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BEHAVIOUR OF BOX-GIRDER UNDER SYMMETRICAL ACTION

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Abstract: *Theoretical investigation of 8 m long steel experimental model of one cell trapezoidal box-girder under four symmetrically arranged transverse forces. Buckling of wide flange in compression when girder was in normal position, buckling of narrow flange in compression when girder was in reverse position, and buckling of box-girder web in combined shear and bending. Global and local buckling. Shear lag. Comparison of experimental and theoretical values and evaluation of results.*

Keywords: Steel, box-girder, buckling of stiffened flange, buckling of web in shear, shear lag

1. Introduction

The following phenomena were investigated (Baláž, 1980):

1. distribution of direct, shear and comparison stresses in box-girder;
2. resistance of compressed stiffened flange when box-girder was in normal position (the wide flange was in compression, the narrow one in tension);
3. resistance of compressed stiffened flanges when box-girder was in reverse position (the narrow flange was in compression, the wide one in tension);
4. influence of shear lag in both flanges;
5. resistance of the box-girder web under combination of shear and bending;
6. measurements of imperfections of the wide flange in compression and imperfections of the web in combined shear and bending by photogrammetric way;
7. influence of imperfections on buckling resistance of box-girder wide flange and web.

The total length of experimental box-girder is 8,4 m. Its span is 8 m and weight 2000 kg. There are 11 longitudinal L-stiffeners in wide flange and 4 flat longitudinal stiffeners in narrow flange (Fig. 2). Spacing of 9 transverse stiffening frames is 1 m (Fig. 4). The frames are strengthened by diaphragm in the cross-sections where loading is introduced (Fig. 3) and at the supports (Fig. 5). The width of the opening in diaphragm is 470 mm (Figs. 3 and 5). The strength properties of the used steel are: yield strength f_y = 262 MPa and ultimate tensile strength f_u = 390 MPa.

The box-girder was loaded by 2 pairs of antisymmetrically arranged transverse forces *F* (case a) in Fig. 4) and by 4 symmetrically arranged transverse forces *F* (case b) in Fig. 4). In this paper only two cases b) are described. The box-girder was first loaded by 4 symmetrical forces *F* in normal position when the wide flange was in compression (Figs. 1, 2, 3, 4). This is denoted as case b1). After that the experimental model was loaded by 4 symmetrical forces *F* in reverse position when the narrow flange was in compression (Fig. 5). This is called case b2). In the case b2) it was necessary before loading to weld another strengthening in the form of stiffened plate to the box-girder from its outer side in the sections where loading was introduced. It is possible to see it in Fig. 5. The purpose was to keep distance of pair of hydraulic jacks in transverse direction 1606 mm as it was in normal position (case b1).

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The maximum capacity each of 4 hydraulic jacks was 500 kN. The strains and stresses were evaluated in 204 points with the help of the logger TSA-63. The deformations were measured with the exactness 0,1 mm in the sections 0, L/8, L/2, 3L/8 and L.

