum resistance of 2659 kN and in terms of displacements well to in the softening range.

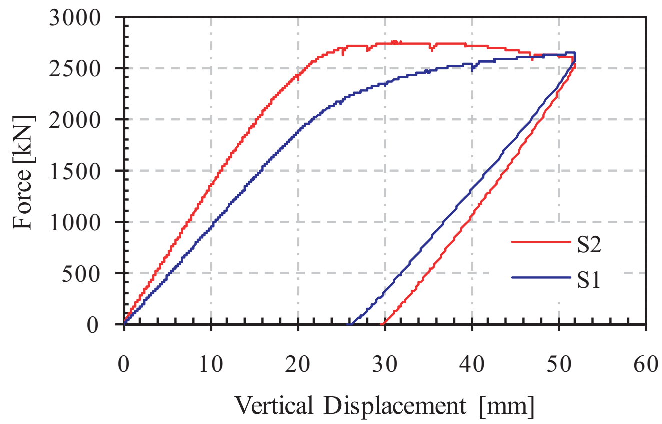


Figure 5: Load-deflection curves for tests S1 and S2

In Fig. 6 the average strains over the thickness of the transverse stiffener are plotted. The resulting maximum membrane stress for stiffener S1 is obtained at the position of strain gauge L12 in the web plate with the value of -210 MPa, which is less than the measured yield stress of material. In test S2 plastic strains were observed only in point L11 with the maximum average strain of 0.46%. This strain was obtained after the peak load had already been attained. The strain at the maximum load was 0.30%. In both tests the maximum average strains were measured in the cross-section near the longitudinal stiffener. This is due to the fact that this cross-section is directly in the area where the diagonal tension field is anchored into the transverse and longitudinal stiffener. In this cross-section (1-1, see Fig. 7) the strains are relatively high, while in the other two cross-sections (2-2 and 3-3) the strains are smaller and also more representative for the determination of the axial force in the intermediate transverse stiffener.

In each cross-section the axial forces were evaluated from the measured strains. The results are gathered in Table 2. For comparison, 100% (100% TFA) and 50% (50% TFA) of axial force from tension field action according to EN 1993-1-5 are given. As can be seen, the maximal compression is obtained in section 1-1 (see Fig. 7). One of the measured points (L11) was directly in this diagonal tension field where the strains are extremely high. In the middle section 2-2 the axial force is much smaller, while in section 3-3 the smallest value is obtained. It is reasonable to assume that section 2-2 is relevant for determining the representative (average) value of the axial force in the stiffener. This axial force presents only 56% of the calculated axial force arising from tension field action using truss analogy.

Table 2: Axial force in the transverse stiffener at maximal girder resistance, taking into account effective part of the web $15\varepsilon t_w$

N_{ten} [kN]	Stiffener S1			Stiffener S2		
SECTION	1-1	2-2	3-3	1-1	2-2	3-3
TEST	- 329.1	**- 290.0**	- 223.4	- 653.9	**- 280.7**	- 160.4
100% TFA		- 514			- 504	
50% TFA		- 257			- 252	

