Girders with structured web- ongoing research

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Abstract
In an ongoing research project, welded girders with I-section and thin “honey-comb” structured web were investigated. A series of plate girders with different webs (flat, profiled or structured) were fabricated. The aim of the tests is to study if the behavior of girders with structured web differs from comparable flat or even corrugated web.

1. Introduction

Multi-dimensional structures are used today in the field of the car industry or the home appliance. These structures are only used in the field of steel construction, mostly as webs in steel structures – trapezoidal shaped or sinusoidal corrugated. The failure of girders with flat and slender webs under shear force is observed with buckle of the web in consequence of the shear stress.
Afterward due to the deflection a tension field develops over the whole web height. With higher shear forces plastic hinges are formed in the flange.

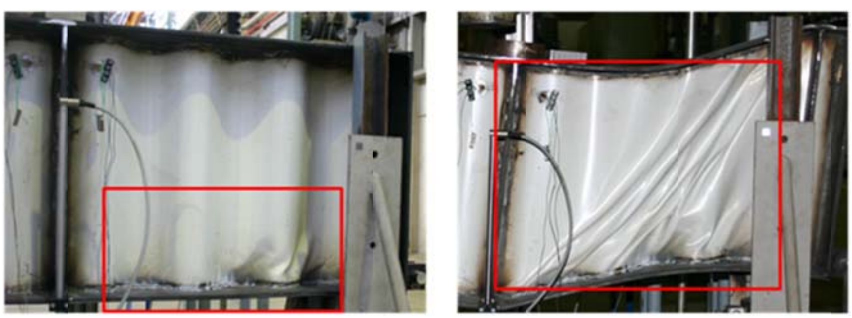

Figure 1: Girder with sinusoidal web local and global buckling

But the failure of girders with trapezoidal shaped or sinusoidal corrugated webs – with a thickness of the web of 1,0 mm or and 0,88 mm – is different. The profiled webs collapse in an interaction of local and global buckling, which is seen in Fig.1. In this project the implementation of multi-dimensional structures should give an alternative to profiled webs.

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Structured metal sheets improve the essential properties of the initial material, e.g. its stiffness. Structured metal sheets with regular bumps offer a higher bending stiffness compared to flat sheets. The application of those structured sheets requires new investigations regarding their strength and deformation behavior in welded I- girders.

2. State of the art

Structured plates are an innovated lightweight product. There are two types of production methods. The first is the "buckling-structuring" which is used by Dr. Mirtsch GmbH, the second is the hydro forming for structured plates produced by FQZ GmbH or borit® Leichtbau-Technik GmbH (Fig. 2). In this research the sheets are produced by hydro-forming. The FQZ structure is a hexagonal regular bump structure with a small bridge of 2 mm between the bumps and a depth of the bump about 3 mm. The basic material is the low alloyed steel DC04 (1.0338).

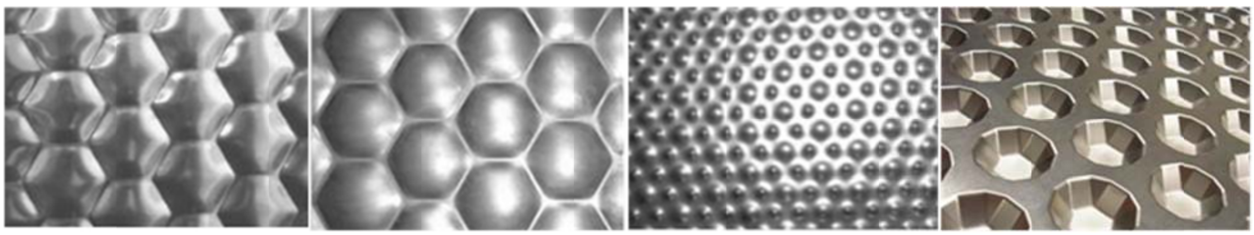


Figure 2: Example of structured plates- structure from Dr. Mirtsch, FQZ- structure, Borit structure, Borit structure 12 angled [Borit2012], from left to right

The thickness of the metal sheet is 0,5 mm. During the hydro-forming manufacturing process from flat sheet to a structured sheet, the material thickness is reduced particularly. In order to find the real material properties it is necessary to adapt the specimen dimension from DIN EN ISO 6892-1. Therefore, the specimen test length in adaption of the proposed ratio between width and length in the DIN code was modified. In Fig. 3 are given the stress-strain relationship for one selected specimen dimension.