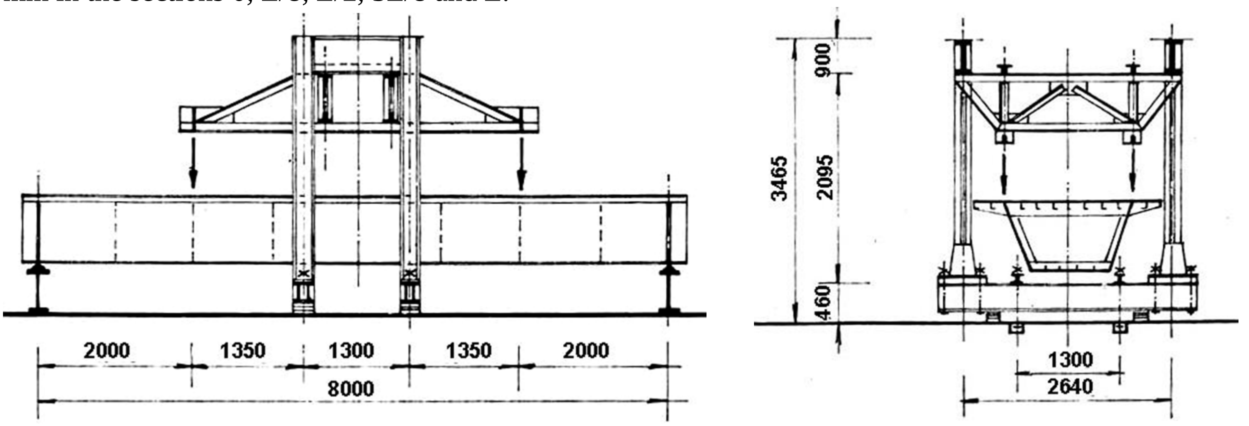

Fig. 1: Arrangement of loading frame. Four hydraulic jacks with capacity 500 kN each