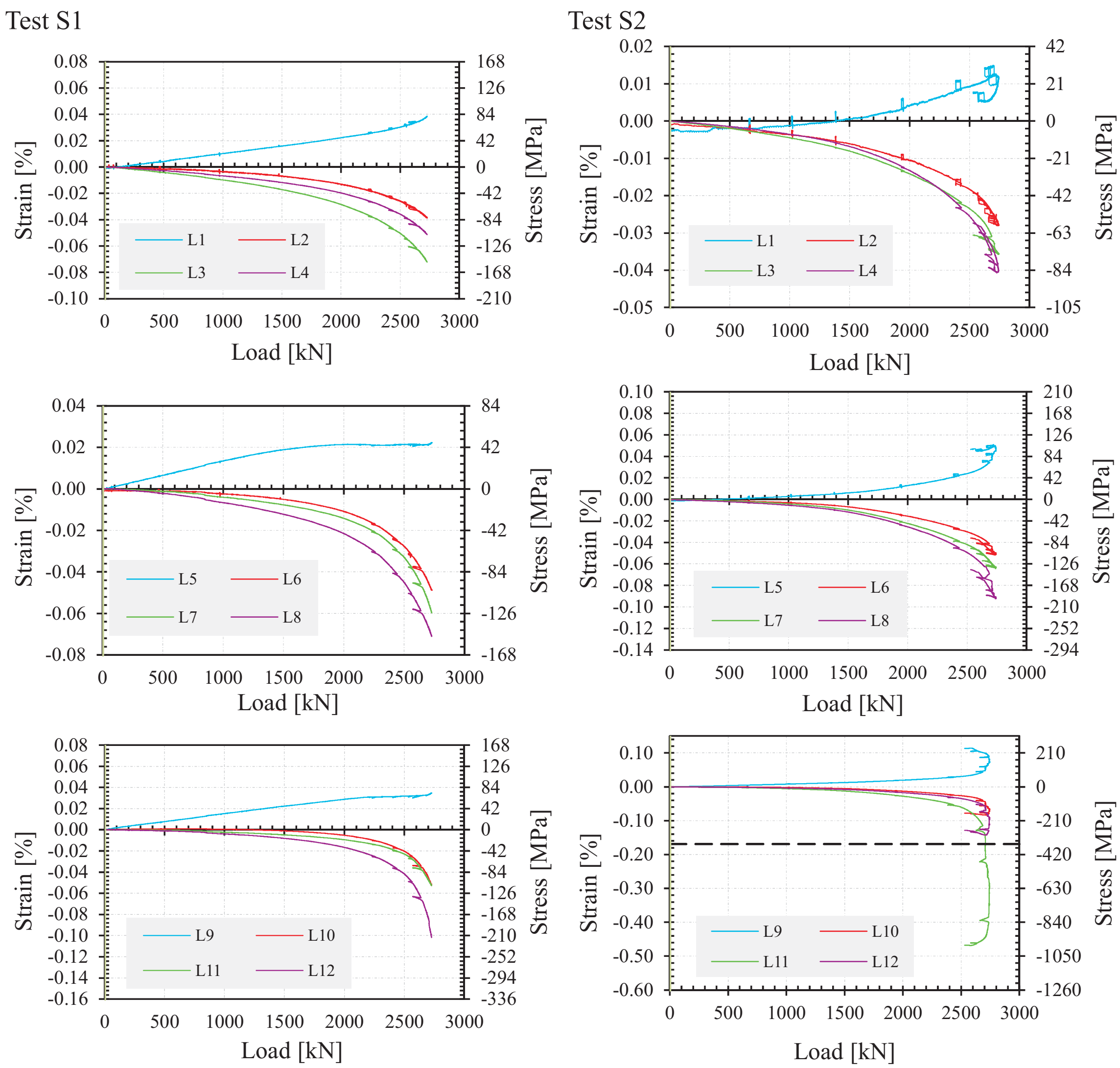


Figure 6: Strain measurements in the transverse stiffeners

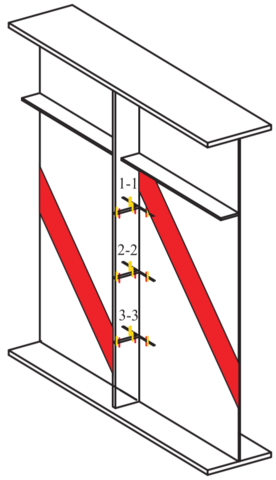


Figure 7: Cross-sections in the stiffener where the axial forces were evaluated

4. Numerical simulations

4.1 Numerical verification

The numerical model was developed in the multi-purpose code ABAQUS and was verified against the test results. The measured initial geometrical imperfections and nonlinear material behavior based on tensile tests were considered. The verification of numerical model was performed by comparing initial stiffness, maximum capacity and load-deflection curve.

In Fig. 8 the comparison of experimental and numerical results through load deflection curve is shown. The initial stiffness of numerical model S1 is slightly higher than the experimental one. The transition from elastic to plastic zone is very similar, while the maximum capacities cannot be compared, since the test had been stopped before resistance was reached. However, comparing the load obtained at the same vertical displacement, the difference between numerical and experimental values is small. As noted in previous case, also the initial numerically obtained stiffness of test S2 (see Fig. 9) is slightly higher than the experimental one. The calculated resistance is lower by 3.7% in comparison to the experimental results.

