Optimising plate girder design

R. Abspoel[1]
[1]*Division of structural engineering, Delft University of Technology, Delft, The Netherlands*

ABSTRACT: In the design of steel plate girders a high degree of optimisation is possible. In the sight of rising steel demands from booming economies and environmental aspects of material production, optimisation in terms of material use is becoming more and more beneficial.
Optimising a girder for bending action is achieved by moving material away from the neutral axis of the beam, in other words, by making the web of the plate girder more slender. When lateral supports are used to prevent lateral torsion buckling, then flange induced buckling, torsion buckling of the flange or yielding of the flange will become the critical failure mechanism. The high slenderness causes that the deflection of the beam is not governing. In this strength driven design it is possible to take advantage of higher steel grades and thus to achieve even further reduction of the section. To study the design aspects of very slender steel plate girders in depth, a FEM model was built. This model is used to examine the failure behaviour of a beam in a 4-point bending test setup. A series of 10 steel plate girders with slenderness up to 800 were loaded to failure to calibrate the model. In this paper the results of the laboratory tests are presented and discussed in relation to the results of the FEM models.

1 MAXIMUM WEB SLENDERNESS ACCORDING TO EN1993-1-5

1.1 *Maximum web slenderness according to Basler*

Restrictions regarding the maximum web slenderness as given in EN1993-1-5 [1] are based on the research of Basler [2], [3], [4]. This maximum web slenderness is based on column buckling of the web by additional in-plane stresses caused by curvature of the girder. The Basler test girder named G4-T2 is a transverse stiffened plate girder with a web slenderness of 388 see Figure 1.

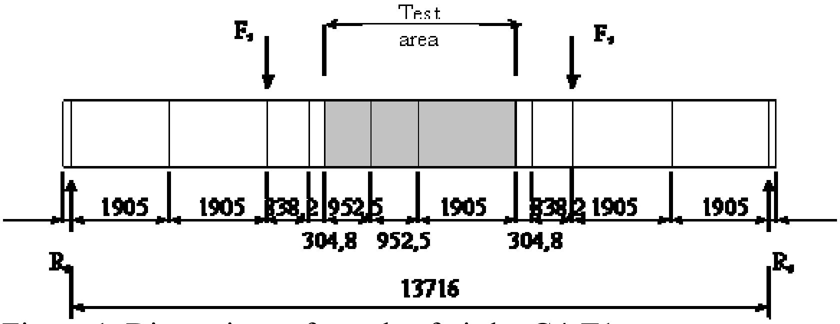


Figure 1. Dimensions of panels of girder G4-T1

According to Basler the girder collapsed with an explosive sound. The expression is according to Basler is rather rough and so not very accurate. The expression for the maximum web slenderness is:

$$\beta_{\max} = \left(\frac{h_w}{t_w}\right)_{\max} = 0,55 \cdot \frac{E}{f_y} \cdot \sqrt{\frac{A_w}{A_f}} \qquad (1)$$

To start a parameter study a FEM-model made in MscMarc is calibrated on the results of this laboratory test results. Flange induced buckling occurs in one of the two small plate panels. Because of the small distance between the transverse stiffeners torsional buckling of the top flange is impossible and so additional laboratory test are carried out. From the FEM-model it can be seen, the girder did not collapsed by flange induced buckling but by yielding of the flange. Flange induced buckling arise in the declining part of the P – δ diagram.

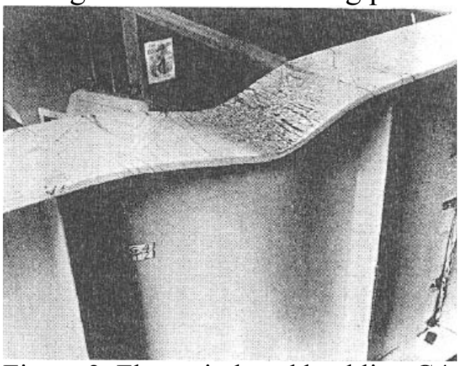


Figure 2. Flange induced buckling G4-T2 [4].