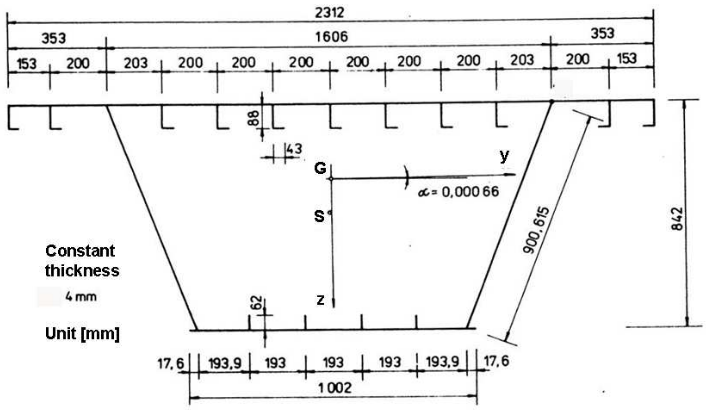

Fig. 2: Box-girder cross-section

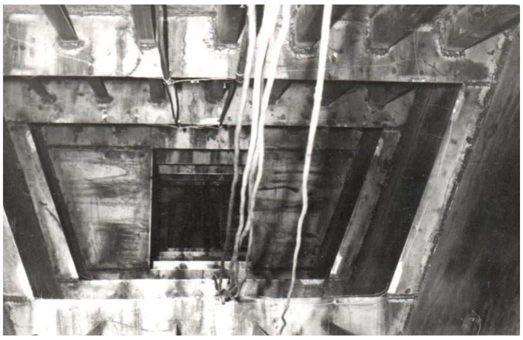

Fig. 3: Transverse stiffening frames

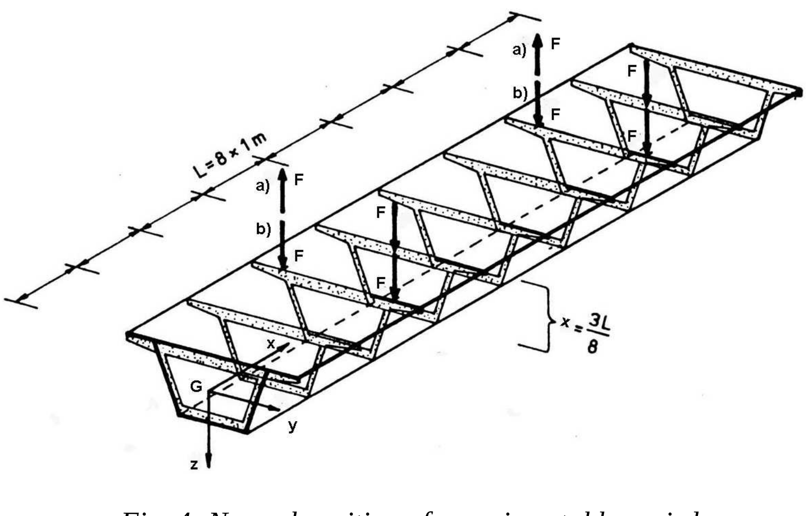

Fig. 4: Normal position of experimental box-girder

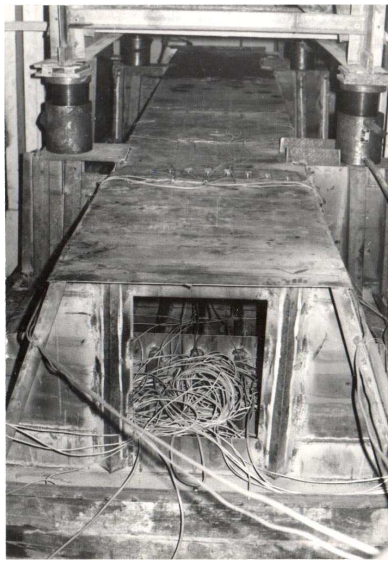

Fig. 5: Reverse position

The 5 tests were performed in the following order in which the box-girder was under: 1) verification symmetrical loading, 2) the first antisymmetrical loading, 3) the second antisymmetrical loading, 4) symmetrical loading of girder in normal position, 5) symmetrical loading of girder in reverse position.

2. Experimental box-girder in normal position under symmetrical action

At one end of the box-girder in the field between sections 7 m and L = 8 m the both box-girder webs were strengthened in the middle by longitudinal stiffener to increase their shear resistance. At other end of the box-girder in the field between sections 0 m and 1.0 m the both box-girder webs were unstiffened. The shear resistance of this webs limited the resistance of the box-girder under symmetrical action.

2.1 Theoretical calculation of the box-girder in normal position according to EN 1993-1-5

Material, geometrical and cross-sectional properties and resistances:

$$E = 210GPa\,,\ \nu = 0.3\,,\ f_y = 262MPa\,,\ a = 1m\,,\ h = 842mm\,,\ d = 900.6mm\,,\ t = 4mm\,,\ z_G = 277.7mm \quad (1)$$

The elastic bending moment of the cross-section resistance $M_{el.R}$ and related force $F_{el,R}$ are

$$W_{el} = 5475.22cm^3\,,\ \ M_{el,R} = W_{el}\, f_y = 1434.51kNm\,,\ \ F_{el,R} = M_{el,R} / 2m / 2 = 358.63kN \quad (2)$$

The plastic bending moment of the cross-section resistance $M_{pl.R}$ and related force $F_{pl.R}$ are

$$W_{pl} = 7142.29cm^3\,,\ \ M_{pl,R} = W_{pl}\, f_y = 1871.28kNm\,,\ \ F_{pl,R} = M_{pl,R} / 2m / 2 = 467.82kN \quad (3)$$

The bending moment resistance $M_{f,R}$ of cross-section consisting of flanges only and related force $F_{f.R}$ are

$$W_f = 4018.46cm^3\,,\ \ M_{f,R} = W_f\, f_y = 1052.84kNm\,,\ \ F_{f,R} = M_{f,R} / 2m / 2 = 263.21kN \quad (4)$$

The box-girder cross-section is Class 4. The upper flange is under compression stress

$$\sigma_{com} = f_y z_G / h = 86.41MPa \quad (5)$$

For such small compression stress the plate and longitudinal stiffeners may be taken as fully effective concerning local buckling even if the plate and height and flange of the longitudinal L-stiffener of the girder wide flange are Class 4. Consequently all reduction factors of local buckling of all compressed parts of upper flange are ρ = 1. The shear lag reduction factors calculated by adopting elastoplastic model are in wide flange also negligible because they do not differ much from 1.0:

$$b_0 = 803mm\,,\ \alpha_0 = 1.253\,,\ \beta^{\kappa} = 0.908^{0.126} = 0.988\,, \text{ for part of wide flange between girder webs} \quad (6)$$

$$b_0 = 353mm\,,\ \alpha_0 = 1.32\,,\ \beta^{\kappa} = 0.979^{0.058} = 0.999\,, \text{ for cantilever parts of wide flange of box-girder} \quad (7)$$

