Beams and Columns with sinusoidal corrugated webs and crane brackets

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1 Abstract

Welded girders with sinusoidal corrugated webs are an interesting alternative for rolled section in single-storey buildings. The key to a successful application was the development of an automated production line, solved by Zeman & Co GmbH, Austria, in the early 90ies [1].
It was found that the sinusoidal corrugated web has a better buckling performance than "classic" welded sections and even comparable trapezoidally-shaped web.
The paper describes former investigations on the shear capacity of the web, ongoing numerical analysis and experimental tests on global and local buckling of girders. Moreover, the load capacity of crane brackets is analysed numerically and experimentally.

2 Keywords

girder with sinusoidal corrugated web, crane bracket, load capacity, buckling

3 State of the Art

The starting point were the German (DASt-Ri 015 [2]) and the European (EC3, Part 1.5) codes for girders with trapezoidally corrugated web. The shear capacity is given in dependence of the relative slenderness $\overline{\lambda}_p$.

$$V_{RD} = 0{,}6 * \kappa_\tau * \frac{f_{y,k}}{\sqrt{3} * \gamma_M} * h * t \qquad (1)$$

with $\kappa_\tau = \frac{0{,}84}{\overline{\lambda_p}}$ for $\overline{\lambda_p} > 0{,}84$ and

$\kappa_\tau = 1{,}0$ for $\overline{\lambda_p} \leq 0{,}84$

The interaction of local and global buckling was taken into account by the factor 0,6.

Are the design rules also suitable for girders with sinusoidal corrugated webs? With help of finite elements and tests extensive investigations on the load capacity of various geometries have been carried out. The wave depth 10, 20 and 40*mm* as well as the wave length 155 and 310*mm* as well as different girder heights were examined.

Girder WT40-155

Web Height [mm]	Web Thickness [mm]								
	0,2	0,3	0,4	0,5	1,0	1,5	2,0	2,5	3,0
500	local	local	local	local	local	local	local	local	local
1000	local	local	local	local	local	local	global	global	global
1500	local	local	local	local	local	global	global	global	global

Girder WT20-155

Web Height [mm]	Web Thickness [mm]								
	0,2	0,3	0,4	0,5	1,0	1,5	2,0	2,5	3,0
500	local	local	local	local	local	local	local	global	global
1000	local	local	local	local	global	global	global	global	global
1500	local	local	global	global	global	global	global	global	global

Girder WT10-155

Web Height [mm]	Web Thickness [mm]								
	0,2	0,3	0,4	0,5	1,0	1,5	2,0	2,5	3,0
500	local	local	local	local	local	global	global	global	global
1000	local	local	global	global	global	global	global	global	global
1500	global	global	global	global	global	global	global	global	global

Girder WT40-310

Web Height [mm]	Web Thickness [mm]								
	0,2	0,3	0,4	0,5	1,0	1,5	2,0	2,5	3,0
500	local	local	local	local	local	local	local	local	local
1000	local	local	local	local	local	local	local	local	local
1500	local	local	local	local	local	local	local	global	global

Girder WT20-310

Web Height [mm]	Web Thickness [mm]								
	0,2	0,3	0,4	0,5	1,0	1,5	2,0	2,5	3,0
500	local	local	local	local	local	local	local	local	local
1000	local	local	local	local	local	local	local	global	global
1500	local	local	local	local	local	global	global	global	global

Buckling values can be derivated very simple:

local buckling:

$$k\tau,l = 5{,}34 + \frac{f*s}{h*t} \tag{2}$$

global buckling [3]:

$$k\tau,g = 15{,}065 + \left(\frac{q*2f}{h*t}\right)^2 \tag{3}$$

Comparing the calculated buckling values (Eq. 1 and 2) to the values received by finite elements, it may be observed that the calculated values lie on the safe side.

For girders with sinusoidal corrugated web **with** support stiffeners a modified model was developed [4] to describe the shear capacity:

$$V_{RD} = \kappa_\tau * \frac{f_{y,k}}{\sqrt{3} * \gamma_M} * h * t \tag{4}$$

with $\kappa_\tau = \frac{1{,}0}{\overline{\lambda_p}^{1,5}}$ for $\overline{\lambda_p} > 1{,}0$ and

$\kappa_\tau = 1{,}0$ for $\overline{\lambda_p} \leq 1{,}0$

It may be noted, that there is no interaction between the two modes of buckling.