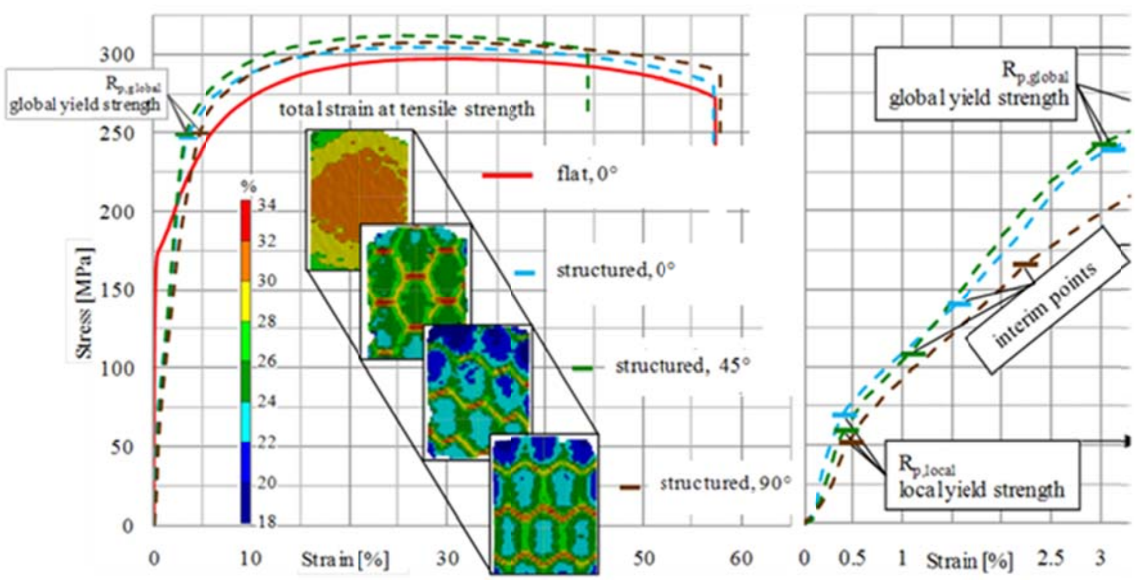
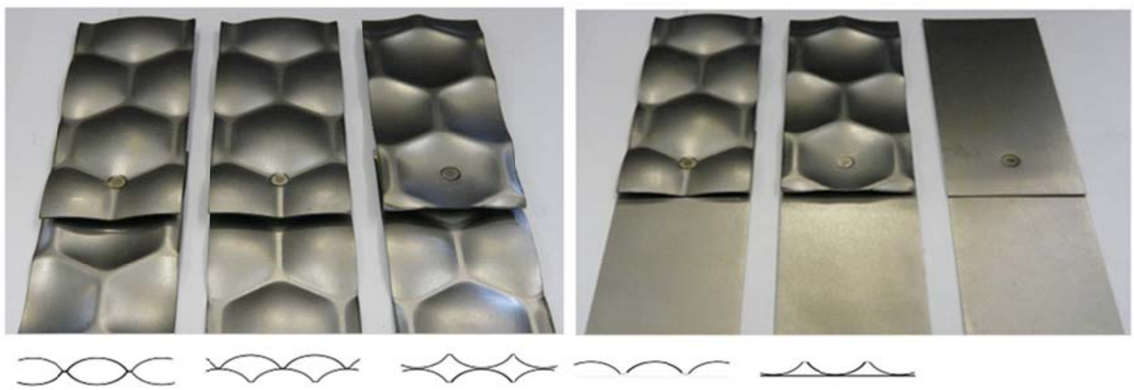


Figure 3: Stress-strain curves for a selected specimen dimension for three tested structure positions and a flat sheet metal with corresponding deformation images [Fritsche 2011]

The other structured webs (two types), which are used, are produced from borit® Leichtbau-Technik GmbH. The sheets have a twelve-angled regular bump structure. Both sheet- metal has a thickness of 0,6 mm.
Another research topic is spot welding of structured plates. For retaining the structure and the properties of the sheets during the welding process, not all positions of fixing two plates are possible. As well a stabile position is one condition for welding two sheets for a sandwich assembly.
There are 7 variants to create a sandwich with two structured plates. Fig. 4 shows the chosen variant with the joining comb-comb and other possibilities [Schleuß 2010]. For producing a sandwich element consisting of two sheets from Borit®, the company uses a bonding technology.



Bridge-Bridge / Bridge- Comb / Comb-Comb / Bridge-Plane / Comb-Plane / Plane-Plane
Figure 4: Variants of joining [Schleuß 2010]

The design of welded I-section girders (with a planar or profiled web) contains DIN EN 1993-1-5:2010. Another design method can be found in the German DASt-Richtlinie 015. For the design of girders with structured webs these methods can be adapted.

3. Numerical Simulation

3.1 Verification of the experiments

For modeling the girder under a mid-span load, the software ABAQUS [Abaqus2010] was used. In order to find the best model, which behavior is near to the real shear load test, a lot of models were tested.