Consequently the bending moment resistance $M_{eff,R}$ of effective^p cross-section taking into account only local buckling of inclined webs in bending (ψ = -2.032, k_σ =54.98, ρ = 0.844, b_{e1} = 100.3 mm, b_{e2} = 150.4 mm) and related force $F_{eff.R}$ are

$$W_{eff} = 5479.35cm^3\,,\ \ M_{eff,R} = W_{eff}\, f_y = 1435.59kNm\,,\ \ F_{eff,R} = M_{eff,R} / 2m / 2 = 358.90kN \quad (8)$$

Also this influence is negligible because of very short part of inclined web in compression and small contribution of the inclined web to the bending moment resistance of girder cross-section.
The shear resistance of the box-girder web and related force $F_{V,R}$ are

$$\varepsilon = 0.947\,,\ k_\tau = 8.584\,,\ \bar{\lambda}_w = 2.17\,,\ \chi_w = 0.378\,,\ \ V_{bw,R} = \chi_w d t f_y / \sqrt{3} = 205.96kN \quad (10)$$

$$b_f = 17.6mm + 15\varepsilon t = 74.42mm\,,\ c = a\left(0.25 + 1.6 b_f t^2 / t / d^2\right) = 250.59mm \quad (11)$$

$$V_{bf,R} = b_f t^2 f_y / c = 1.245kN\,,\ \ V_{b,R} = V_{bw,R} + V_{bf,R} = 207.205kN\,,\ \ F_{V,R} = V_{b,R} h / d = 193.722kN \quad (12)$$

The force F with minimum value from above calculated values is resistance of the box-girder

$$F_R = \min(F_{eff,R} \approx F_{el,R}, F_{V,R}) = \min(358.90kN \approx 358.63kN, 193.72kN) = 193.72kN \quad (13)$$

Verification conditions according to EN 1993-1-5 evaluated for the force F_R = 193.72 kN are

$$M_{E,\max} = 2F_R\, 2m = 774.89kNm\,,\ \ M_{E,\max,red} = \min(0.4a, 0.5d) M_{E,\max} = 309{,}96kNm \quad (14)$$

$$\bar{\eta}_3 = F_R / (V_{b,R} h / d) \le 1\,,\ \bar{\eta}_1 = M_{E,\max,red} / M_{pl,R} = 0.166\,,\ M_{E,\max,red} / M_{f,R} = 0.294 \le 1.0 \quad (15)$$

$$\bar{\eta}_1 + \left(1 - M_{f,R} / M_{pl,R}\right)\left(2\bar{\eta}_3 - 1\right)^2 = 0.603 \le 1.0\,,\ \ M_{E,\max} / M_{eff,R} = 0.54 \le 1.0 \quad (16)$$

2.2 Experimental data from the test of the box-girder in normal position

The strains and displacements were measured in chosen points (Fig. 6) for the following 4 transverse forces F (Fig. 4): F = 0 kN – 200 kN – 0 kN – 250 kN – 300 kN – 325 kN. The clearly visible buckling shape of unstiffened girder web under shear was achieved at F = 250 kN (Fig. 8). The value of the transverse force at collapse was F_{coll} = 340 kN. The transverse stiffening frame creates very weak nonrigid end post. At the value F_{coll} the welds in the anchorage of the web tension field were broken at the upper flange(Fig. 9).