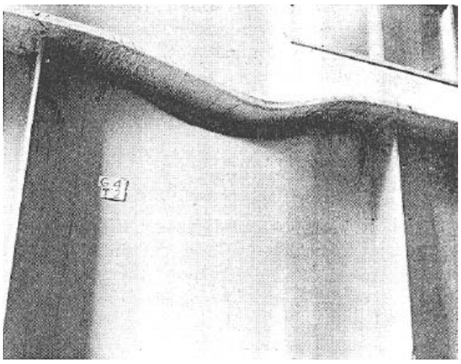


Figure 3. Flange induced buckling G4-T2 [4].

To calibrate the FEM-model the level of residual stresses is varied. The initial imperfection of the test girder is given by Basler. The residual stress level influences especially the deflection of the plate girder, not the ultimate load. A residual stress level of 40% of the yield strength gives the best fit of the FEM-model and the laboratory test girder, although the influence of the level of residual stress seems rather small. This value is also used for FEM-calculations of ten additional laboratory test girders, un-stiffened in the test panel.

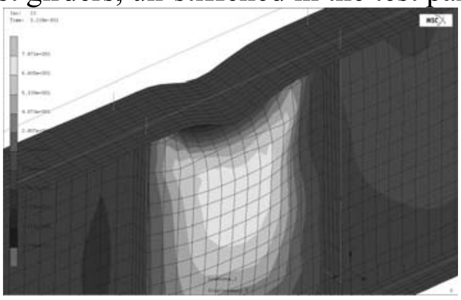


Figure 4. Flange induced buckling FEM G4-T2.

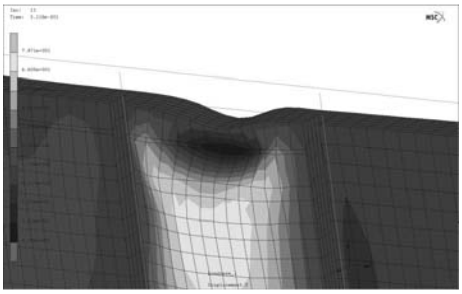


Figure 5. Flange induced buckling FEM G4-T2.

1.2 *Dimensions of the additional laboratory test girders*

To restrict the span and the material use the additional test girders have a web thickness of 1 mm only. These webs are welded at one side only, after tack welding at the other side. The height of the web is varied from 400, 600 to 800 mm. The span of the girder is 6,00 m. The web underneath the loading locations and near both supports is transverse stiffened to prevent local buckling, crippling and crushing. The test panel (length 3,0 m) is located between these two forces. The web thickness of the end panels is 4 mm to prevent shear buckling. The top flange and bottom flange are in principle equal and the dimensions are varied to look to the influence of the ratio between web area and flange area, see equation (1), and to the influence of the flange thickness in relation to torsional buckling of the top flange, the compressive flange. The test girder is represented in figure 6. The flanges are 50x4 mm^2, 80x5 mm^2 and 100x4 mm^2.

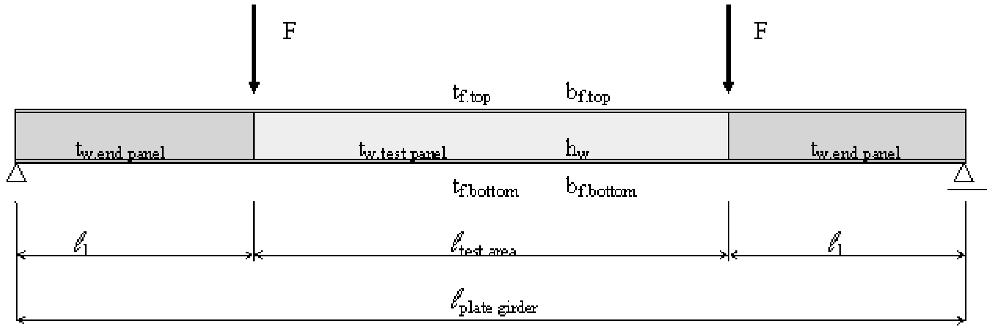


Figure 6. Laboratory test girder.