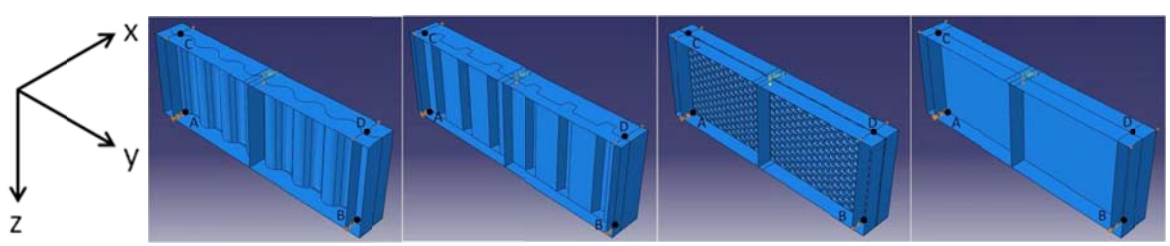


Figure 5: Geometry of all girders in ABAQUS

As material properties, the true stress and true strain curve from the tensile test were used. The boundary conditions are defined as shown in Fig. 5 and Table 1. The several parts of the girder are modeled with shell element S4R5 and meshed with a size of 20 mm.

Table 1: Boundary conditions of the girders (not constraint = 0; constraint = 1)

Location	u_x	u_y	u_z	rot_x	rot_y	rot_z
Point A	1	1	1	0	0	0
Point B	0	1	1	0	0	0
Point C	0	0	1	0	0	0
Point D	0	0	1	0	0	0

The first step for the Finite Element Model was a linear buckling analysis. The initial imperfection (geometric imperfection and residual stress) [Beg2010] was measured at the real test sample. Later it was imported to the next step, the general static analysis which lets one find the ultimate load. The numerical results of the girders with a planar, trapezoidal shaped or sinusoidal corrugated web are shown in Fig. 6. The results of 4 girders with a structured web are shown in Fig. 7. All results are listed in Table 3. An Overview about all test parameters is given in Table 2. Generally, the results from the FEM of the girder with planar web confirm those from the tests.

Table 2: An overview about all parameters of all girders

web	planar		trapez		sinus			FQZ							Borit			
VK	1.1	1.2	2.1	2.2	3.1	3.2	3.3	4.1	5.1	9.1	10.1	11.1	12.1	13.1	6.1	7.1	7.2	8.1
joining	-	-	-	-	-	-	-	w-w	w-w	-	-	s-s	w-w	w-w	glue	glue	glue	glue
direction								0°	90°	90°	0°	90°	45°	90°	0°	90°	90°	0°
bump								33	33	33	33	33	33	51	4.2	4.2	4.2	9.2
t [mm]	1	1	1	1	0,88	0,88	0,88	2x0,5	2x0,5	1,0	1,0	2x0,5	2x0,5	2x0,5	2x0,6	2x0,6	2x0,6	2x0,6

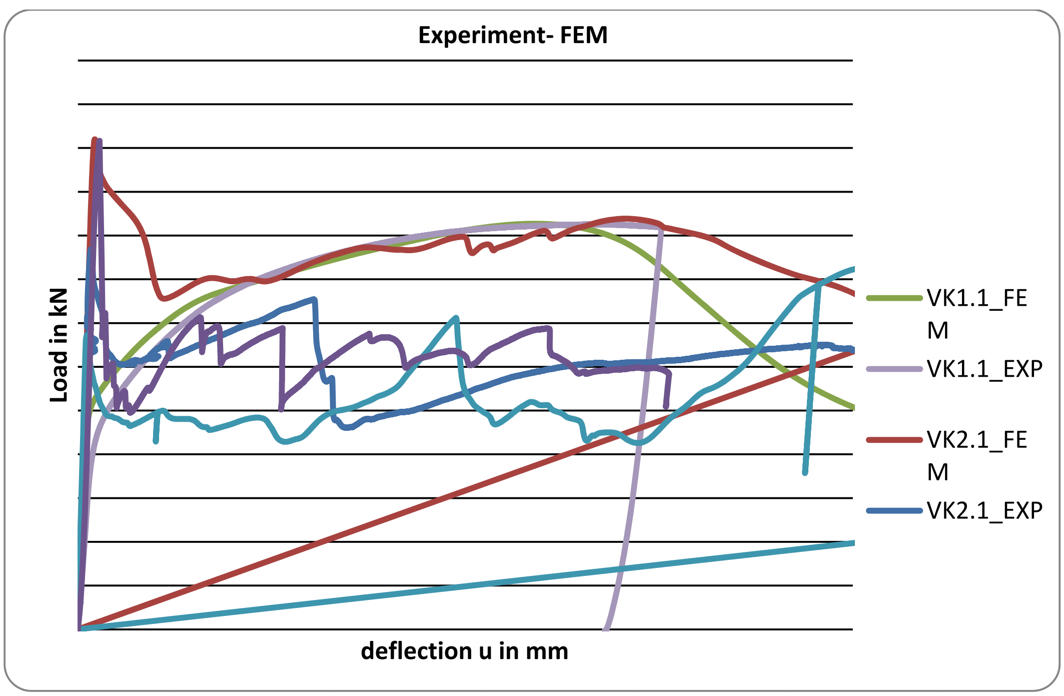


Figure 6: Load-deflection curve for girders with planar, trapezoidal or sinusoidal corrugated web