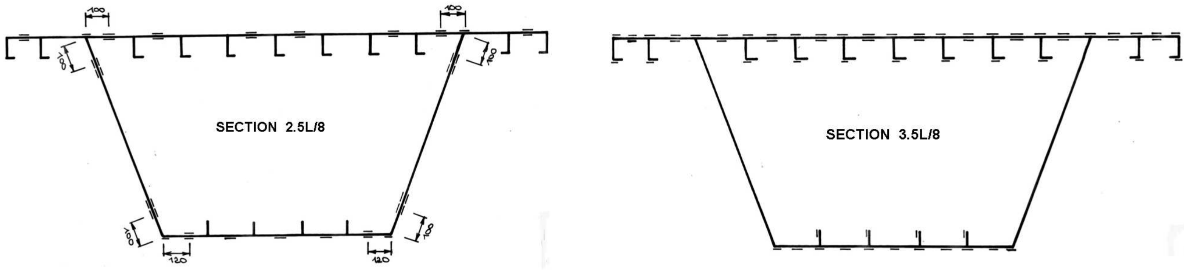

Fig. 6: Location of strain gauges in sections 2.5L/8 and 3.5L/8

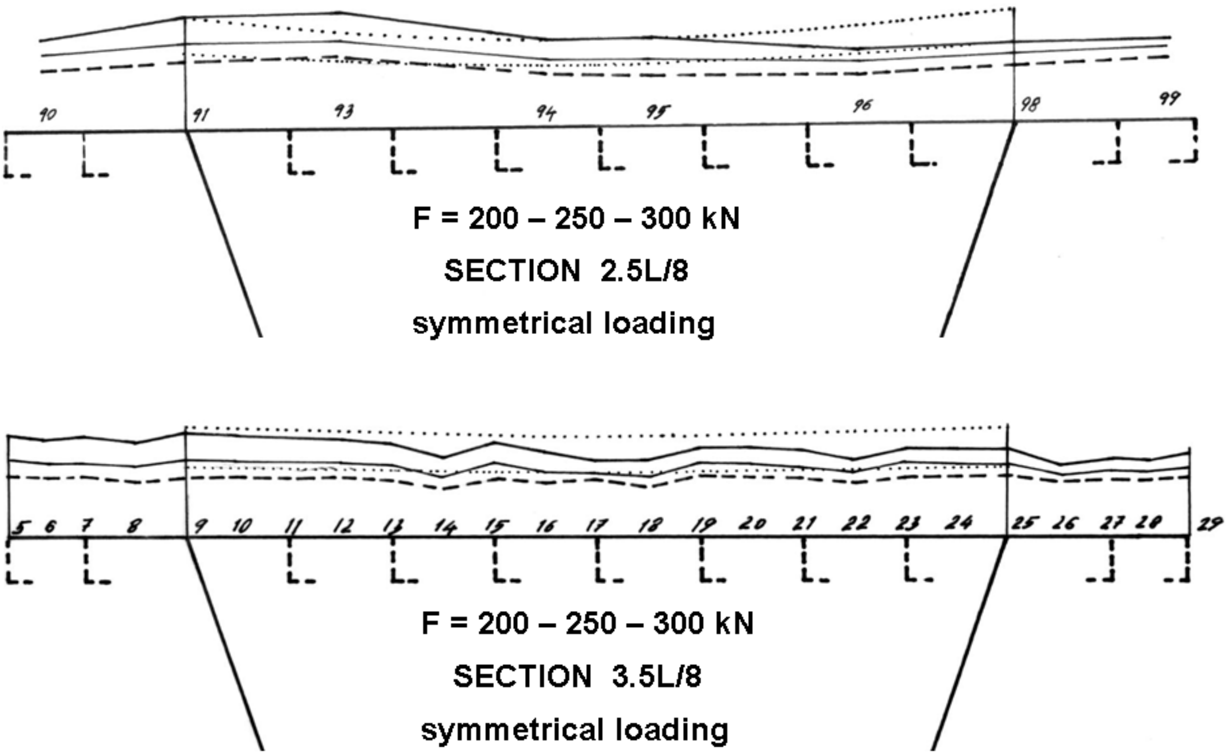

Fig. 7: One dashed and two solid lines represent distributions of experimental stresses for F = 200 kN, 250 kN, 300 kN. Two dotted lines represent distributions of theoretical stresses for F = 200 kN and 300 kN. Maximum value of theoretical stress is 71.4 MPa for F = 200 kN and 107 MPa for F = 300 kN.