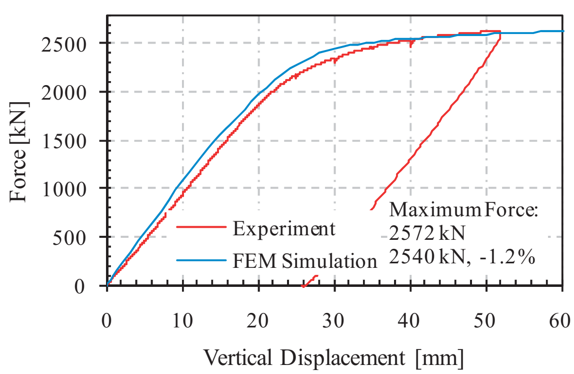


Figure 8: Comparison of load-deflection curves for test S1

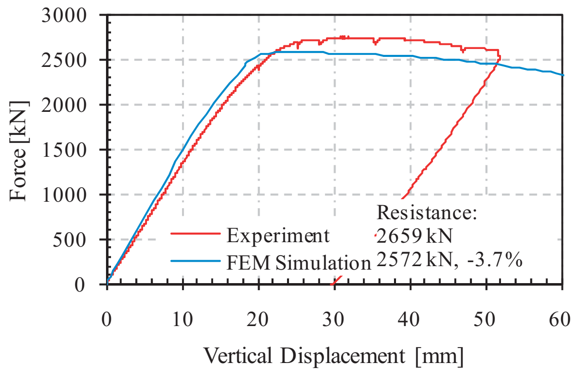


Figure 9: Comparison of load-deflection curves for test S2

4.2 Parametric study

Three sets of numerical analysis were performed. First the influence of the stiffness of transverse stiffeners was studied on longitudinally stiffened girders subjected to combination of high bending moment and shear load. The second series was performed on transversally stiffened girders subjected only to shear load. In the last set the influence of stiffness of transverse stiffeners was studied on plate loaded with axial force only.

The bilinear material model with yield strength $f_y = 355\ MPa$ was used in the parametric studies. Following EN 1993-1-5 the equivalent geometric imperfection of the transverse stiffener under consideration was taken as a half sine wave imperfection with the amplitude $w_0 = h_w/300$. All free edges, or the one connected to adjacent transverse stiffeners and flanges, were supported out-of the plate plane.

4.2.1 Longitudinally stiffened girder subjected to high bending moment and shear force

Numerical model used in parametric study where the influence of deviation forces due to bending moment and axial force due to tension field action on transverse stiffener is shown in Fig. 10.

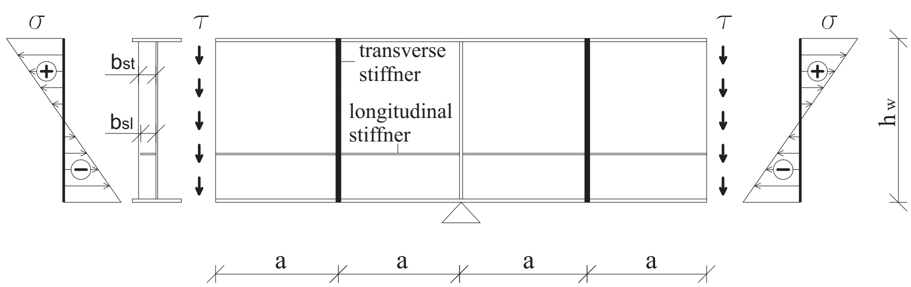


Figure 10: Numerical model of stiffened plate girder under combination of high bending moment and shear force

The varied parameters were: the stiffness of transverse stiffener, the web slenderness, the ratio of flange area over web area, the stiffness of longitudinal stiffener, and the panel aspect ratio. Seven different geometries of girder cross-section were analyzed. The basic geometry of the girder (girder G1 in Table 3) is defined with the following parameters: $h_w/t_w = 250$, $A_f/A_w = 0.7$, $\gamma/\gamma^* = 3.0$ and $\alpha = a/h_w = 1.0$, where γ denotes the relative stiffness of the longitudinal stiffener and γ^* the limit stiffness of the longitudinal stiffener that prevents overall buckling of the web panel in pure shear including deflection of this stiffener. In all other cases (girders G2-G8) only one parameter is changed, compared to the basic girder (G1). Within each girder the additional parameter was stiffness of transverse stiffeners. The geometry of transverse stiffeners in the parametric study is gathered in Table 3.