Table 3: Comparison of test and simulation results

Specimen	$F_{cr,exp}$ [kN]	$F_{u,exp}$ [kN]	$F_{cr,FEM}$ [kN]	$F_{u,FEM}$ [kN]	$F_{u,FEM}$ / $F_{u,exp}$	$F_{cr,FEM}$ / $F_{cr,exp}$
VK1.1	38,5*	92,6	50,4*	92,7	1,001	1,309
VK2.1	89,7	67,5	107,2	78,6	1,164	1,195
VK3.1	100,5	78,5	67,4	82,7	1,053	0,670
VK4.1	36,38	89,21	43,60	92,99	1,042	1,198
VK5.1	35,61*	89,76	42,77	90,71	1,011	1,200
VK9.1	38,27*	95,62	38,04	92,02	0,962	0,994
VK10.1	35,23*	96,62	38,38	91,89	0,951	1,089

* The critical load was assumed to correspond to a deflection of 1,5 mm

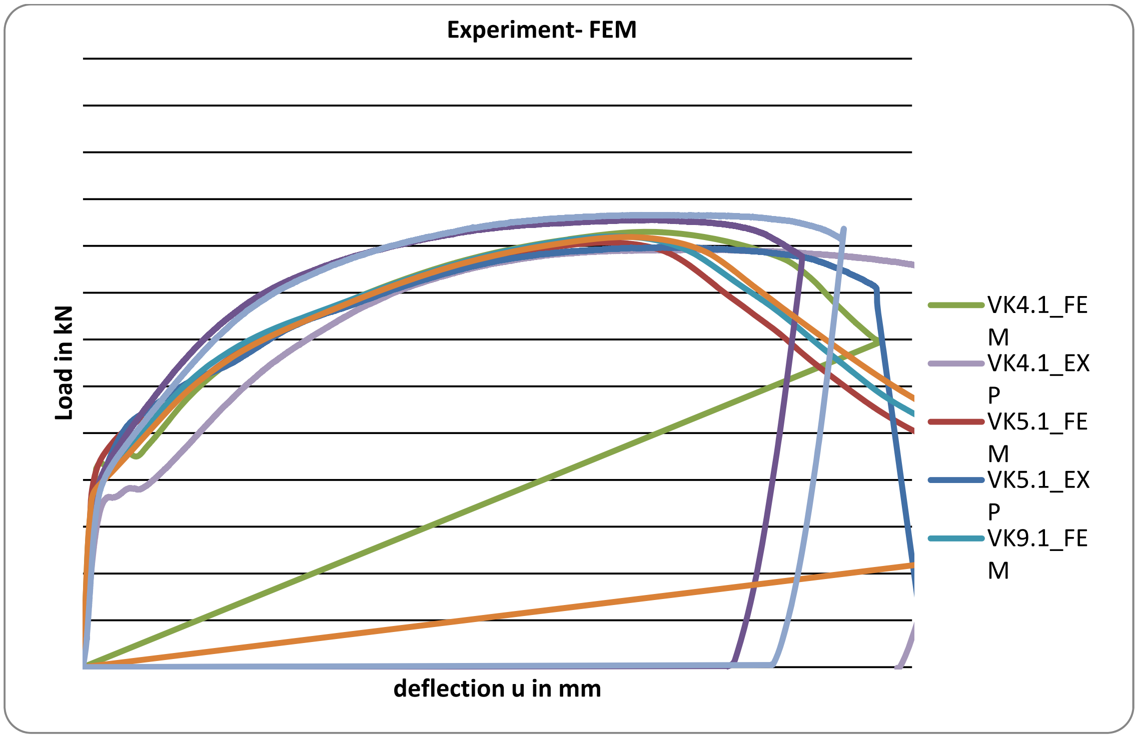


Figure 7: Load-deflection curve for girders with structured web from tests and FE simulations

The modeling of the girder with the structured web as a sandwich element in FEM produces about 20500 shell elements of type S4R5, S3 and S4R. The single structured plate was modeled with the software ProEngineer [ProE2011].

3.2 Parameter analysis of the girders (planar, trapezoidal shaped or sinusoidal corrugated)

After calibration of the tests with ABAQUS the sensivity analysis starts with different parameters. For all web geometry there were carried out about 40 models with differences in length, height and thickness of the web; shear aspect ratio and thickness to height ratio. An overview of the differences is given in Table 4. The results are shown in Fig. 8 and Fig. 9 for the first sensivity analysis for all girders.