The dimensions of all test girders are measured and represented in table 1, next to the theoretical maximum web slenderness β according equation (1). Notice the web slenderness of 4 test specimen exceeds this maximum web slenderness, namely for TP 600x1 and 800x1 with flanges 80x5 mm^2 or 100x4 mm^2, see table 1

Table 1. Real dimensions of the elements of the test specimen

Test girder	b_{tf} [mm]	t_{tf} [mm]	b_{bf} [mm]	t_{bf} [mm]	b_{tf1} [mm]	b_{tf2} [mm]	b_{bf1} [mm]	b_{bf2} [mm]	h_w [mm]	t_w [mm]	β [-]	β max
TG 400x1 + 50x4	49,7	4,4	49,8	4,3	25,4	24,3	25,6	24,2	400.0	1,0	400	590
TG 400x1 + 80x5(1)	80,1	5,4	90,0	5,3	41,8	38,3	39,4	40,6	399,3	1,0	399	417
TG 400x1 + 80x5(2)	80,1	5,6	79,8	5,5	40,1	40,0	38,9	40,9	399,8	1,0	400	417
TG 400x1 + 100x4	98,7	4,3	98,9	4,4	48,8	49,9	49,4	49,5	400,1	1,0	400	417
TG 600x1 + 50x4	49,6	4,5	49,9	4,5	24,6	25,0	25,5	24,4	601,6	1,0	602	722
TG 600x1 + 80x5	79,9	5,5	79,9	5,7	39,7	40,2	40,2	39,7	600,2	1,0	600	511
TG 600x1 + 100x4	99,1	4,3	98,7	4,3	49,1	49,9	48,7	50,0	600,1	1,0	600	511
TG 800x1 + 50x4	50,2	4,4	49,5	4,4	24,9	25,3	25,0	24,5	801,0	1,0	801	834
TG 800x1 + 80x5	80,2	5,6	80,1	5,6	40,6	39,5	40,1	40,0	799,4	1,0	799	590
TG 800x1 + 100x4	98,8	4,2	98,7	4,2	48,9	49,9	48,5	50,2	799,4	1,0	799	590

1.3 *Test girder material properties*

The stress-strain relation of the components of the plate girder was determined by tensile tests. The yield strength of the flanges is much higher than the yield strength of the web, this in contradiction to the Basler test girder G4. The results of these tensile tests are substituted into the FEM-models. The strain-hardening is put in as a natural logarithm using Cauchy stresses according to large displacements calculations. The yield strengths are represented in table 2.

Table 2. Yield strength of the elements of the test specimen

Element	Flange 50 mm [N/mm^2]	Flange 80 mm [N/mm^2]	Flange 100 mm [N/mm^2]	Web [N/mm^2]
f_y Yield strength	338	334	358	277

1.4 *Test girder properties*

The girders properties depend on the girder dimensions and the material properties. The elastic, plastic, critical and effective bending moment resistance is determined for the 10 test girders. The effective bending moment resistance is determined by one iteration calculation only. In table the resistances of the test girder is represented. In the table the bending moment resistance according to the elastic theory is based on the yielding of one of the flanges and not to the yielding of the web, which will be always a smaller value. The effective bending moment resistance is based on the effective cross section based determined by one iteration only. Because of this effective cross section the buckling factor will change and also the neutral axis will shift.