Table 3: Parameters taken into account for girders loaded with high bending and shear load

STIFFENER	I1	I2	I3	I4	I5	I6	I7	I8
$b_{st}\times t_{st}$ [mm]	20×2	40×4	60×6	80×8	100×10	120×12	150×15	200×20
GIRDER	G1	G2	G3	G4	G5	G6	G7	G8
	h_w/t_w=250	A_f/A_w=0.3	A_f/A_w=1.1	γ/γ^* = 0.30	γ/γ^* = 1.00	α = 0.5	h_w/t_w =150	h_w/t_w =350

In Table 4 second moments of area for all transverse stiffeners (I1 - I8) are given. The dimensions are calculated following Eq.(6) and in the last two columns according to strength and stiffness checks assuming deviation forces and forces due to tension field action. 100% TFA denotes that full tension filed action was considered, and 50% TFA denotes that only 50% of tension field action was taken into account in the design of the stiffener.

Table 4: Required stiffener's stiffness considering different requirements

I_{req} (cm^4)	EN 1993-1-5 Eq. (6)	100% TFA	50% TFA
G1-G5	153.6	3617.4	887.1
G6	614.4	1696.0	697
G7	711.1	710.2	349.6
G8	56.0	2529.7	753.8

The out-of-plane deflections of transverse stiffeners loaded with high combination of shear force and bending moment are plotted in Fig.11. The curves are plotted for girder G1 and for different transverse stiffeners (see Table 4). The deflection shape depends on the stiffness of the stiffener. By increasing the stiffness the deflection of the stiffener is transformed from the "S" shape to the "C" (I5) shape. In Fig. 12 the resistance of girders obtained at the deflection of $h_w/300 = 6.67$ is plotted. The resistance was normalized with the maximum force obtained within all analyzed girders of the same cross-section properties, while the actual stiffness is normalized with the required stiffness given with Eq. (6) and with the required stiffness to fulfill strength and stiffness conditions taking into account 50% or 100% of the tension field action. When on the y axis value 1 is reached the resistance of the girder prove its maximum resistance and at the same time the out-of plane deflection of the intermediate transverse stiffener is under limit value of $h_w/300$. At this point minimum stiffness can be read to fulfill stiffness criteria. As it can be seen, the EN 1993-1-5 stiffness requirement generally covers most of design cases since the value 1 on y axis is reached before value 1 on x axis.

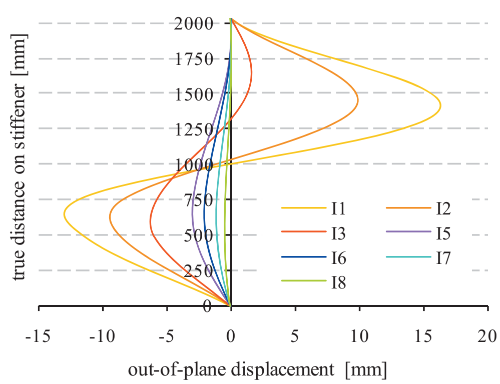


Figure 11: Out-of-plane displacement along the transverse stiffener for girder h_w/t_w=250, α=1, γ/γ^*=3.0, A_f/A_w=0.7