Table 4: Differences in sensivity analysis; *E= equal; *D= different

Sensivity analysis	Length	Height	Thickness	Shear aspect ratio	Thickness/ Height ratio	Status
1	E	E	D	E	D	Done
2	D	E	E	D	E	Done
3	E	D	E	D	D	Done
4	D	D	D	E	E	Done
5	D	D	E	E	D	Not finished
6	D	E	D	D	D	Not finished
7	E	D	D	D	E	Not finished

The influences of thickness and the shear aspect ratio of the web on the shear load are not new. The analysis 1 describes nearly a direct linear relationship between the thickness and the load for all 3 types of girders. But for the trapezoidal and sinusoidal corrugated web in the analysis 2 one can realize that the influence is not so big because of the local buckling behavior of the web.

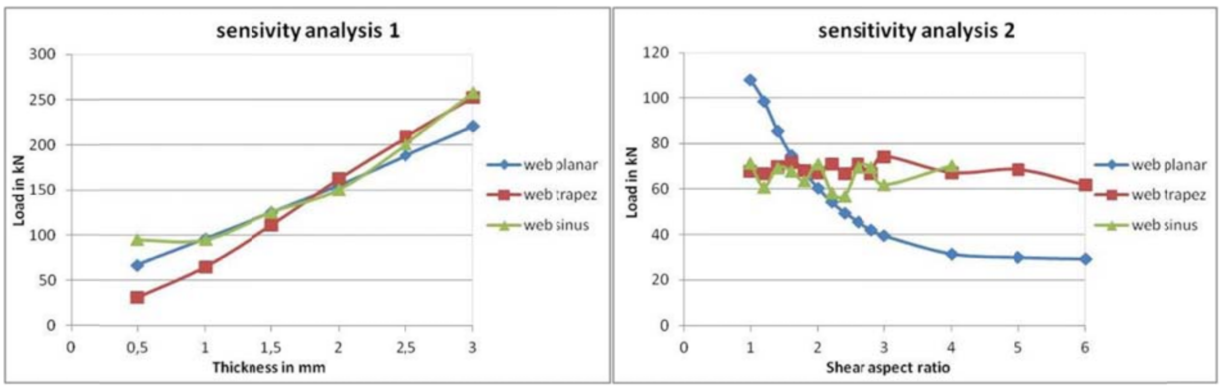


Figure 8: Load over shear aspect ratio and thickness - results from FE- simulation, 1 and 2

Even in analysis 3 the girder with a sinusoidal corrugated web has an indirect relationship until a shear aspect ratio of 3. In analysis 4 the ultimate loads of the girder with a trapezoidal and sinusoidal corrugated web are higher than those of the girder with a planar web (constant thickness assumed).

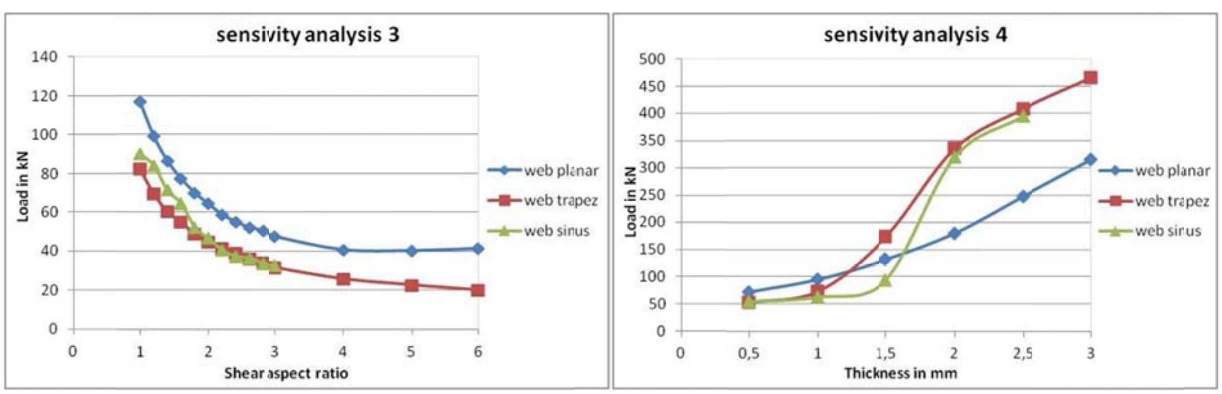


Figure 9: Load over shear aspect ratio and thickness - results from FE- simulation, 3 and 4

4. Shear load test

The static system of the girder is a beam with two bearings, one fixed and one moveable (Fig. 10). Additionally the girder was also fixed in the horizontal direction for elimination tilting vertically to the moment plane. A concentrated force was put in the middle of the girder at the transversal stiffener.