For girders **without** intermediate stiffeners the load capacity can be calculated from [5]

$$F_{ult} = 10 * \left(\frac{W_{el}}{I/t} \right)^{0,4} * 2f * t * f_y \tag{5}$$

with

W_{el}	-section modulus of the flange
I	-moment of inertia of one wave about the horizontal symmetric axis
t	-thickness of the web
2f	-depth of the wave (2x wave amplitude)
f_y	-yield stress of the web.

4 Additional stability investigations: local and global buckling

In the context of the ongoing research different instabilities of thin-walled girders with sinusoidal corrugated web were examined.

4.1 Tests

The following test carried out:

Shape of the wave: WT40-155
Thickness of flange: 20*mm*
Thickness of the web: s_1 = 2,5*mm* s_2 = 3,3*mm*
Height of the web: 1000*mm*
Length of the girder: 6*m*

Furthermore the load area was varied:

Le_1 = 23*cm*	Le_2 = 2 x 28*cm*	Le_3 = 60*cm*	Le_4 = 100*cm*

The test specimen is shown in Figure 1. The loading was introduced with a 1000*kN* hydraulic machine. The load was brought in with the hydraulic machine in the center of the test-girder with various length of loading. The hinged guidance of the machine makes the vertical loading on the top flange of the girder possible.

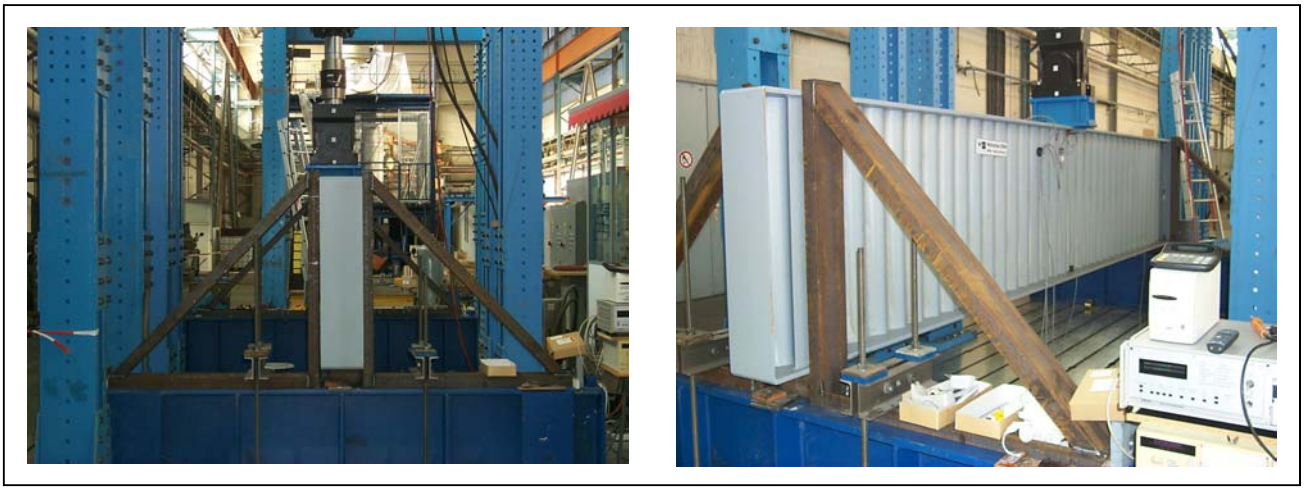

Figure 1: Test

Web thickness 2,5*mm*

The test girder with $Le_1 = 25cm$ appears a local buckle below the loading area. With the capacity load of 410*kN* the first local buckle appears 10*cm* below the upper flange in the web area (Figure 2). During the second test with 2 loading areas in a distance of 30*cm* $Le_2 = 28cm$ the failure behaviour is very interesting. With a load of 520*kN* appears suddenly lateral displacement in z-direction (displacement difference: 12*mm*). The load displacement diagram (figure 3) shows the rapid load decrease and indicates a malicious failure of the girder. The girder puts into a balanced position and load rise is possible. With the reach of the bearing capacity of 590*kN* plasticity appears in web regions and local buckles below the loading area can be recognized.
The following test girder (same girder dimensions) and a loading area of 60*cm* reach a bearing load of 607,5*kN*. Local buckles appear in the whole area of loading. The loading area 100*cm* achieves a maximum bearing load of 780*kN*.