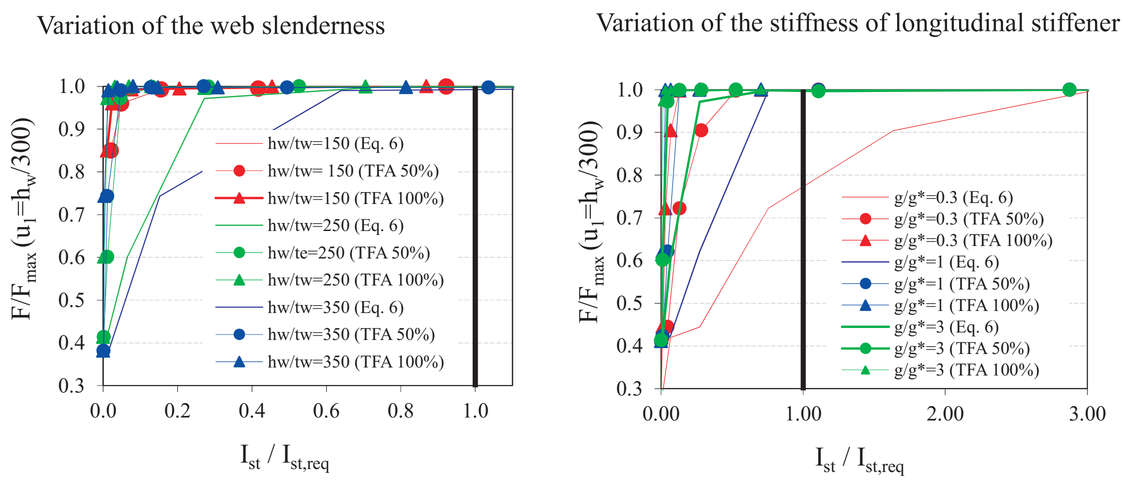


Figure 12: The normalized force obtained at out-of-plane displacement of $h_w/300$ for different stiffness of stiffener

4.2.2 Girders subjected to shear force

Numerical model used to study the influence of tension field action on the behavior of intermediate transverse stiffener is shown in Fig. 13.

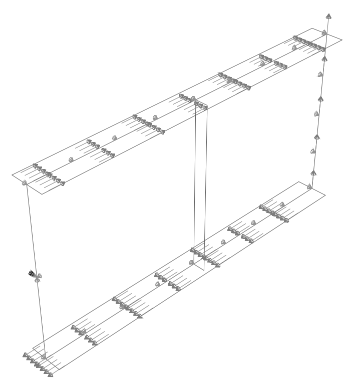


Figure 13: Numerical model of plate girder under shear force

The influence of the stiffness of the transverse stiffener was studied on transversally stiffened girders subjected to shear force only. The parameters were: slenderness of the web plate $h_w/t_w = 150 - 400$, panel aspect ratio $\alpha = a/h_w = 0.5 - 2.5$ and stiffness of the transverse stiffener. The ratio of flange area to web area was set to $A_f/A_w = 0.3$. The reason for such small A_f/A_w ratio was to minimize the influence of the flange restrain on the stiffness of the transverse stiffener.
In Fig. 14 the required moment of inertia I_{st} of the stiffener is plotted. The required moment of inertia (z-axis) is plotted as a function of the web slenderness (x-axis) and panel aspect ratio (y-axis). The EN 1993-1-5 stiffness requirement given with Eq. 6 is shown in Fig. 14a. The maximum stiffness is required for short panels and for small web slenderness. In Fig. 14b the minimum stiffness obtained from numerical simulations is plotted. This stiffness ensures that the additional deflection remains bellow $w_{max} \leq h_w/300$. As it can be seen, the required stiffness is mainly a function of the web slenderness. EN 1993-1-5 requirement given with Eq. 6 is found to be conservative for small web slenderness $h_w/t_w \leq 200$ and for small panel aspect ratio $\alpha < 1.0$, while for other parameters the stiffness requirement is too small. The highest difference is found for large web slenderness.