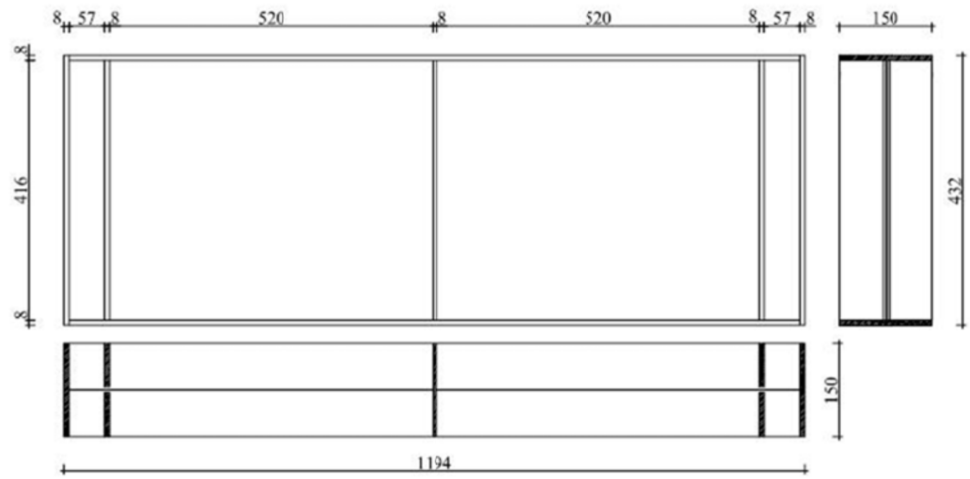


Figure 10: Geometry of all test specimen

Beside a planar web trapezoidal and a sinusoidal web were included in the investigations (Fig. 11 and 12). The test speed was 1 mm/min. It is an acceptable value for having comparable test results in reference to the buckling time and regarding the relation between buckling and shear load.

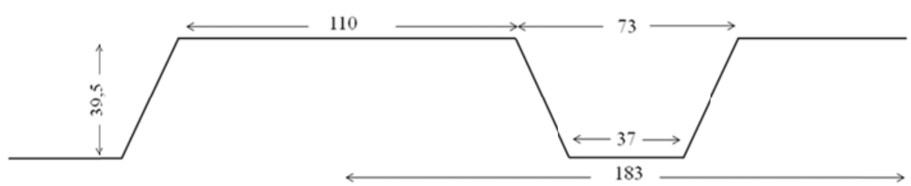


Figure 11: Geometry of the trapezoidal profile

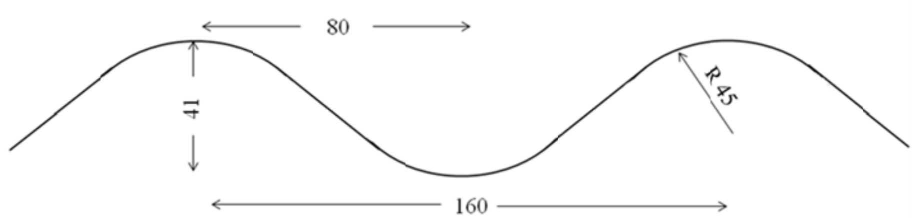


Figure 12: Geometry of the sinusoidal profile

For analysis the horizontal deflection of the web, the vertical deflection of the girder, the strain in the web and the ultimate load were considered. Fig. 13 and Fig. 14 shows the test: two load cells, four strain gauges in all girders with a flat web as well as 10 displacement transducers. To find the material properties of steel used for the web and the flange there were carried out tensile tests. Table 5 shows the average from all tests.