Table 3. Test girder theoretical properties

Test girder	$M_{y.pl}$ [kNm]	$M_{y.el}$ [kNm]	$M_{y.cr}$ [kNm]	$M_{y.ef}$ [kNm]	M_{lab} [kNm]	$M_{Veljkovic}$ [kNm]	$M_{y.FEM}$ [kNm]	Failure mode
TG 400x1 + 50x4	42,1	38,2	3,3	33,8	36,1	32,9	32,6	Yielding top fl.
TG 400x1 + 80x5(1)	71,0	66,1	5,9	62,6	58,9	61,6	-	
TG 400x1 + 80x5(2)	72,5	67,9	6,0	63,8	61,0	63,3	62,9	Yielding top fl.
TG 400x1 + 100x4	74,6	70,3	7,5	64,9	62,0	65,2	63,0	Yielding top fl.
TG 600x1 + 50x4	74,0	65,7	2,5	55,9	55,2	50,8	-	
TG 600x1 + 80x5	119,6	110,2	4,3	97,9	95,5	96,3	95,1	Yielding top fl.
TG 600x1 + 100x4	121,4	113,1	4,1	99,8	97,9	99,6	85,5	
TG 800x1 + 50x4	109,9	95,3	2,1	80,3	69,2	64,7	68,5	Yielding top fl.
TG 800x1 + 80x5	172,2	157,4	3,4	136,0	106,0	130,9	120,7	Yielding top fl.
TG 800x1 + 100x4	172,0	158,2	3,3	135,4	105,1	131,2	116,2	Yielding top fl.

1.5 *Test rig*

The test rig is built up with standard European hot rolled sections. The actuator has a capacity of 40 tons. The supports can be built up, so for different plate girder heights the supports are adapted. The top flange is lateral supported at both sides by UNP sections. The friction is restricted by using Teflon strips, glued on the flange of these UNP section.

1.6 *Measurement on the test girder*

There are placed several lvdt's at the girder, located on the locations were the load is introduced onto the test girder. Horizontal lvdt's are located at both ends of the girder to measure the horizontal displacement of the girder at the top flange, caused by curvature of the plate girder.

In the middle of the girder there are placed strain gauges on both sides of the web, three at the top of the top flange and at the bottom of the bottom flange, two strain gauges at the inner side of the top and bottom flange.

Special equipment is made to measure the horizontal displacement of the test web and the vertical displacements of the bottom flange. During testing of the first two test girders with relative wide flanges, 80 and 100 mm respectively, the vertical displacement of the top flange was also measured by two horizontal lasers, using mirrors to bow the ray. For the third test girder with a flange of 50 mm the mirror to reflect the horizontal ray of the lasers into a vertical ray break immediately by the rather big initial deflections of the web.

The rotations of the top flange of the rest of the test girders were measured by incline gauges. The measured initial deflections of the web are used into the FEM-calculations. After each load step, an incremental displacement, the lasers scanned the web of the test panel.

These measurements started at the left transverse stiffener and stopped about 150 mm before the second transverse stiffener.

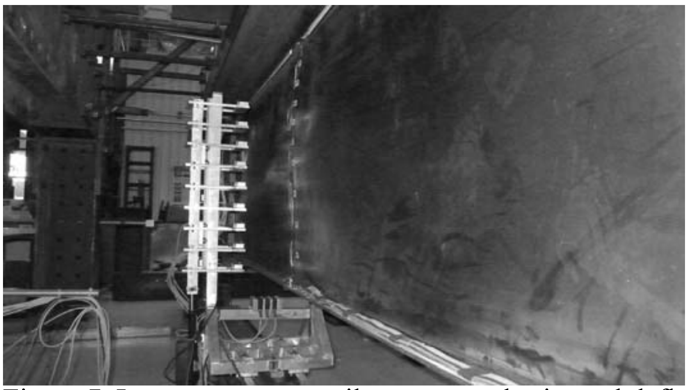


Figure 7. Laser scanner on rail to measure horizontal deflections of the web

2 FEM CALCULATIONS

2.1 *Model*

The FEM-models of the test girders are built up with 4-node shell elements, 30 vertically positioned for the web, 200 over the length of the test area and 100 elements over the length of the end panels. Over the width of the flange are situated 10 elements.