Figure 2: Local Buckle

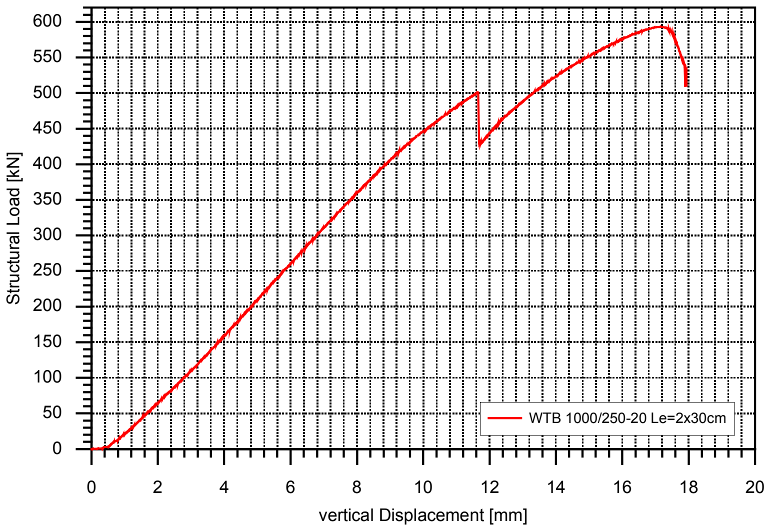

Figure 3: Load Displacement Curve

Web thickness 3,3*mm*

The test girder with a web thickness of 3,3*mm* shows a completely different failure mode with the same boundary conditions (test erection and realization).
The first girder fails with a maximum load of 810*kN* and a lateral displacement (z-direction) of 9,5*mm* is connected to a muffled bang. After a loading decrease of approx. 3-4% is a renewed

increase of the load and an ongoing rise of the lateral displacement of the upper flange could be noted. The load obtained once however isn't exceeded by 810*kN*.

How can we explain the jump in the load-deformation curve?
A cause has to be sought in the faulty type of the lateral support construction (fork store).
That means: The girder ends weren't conclusively on the channel profile (fork store). There was therefore the possibility, that the girder with its movement in the middle of the upper flange and connected to this with the possibility that the girder ends move (z-direction). The load decreased until the girder pushed against the lateral support. The girder was renewed in a balanced position and a repeated load rise happened. The failure mode is a pure lateral torsional buckling mode without plasticity and without connected local buckling (figure 4).

Figure 4: Lateral Torsional Buckling Test 1

Figure 5: Lateral Torsional Buckling Test 2

In the second test a load was obtained by approx. 780kN at a vertical moving of the cylinder head of approx. 16.5mm and a horizontal deflection of the girder of approx. 15.5mm. A load scrap was carried out on approx. 740kN. Till there no clear failure mechanisms are recognizable.
At a strength of 740kN a muffled noise is to hear suddenly and a abruptly horizontal movement of the girder (figure 5) is to record.

4.2 Comparison FEM/Test

With help of the finite element program Abaqus a girder with sinusoidal corrugated web was erected. The FE model has maximum deviations of the load maximum - after various changes and under consideration of the available material law – in comparison to the test of 3-4 %. A calibration of the FEM model was renounced since the deviation accepts only very little results.
At present the made FE model is based on a FE parameter study and examines the global stability behaviour of the girder with sinusoidal corrugated web.

5 Girders in the area of crane brackets

The load capacity of a sinusoidal corrugated column-web, which is loaded by a crane bracket shall be examined. How far the corrugation takes part as stiffeners against local as well as global buckling. It is the aim to determine the bearing capacity behaviour. Beyond this innovative advantage solutions and constructive notes shall be given for the crane bracket connection.