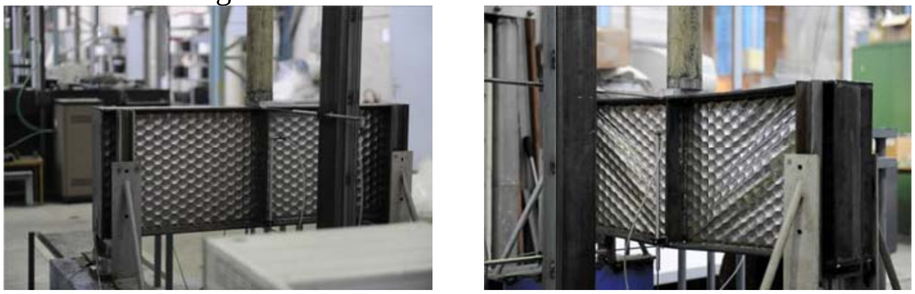


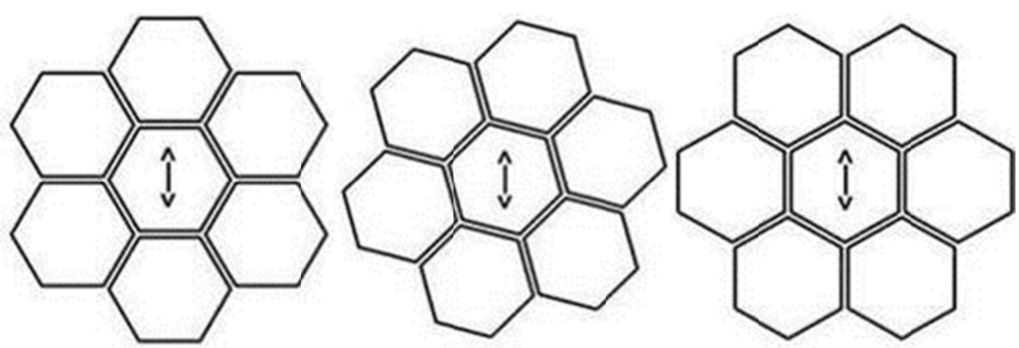
Figure 13: Test girder 4.1 during the shear load test

Figure 14: Test girder 6.1 during the shear load test

Table 5: Material properties (results in N/mm²)

	material	E	$R_{p0,2}$	R_{eH}	R_{eL}	R_m
web flat	DC01	209141	183	x	x	327
web trapez	x	180964	x	301	291	355
web sinus	x	178687	x	319	298	332
web flat	DC04	165000	170	x	x	295
FQZ	DC04	x	x	x	x	305
flange	S355	215228	x	411	391	534

Due to the difficulties of fabrication of the structured plates with a thickness of 1 mm it was decided to create a sandwich construction with 2 plates of 0,5 mm first. Fig. 15 shows 3 possible orientations of the structured web related to the load direction.



a) 0° b) 45° c) 90°

Figure 15: Orientation of the structured web in dependence to the load direction

Before the tests started the geometrical imperfections of the girders with planar and structured plates were measured in the middle of the web. The imperfections of the web have an influence on the buckling behavior.

Table 6: Measured imperfection

girder	Imperfection shear field 1 in mm	Imperfection shear field 2 in mm
1.1	2,3	3,2
1.2	1,51	1,58
4.1	2,4	1,4
9.1	4,61	4,02
10.1	2,66	2,46
11.1	0,77	1,42
12.1	0,42	0,68
13.1	0,72	1,35

Table 6 shows all initial imperfections of the tested girders. For the test specimen with a trapezoidal or sinusoidal corrugated web the horizontal geometric imperfection were not measured because of the local buckling behavior. Two different test series are made with different length, aspect ratios and rigid or non-rigid end post.
Up to this date, 17 tests have been carried out in series 1 and two tests in series 2. Obviously, the shear area ratio has an influence on the ultimate force and the stiffness of the rigid end post has an effect, too. But for further data interpretation have been used only all test with the same length 1,194 m and a shear ratio of 1,25 to show the influence of the thickness and the design of the different webs. In comparison to all tests it can be seen, that the experimental tests of the girders with a plane and a structured web have a similar behavior and those test of the girders with a trapezoidal or sinusoidal corrugated web.
Fig. 16 shows the load-vertical deflection curves for girders with a planar and a structured web. In Fig. 18 are shown load-vertical deflection curves (2) for girders with trapezoidal and sinusoidal corrugated web.

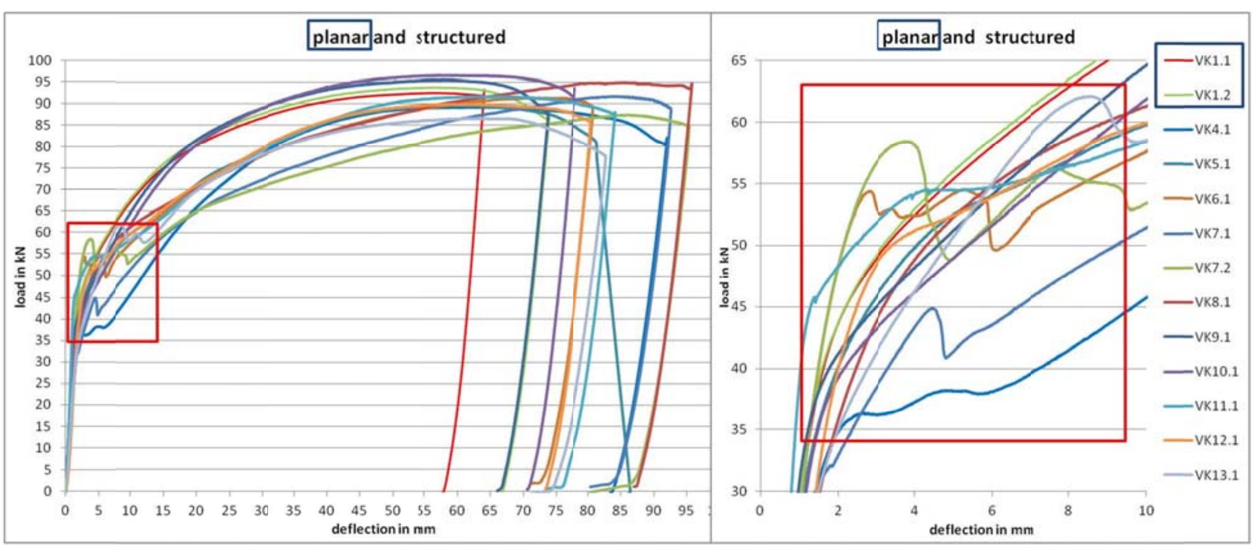


Figure 16: Load- vertical deflection curves of the girders with planar and structured web