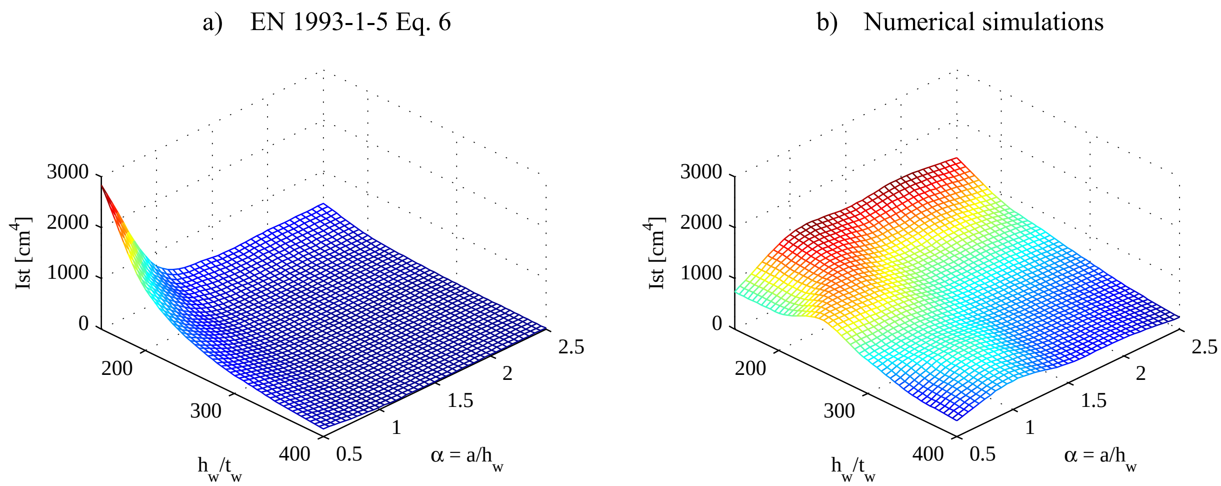


Figure 14: Required stifness of stiffener as a function of web slenderness and panel aspect ratio

In Fig. 15 the dimension of the flat stiffener b_{st} (b_{st} / t_{st} = 10), which satisfies stiffness requirements given in Fig. 14, is plotted. In most cases the flat stiffener with dimensions of 150×15 mm (see Fig. 15b) is large enough to meet deflection criteria given in EN 1993-1-5.

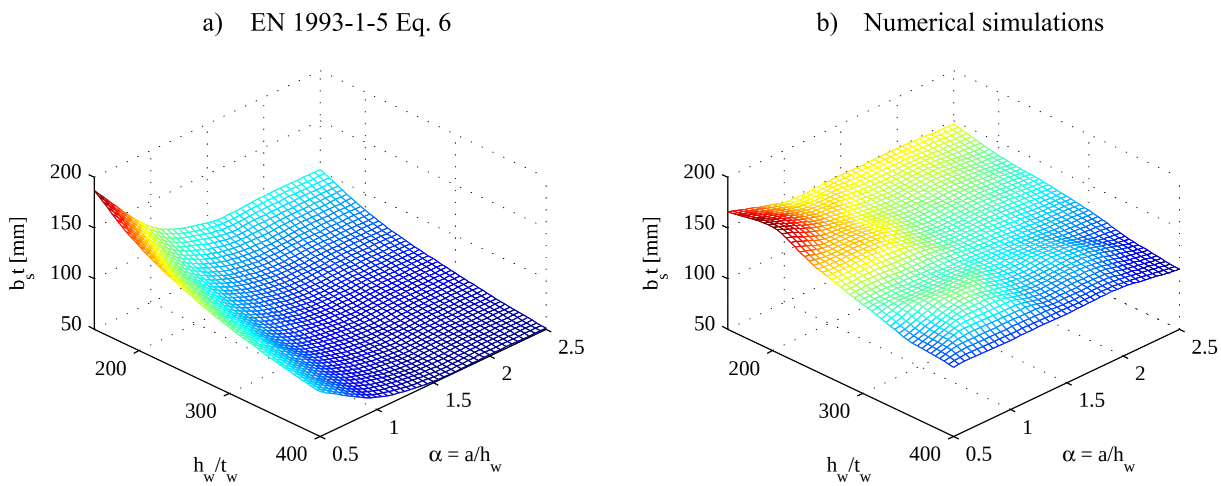


Figure 15: Size b_{st} (t_{st} = b_{st} /10) of the flat stiffener to fulfill stifness condition from Fig. 14

4.2.3 Plate loaded with axial force

Numerical model used to study the influence of deviation forces due to axial force on the behavior of intermediate transverse stiffener is shown in Fig. 16.

The influence of the stiffness of the transverse stiffener was studied on transversally stiffened plate subjected to axial force only. The varied parameters were slenderness of the web plate $h_w/t_w = 50 – 250$, panel aspect ratio $\alpha = a/h_w = 0.5 – 2.0$ and stiffness of the transverse stiffener.
In Fig. 17 the required moment of inertia I_{st} of the stiffener is plotted. The required moment of inertia (z-axis) is plotted as a function of the web slenderness (x-axis) and panel aspect ratio (y-axis). The EN 1993-1-5 stiffness requirement is shown in Fig. 17a and 17b. The maximum stiffness is required for short panels and for small web slenderness. In Fig. 17c the minimum stiffness obtained from numerical simulations is plotted. This stiffness ensures that the additional

deflection remains bellow $w_{max} \leq h_w/300$. As it can be seen, the required stiffness is mainly function of the web slenderness. EN 1993-1-5 requirement given with Eq. 6 is conservative for small aspect ratios $\alpha < 0.75$ and small plate slenderness. Both requirements Eq. 6 and Eq. 9 seem to be unsafe for large plate slenderness and for large aspect ratios (see Fig. 17). This is even more evident from Fig. 18 where the required width of the intermediate flat stiffener is plotted assuming that $b_{st}/t_{st} = 10$. The reason that both EN 1993-1-5 requirements (Eq. 6 and Eq. 9) are unsafe at large slenderness and large aspect ratios can be explained by the deformed shape of the plate panel just before reaching the maximum resistance (see Fig. 19), which differs significantly from the calculation model in Fig. 2.