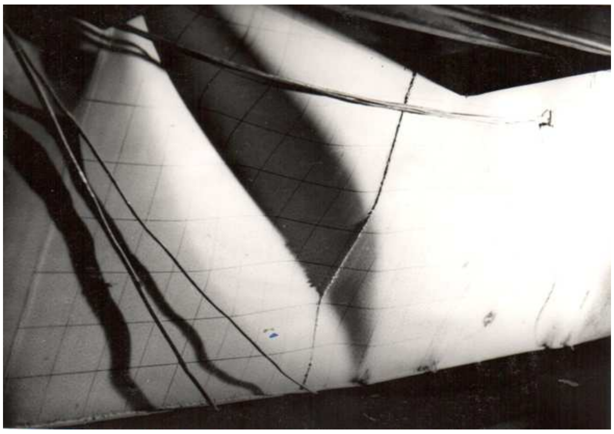

Fig. 8: Inclined web under shear at F = 340 kN

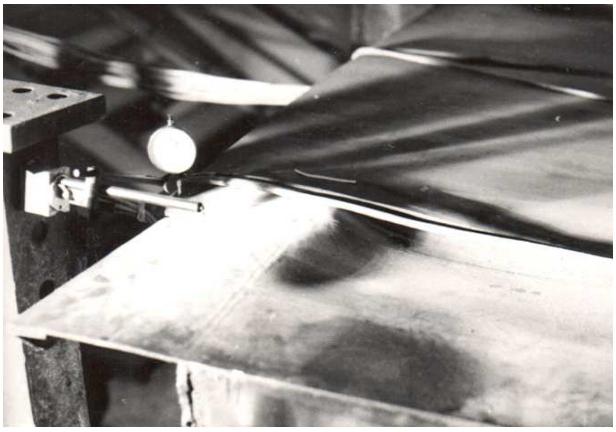

Fig. 9: Anchorage of the web tension field

3. Experimental box-girder in reverse position under symmetrical action

This test was not originally planned. Nevertheless, after the first symmetrical test the box-girder was put in reverse position and the second symmetrical test was performed on the same partly damaged girder.

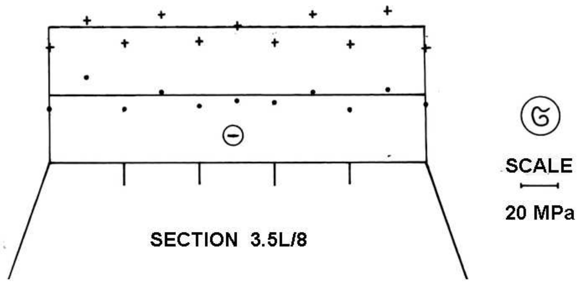

Fig. 10: Comparison of direct stresses in narrow flange when box-girder is in reverse position. Two solid lines represent distributions of theoretical stresses for F = 100 kN and 200 kN. For F = 200 kN the value of theoretical stress is 144 MPa .

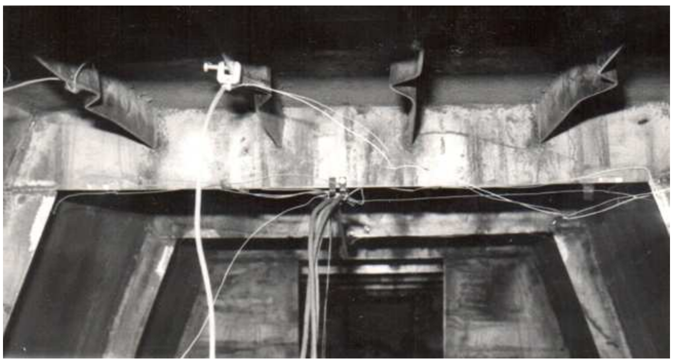

Fig. 11: Lost of stability of longitudinal stiffeners at the gap of intermittent fillet welds