5.1 Tests

Six structural load tests were done and at this varied three parameters. The used specimen were chosen realistically, this means that all elements of the specimen, column as well as crane bracket, are applied in the hall structure in this form. The dimensions of the specimen correspond to the defaults. Furthermore the specimen represent a part from a frame structure. The boundary conditions are chosen so that both sides of the column are restrained. The bracket is connected to the column with an end plate. The specimen is restrained and immovable at the ground. The column is held by metals against lateral movements. These metals are welded on the upper end plate of the column and connected with the test frame and a further independent support. Figure 6 shows the test erection. The loading is carried out with the 1000kN hydraulic cylinder. The bracket is loaded with a 40mm thick metal instead of punctual loading.

Figure 6: Test Erection

TABLE 1
DIMENSIONS OF SPECIMEN (GIRDER)

Specimen	Shape of wave 2f/q	Thickness flange sf [mm]	Width flange bf [mm]	Height web hs [mm]	Length column L [mm]	Thickness web ss [mm]
WT1	40/155	12	250	750	2500	2
WT2	40/155	20	250	750	2500	2
WT3	40/155	20	250	750	2500	2
WT4	40/155	12	250	750	2500	2
WT5	40/155	20	250	750	2500	3
WT6	40/155	20	250	750	2500	3

In Table 1 all dimensions of the test girders are listed. The description of the specimen-behaviour follows.

WT1	Backing plate, without horizontal stiffener Displacement controlled with a speed 0,12*mm/min*. With a load of 218*kN* a weld cracking happens in the tension range. The structural load is reached by a loading of 251*kN*. In the pressure area of the bracket connection local buckles appear in a distance of 2-3*cm* from the flange.
WT4	Backing plate, without horizontal stiffener Displacement controlled with a speed 0,12*mm/min*. The load displacement curve shows a continious Load raise until approx. 260*kN*. The structural load is reached with 300*kN*. A local buckle is recognized in the pressure range of the corrugated web. First after a Loading scrap of approx. 10% the first welded seam crack appear.

WT5	Horizontal tension stiffener Displacement controlled with a speed 0,1*mm/s*. The structural load is 593*kN*. With the first buckles in the pressure area high deflections appear because of the plasticity of the steel.
WT6	Horizontal tension stiffener Displacement controlled with a speed 0,1*mm/s*. The structural load is 612*kN*. First buckles are accompanied by plasticity of the steel in the pressure range.
WT2	Horizontal tension stiffener Displacement controlled with a speed 0,12*mm/min*. The structural load is 350*kN*. The first buckle appears with a loading of 342*kN*. A minimal load rise follows until a structural load of 350*kN*. A welded seam crack isn't to be noted.
WT3	Horizontal tension stiffener Displacement controlled with a speed 0,12*mm/min*. The structural load is 368*kN*. First buckles appear with the maximum structural load. A welded seam crack isn't to be noted.

5.2 Comparison FEM/Test

With the finite element program Abaqus a model was developed for the girder - crane bracket connection. At the time, material characteristics data weren't taken into account, the available deviations (22%) also have to be justified for the results of the trials with that.
In the following diagram (figure 7) all load displacement curves of the specimen are compared with load displacement curves of the finite elements analysis.