All dimensions of the elements of the laboratory test girders are measured and averages are used in the FEM-models. The web is not exactly in the centre of the flanges, but a little bit eccentric. The initial imperfections of the web in the test panel of the laboratory test girders are taking into account in the FEM-models by moving these nodes in the horizontal y-axis. By using lasers each imperfection of every node of the test panel of the FEM-model is measured in every laboratory test girder.

2.2 *Strain hardening*

The strain-hardening is based on the results of the tensile tests. The input of these strains is a logarithm, because of using Cauchy stresses for large displacement FEM-calculations.

2.3 *Residual stresses*

The residual stresses are not known in the laboratory tests. Although there are many possibilities to measure residual stresses, the results of these measurements varied very much and are not very useful. According to the EN1993-1-5 [1] the residual tensile stress is equal the yield stress and the compressive residual stress is 0,25 times the yield strength for a symmetric girder.

According to the calibration of the results of the FEM-model to the Basler laboratory test results the level of the residual stresses is reduced to 40% of the yield strength. Later on this level is changed to 100% of the yield strength to fit better with the test results. The values of the compressive residual stresses are a little bit adapted to take into account the eccentricity of the web caused by the a-symmetric connection to the flanges, so this values differ a little bit from 0,25 times the yield strength.

2.4 *Results of the FEM-calculations*

The FEM results of the third laboratory test, girder 400 x 1 + 80x5 is calibrated to the results of the laboratory test. The assumption of 40% of the yield stress for the residual stress, according to the calibration to the Basler test seems much too low and a higher residual stress level is used.

Because the tests are just finished, not all FEM-calculations are made yet. Especially the models of the very slender girders are not very stable. Up to now it is assumed the combination of the initial imperfections, sometimes more than 20 mm, and the residual stresses causes this numerical instability for this very thin web of 1 mm.

3 COMPARISON TEST RESULTS AND FEM RESULTS

3.1 *$P - \delta$ diagrams*

The results of the laboratory test and the FEM-calculations are given in graphics, the $P - \delta$ diagrams. To compare the results measured with the lvdt's and the lasers the point under the load introduction is used and not the deflection at mid-span. For the plate girder 400x1 with flanges 80x5, the second test girder, the graphic is represented in figure 8. Notice the laser measurements for the right force introduction is not exactly measured at this point and so a little bit different from the other laser measurement and the lvdt's measurements.

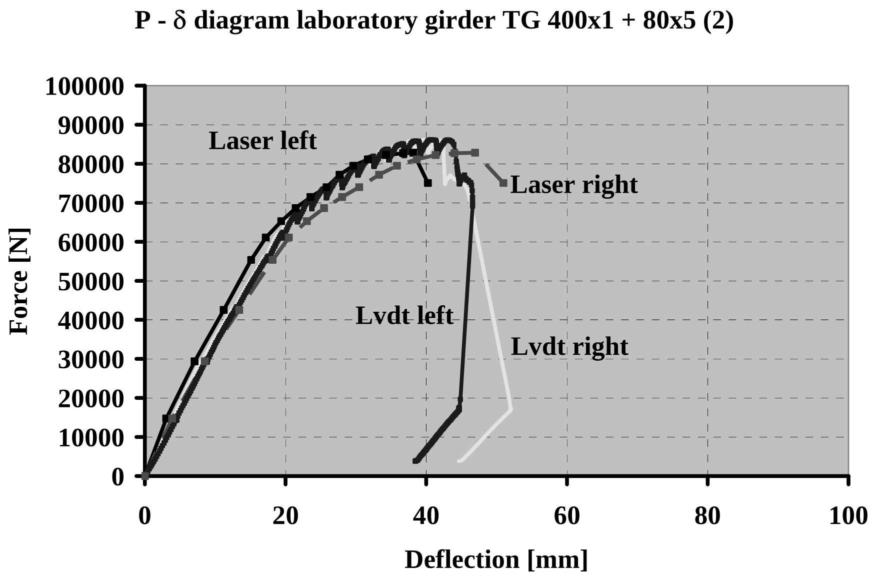


Figure 8. Comparison of the results measured with lvdt's and with the lasers

According to this graphic the measurements fit rather close and so the FEM-results can be compared with the laboratory results measured by the lasers. In Figure 9 this comparison is represented in another graph.