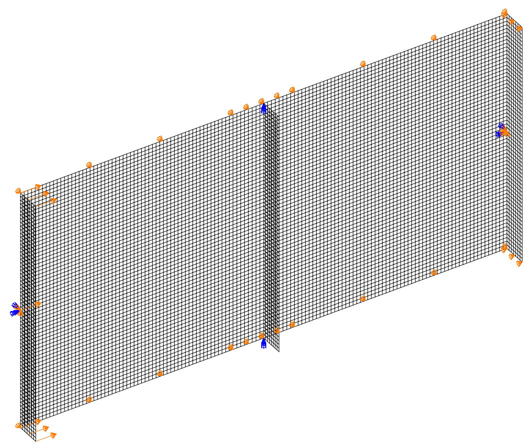
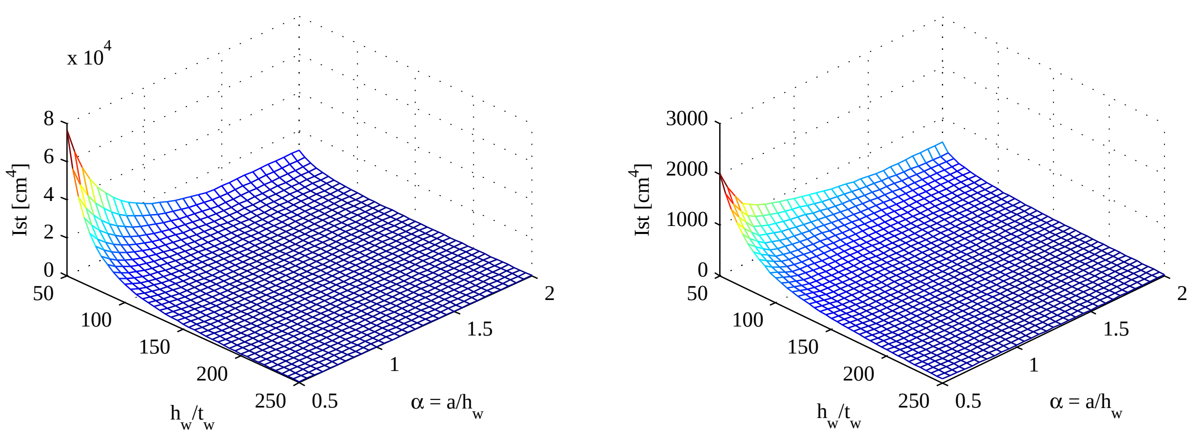


Figure 16: Numerical model of transversally stiffened plate subjected to axial force