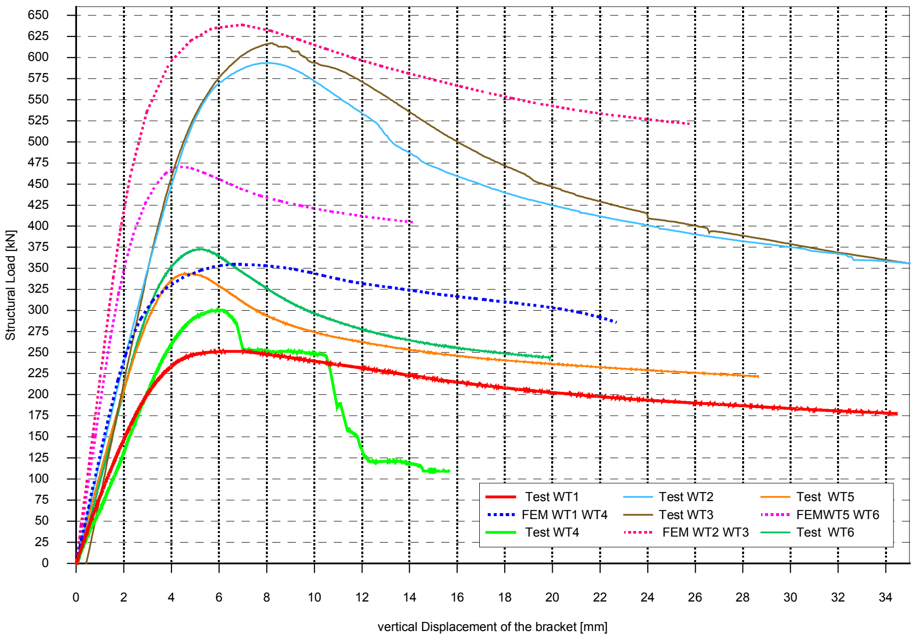

Figure 7: Comparison Test - FEM

5.3 Optimal solution

With help of the made FE model parameter studies were done for a crane bracket connected to a column with sinusoidal corrugated web. The models of the variant examination are in figure 8 represented. The aim is to give statements about the bracing of the column web in the connection area.

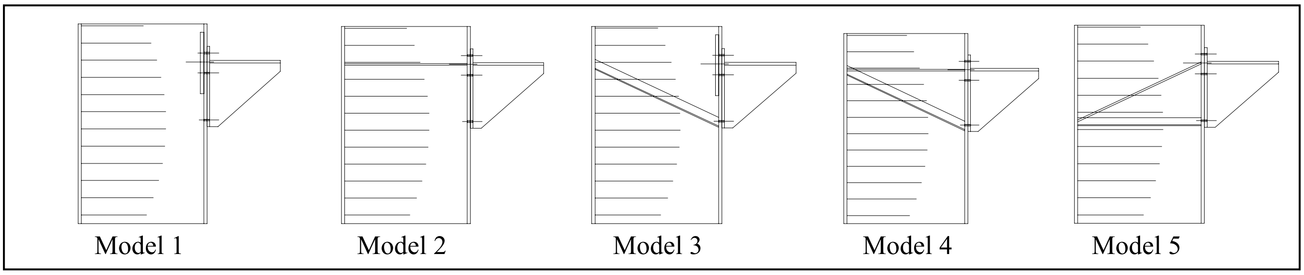

Figure 8: Parameter study models

Model 1 as default model is looked at. The structural load of this connection is 416*kN*. This constructive solution contains the lowest technical effort. In comparison with this a load rise can be obtained of almost 35% with the order of a tension stiffener instead of the backing plate. A comparable load rise is obtained with the order of a diagonal pressure brace and a backing plate model 3 as well as the order of the bracket connection shown in model 5. Model 4 reaches the highest structural load with approx. 740*kN*.
If the column web thickness of model 1 increased twice, a similar load capacity like in model 4 may be achieved.

5.4 Bearing capacity behaviour of knee joints

In the context of a studies carried out at the chair (J. Robra) the sinusoidal corrugated web of a knee joint was examined. In opposite to knee joints with flat and thin-wall knee plate no overcritical structural behaviour appears. With reaching the structural load local buckles appear in the web of the knee joint. A diagonal course is indicated. If one looks at the course of the local buckles a maximum angle of 75° can be recognized. It is not to be equate with the development of a tension field, because the material is in plasticity and no load rise could be mentioned after the development of the buckles.
Conditionally by the present stand of the machine made production of girders with sinusoidal webs the moment of inertia is constant about the complete length and is not adapted to the course of the moment. One possibility to optimize the material deployment is to keep the end and field moment at the same size to avoid a overdimension in the field.

6 Summary

It is known that the sinusoidal corrugated web has a better buckling performance than “classic” welded sections and even comparable trapezoidally-shaped web. The paper describes former investigations on the shear capacity of the web, ongoing numerical analysis and experimental tests on local and global (lateral-torsional) buckling of girders. Moreover, the influence of crane brackets on the girder is analysed numerically and experimentally.

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