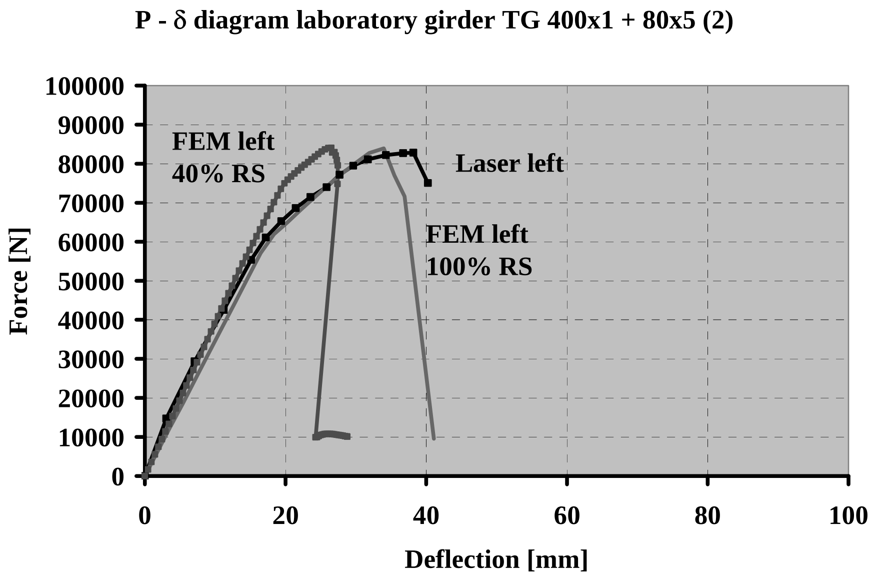


Figure 9. Comparison of the results measured with lvdt's and with the lasers

In this graphic there are given two graphs of the FEM-calculation, one with a residual stress level of 40% of the yield stress and because of the mismatch another graph with a residual stress of 100% of the yield stress of the flanges. It is clear this last graph fits very well with the graph of the results measured by the lasers and so with the results measured with the lvdt's too. The maximum moments in almost all laboratory tests are smaller than the effective bending moment resistance, according to the EN1993-1-5 [1]. The differences increase while the web slenderness increases.

The graphics of the results measured by the lasers and the lvdt's fix very well for all plate girders. Because differences in the results of the laboratory test measured by the lasers (and lvdt's) and the results of the FEM-calculations, using a residual stress level of 100% of the yield stress of the flanges for the other plate girders, the residual stresses are reduced to 80% or 90% of the yield stresses. As mentioned before, the graphs do not fit always and additional research to the residual stresses is necessary, including additional FEM-calculations.