a) EN 1993-1-5 Eq. 6

b) EN 1993-1-5 Eq. 9



c) Numerical simulations

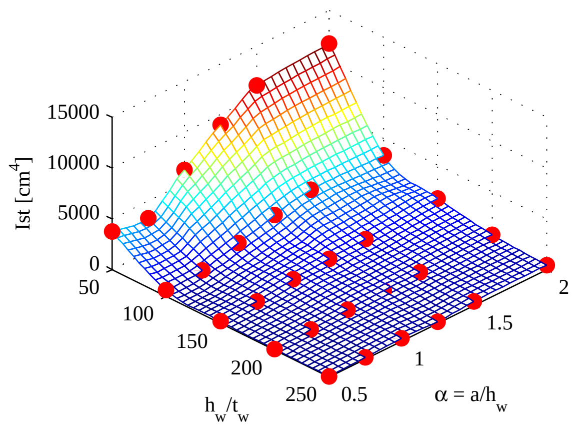
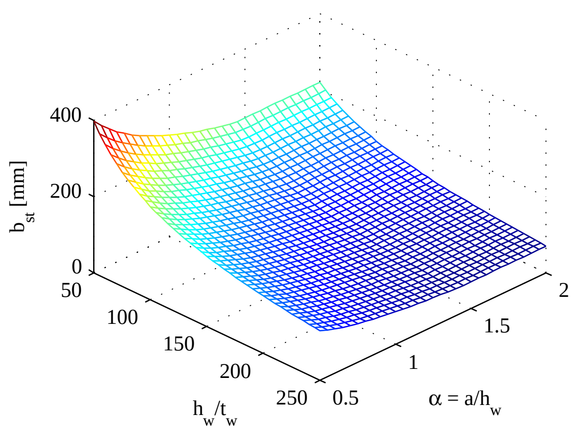
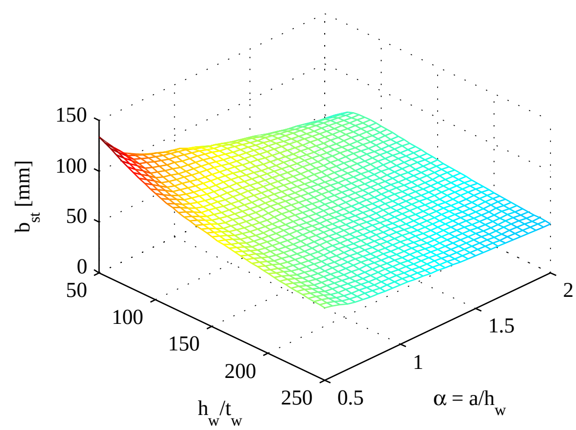


Figure 17: Required stifness of stiffener as a function of web slenderness and panel aspect ratio

a) EN 1993-1-5 Eq. 6



b) EN 1993-1-5 Eq. 9



c) Numerical simulations

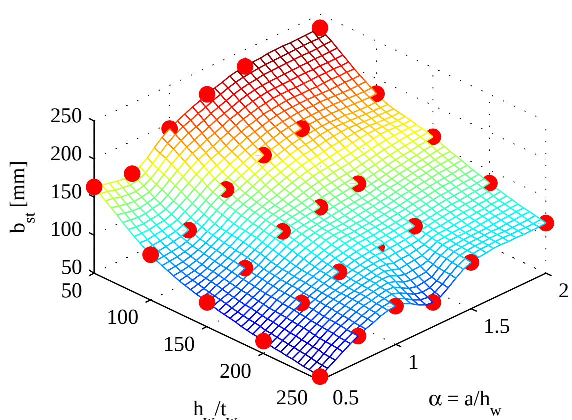


Figure 18: Size b_{st} ($t_{st} = b_{st}/10$) of the flat stiffener to fulfill stifness stifness condition form Fig. 17

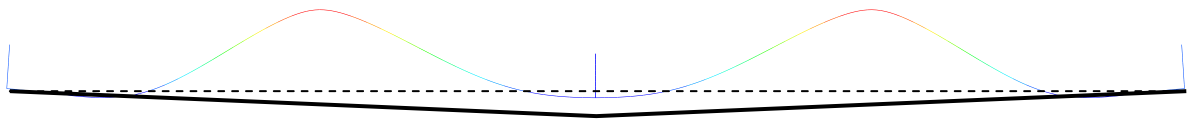


Figure 19: Deformation shape of the plate (h_w/t_w = *50*, α = *2*) at the maximum capacity

5. Conclusions

If the transverse stiffener of a plate girder is designed to deviation forces from bending moments and axial forces from the tension field action according to EN 1993-1-5, this results in much bigger stiffener than was obtained by numerical simulations. This comes from overestimation of axial forces in the stiffener due to the tension field action. The actual force, measured in own tests, represents 56% of the force calculated according to equation (7). Similar observation was also found by Hendy et al. (2008).

This overestimation of the axial force in the stiffener is very important at single sided stiffeners that are mostly used for intermediate transverse stiffeners. It has been demonstrated in this paper that the required performance of rigid intermediate transverse stiffeners of longitudinally stiffened plate girders may be obtained by fulfilling simple stiffness criteria. The final equation is still in development process. Nevertheless, it has been shown that the required stiffness of transverse stiffener is mainly a function of plate slenderness and panel aspect ratio. Further analysis is needed, especially for girders that are stiffened also with longitudinal stiffeners.

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