Fig. 12: Buckling of narrow flange at the gap of intermittent fillet welds

3.1 Theoretical calculation of the box-girder in reverse position according to EN 1993-1-5

The narrow flange in reverse position is under compression stress f_y = 262 MPa. The local buckling reduction factor of longitudinal stiffener ρ_{st} = 0.914 (ψ = 0.926, k_σ = 0.456) and reduction factor of flange plate is ρ_p = 0.841 (ψ = 1, k_σ = 4). The reduction factor for global buckling of the whole stiffened narrow flange ρ_c = 0.632 (for column-like buckling: $\sigma_{cr,c}$ = 529.33MPa, α = 0.49, e = 54 mm, α_e = 0.796, χ_c = 0.632; for plate-like buckling: $k_{\sigma.p}$ = 144.755, $\sigma_{cr,p}$ = 170.435MPa; ξ = 0). The shear lag reduction factor $\beta^\kappa = 0.917^{0.065} = 0.998$. The reduction factor of the girder inclined web due to local buckling in bending ρ = 0.409 (ψ = -0.492, k_σ = 13.274,). The section modulus of effective box-girder section was calculated for reduced height and thickness of longitudinal stiffeners, reduced thickness of the narrow flange plate and reduced width of girder inclined webs as follows

$$h_{st.eff} = h_{st}\,\rho_{st} = 62\text{ mm } 0.914 = 56.66\text{ mm},\quad t_{st,eff} = t\,\rho_c\,\beta^\kappa = 4\text{ mm } 0.632\ 0.998 = 2.521\text{ mm} \tag{17}$$

$$t_{p.eff} = t\,\rho_p\,\rho_c\,\beta^\kappa = 4\text{ mm } 0.841\ 0.632\ 0.998 = 2.122\text{ mm},\quad b_{e1} = 98.77\text{ mm},\quad b_{e2} = 148.16\text{ mm} \tag{18}$$

$$W_{eff} = 2900.86 cm^3,\quad M_{eff,R} = W_{eff}\,f_y = 760.025 kNm,\quad F_{eff,R} = M_{eff,R}/2m/2 = 190 kN \tag{19}$$

Verification conditions according to EN 1993-1-5 evaluated for the force F_R = 190 kN are

$$M_{E,\max} = 2F_R\,2m = 760 kNm,\quad M_{E,\max,red} = \min(0.4a, 0.5d)M_{E,\max} = 304 kNm \tag{20}$$

$$\bar\eta_3 = F_R/(V_{b,R}h/d) = 0.981 \le 1,\ \bar\eta_1 = M_{E,\max,red}/M_{pl,R} = 0.162,\ M_{E,\max,red}/M_{f,R} = 0.289 \le 1.0 \tag{21}$$

$$\bar\eta_1 + \left(1 - M_{f,R}/M_{pl,R}\right)\left(2\bar\eta_3 - 1\right)^2 = 0.567 \le 1.0,\qquad M_{E,\max}/M_{eff,R} = 1.0 \le 1.0 \tag{22}$$

3.2 Experimental data from the test of the box-girder in reverse position

The strains and displacements were measured in chosen points for the following 4 values of transverse forces F (Fig. 4): F = 0 kN – 100 kN – 0 kN – 200 kN. The value of the transverse force at collapse was F_{coll} = 275 kN. The reason was buckling and big plastic deformation of all longitudinal stiffeners in compressed flange (Fig. 11) because intermittent fillet welds were used there (in normal position the narrow flange was in tension). Consequently plate of narrow flange buckled and big plastic deformation occurred in it (Fig. 12).

4. Conclusions

The resistance of the box-girder under symmetrical action was limited: a) by the shear buckling resistance of girder inclined unstiffened webs when box-girder was in normal position, b) by the resistance of the stiffened narrow flange when box-girder was in reverse position. The theoretical values in the cases: a) F_R = 193,72 kN , and b) F_R = 190 kN were confirmed by experimental data. Experimentally achieved collapse values of transverse forces were: a) F_{coll} = 340 kN, and b) F_{coll} = 275 kN.

Acknowledgement

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