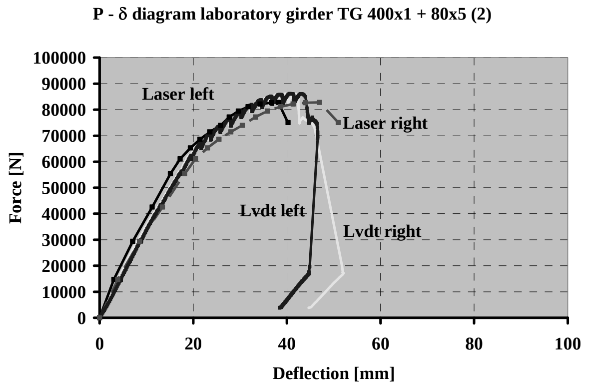


Figure 9. Comparison results lasers and lvdt's
Plate girder 400x1 plus 80x5

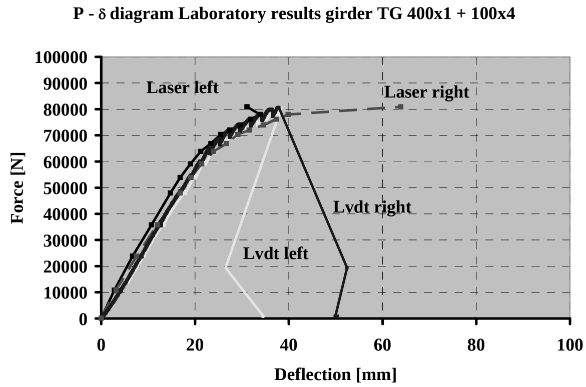


Figure 10. Comparison results lasers and lvdt's
Plate girder 400x1 plus 100x4

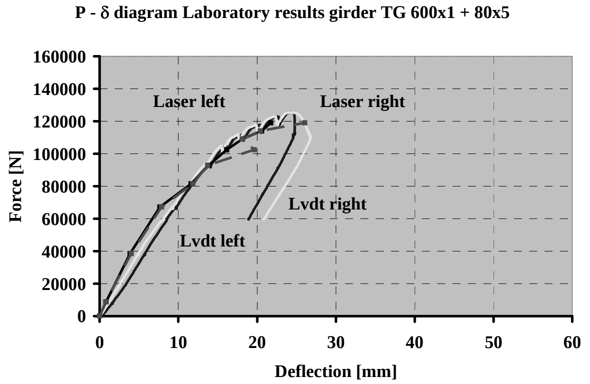


Figure 11. Comparison results lasers and lvdt's
Plate girder 600x1 plus 80x5

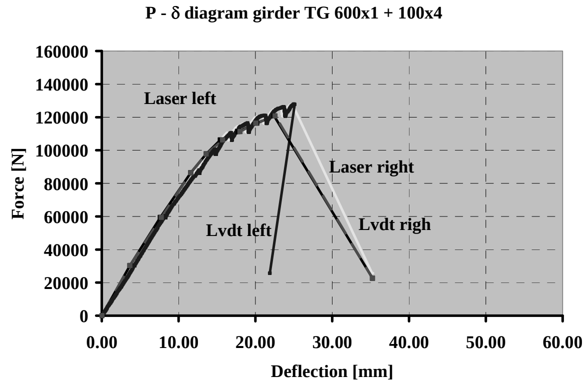


Figure 12. Comparison results lasers and lvdt's
Plate girder 600x1 plus 100x4

In the following graphics the results of the laboratory tests and the FEM-calculations are represented for different residual stress levels. The results of girder 400x1 with flange 80x5 mm^2 do not fit and additional FEM-calculation is made for higher residual stress levels. In the last-but-one column of table 3 the bending moment resistances of the laboratory tests are given.

According to these results of the laboratory tests are smaller than the effective bending moment resistances according to the EN1993-1-5. Notice the difference between the resistance of the effective cross section and the resistance of the laboratory test girder increase with increasing web slenderness, equal to the increase of initial imperfections of very slender webs.

To compare these results with the results given by Veljkovic and Johannson [5] and adapted by Abspoel [6], the resistances of the laboratory tests are given in table 3 too, in the last column.

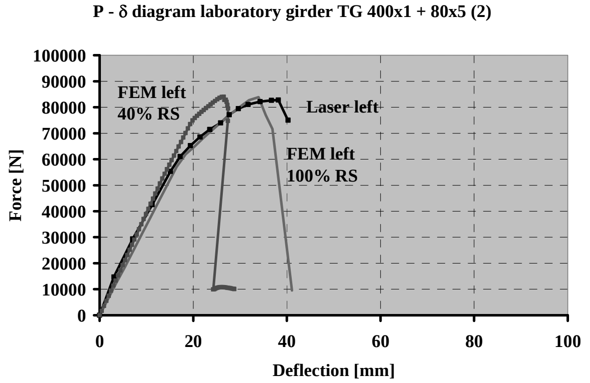


Figure 13. Comparison results lasers and FEM
Plate girder 400x1 plus 80x5

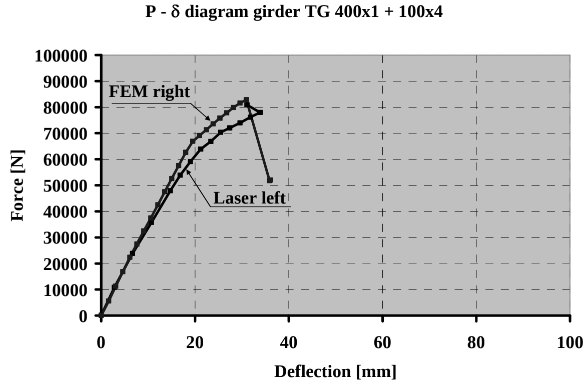
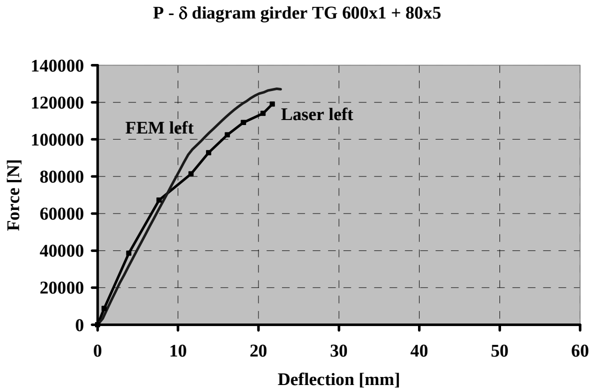


Figure 14. Comparison results lasers and FEM
Plate girder 400x1 plus 100x4



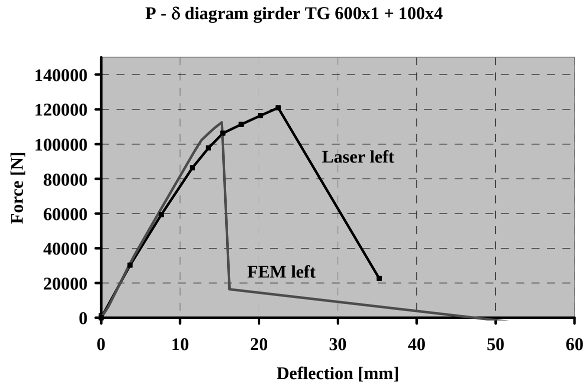


Figure 15. Comparison results lasers and FEM Plate girder 600x1 plus 80x5

Figure 16. Comparison results lasers and FEM Plate girder 400x1 plus 100x4

3.2 *Collapse modes*

The collapse modes look always flange induced buckling or torsional buckling of the compressive top flange in the test panel, but looking to the FEM-results it is not always quiet clear the collapse mode is flange induced buckling or torsional buckling. Most of the time yielding of the compressive and/or tensile flange is the govern collapse mode, the top of the P – δ diagrams. Flange induced buckling and torsional buckling of the flange happen in the inclining part of the graphics. This is as the same result as for the Basler laboratory test.

4 CONCLUSIONS

The following temporary conclusions can be made:

- Flange induced bucking occurs most of the time in the inclining part of the P – δ diagrams
- Yielding of the flanges is the collapse mode for these un-stiffened plate girders;
- The maximum load of the laboratory test girder is always, except one, lower than the effective bending moment resistance based on EN1993-1-5 [1];
- The bending moment resistances of the laboratory test girders determined with the formula given by Veljkovic [5] and Abspoel [6] are smaller than the effective bending moment resistance based on EN1993-1-5 [1].

5 REFERENCES

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