The diagram in Fig. 16 shows that the behavior at the beginning of buckling is different for girders with a planar and a structured web. This phenomenon appears due to the deformation of the sheets (Fig. 17) without of the load. If the structure is nearly complete planar the load rise to the ultimate load.

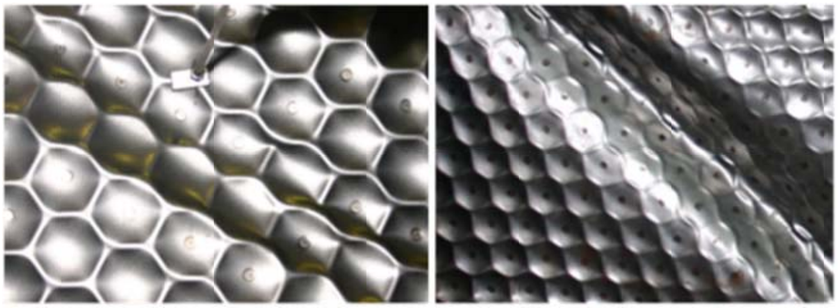


Figure 17: Dispersing and plane of the comb

Differences between the directions of the structure are also recognized. That's why one can define there is a big influence for reaching a higher critical buckling load (buckling behavior) between the direction of the comb and the load direction.
Based on the stiffness of the different structured web from FQZ and Borit® the graphs of the ultimate load are different. The behavior of the girders with trapezoidal and sinusoidal webs is similar as shown in Fig. 18. Based on the beginning of the test the load- deflection curve steeply rising until the critical buckling load (local buckling). After this load one can see a big load drop. At the same time the web have an abrupt local buckling of the trapezoidal or sinusoidal corrugated web

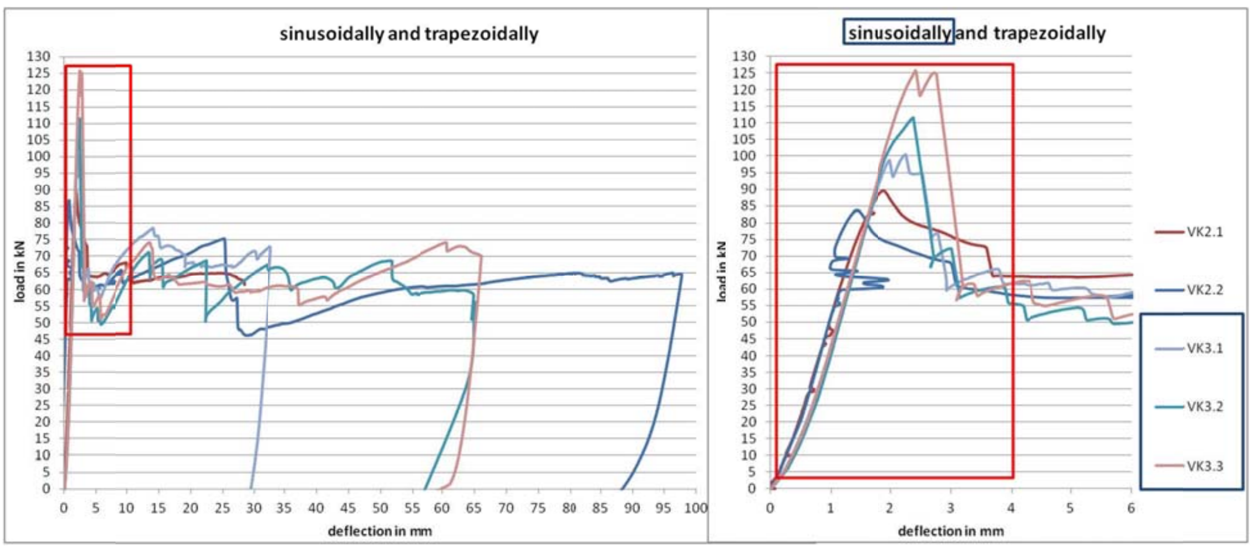


Figure 18: Load- vertical deflection curves of the girders with trapezoidal and sinusoidal web

Furthermore one can note that the horizontal deflection in the center of the shear field depends on the stiffness of the sandwich web. Fig. 19 shows the different behavior of the girder with the planar web and the structured web with regard to the horizontal displacement of the centre of the two shear fields.

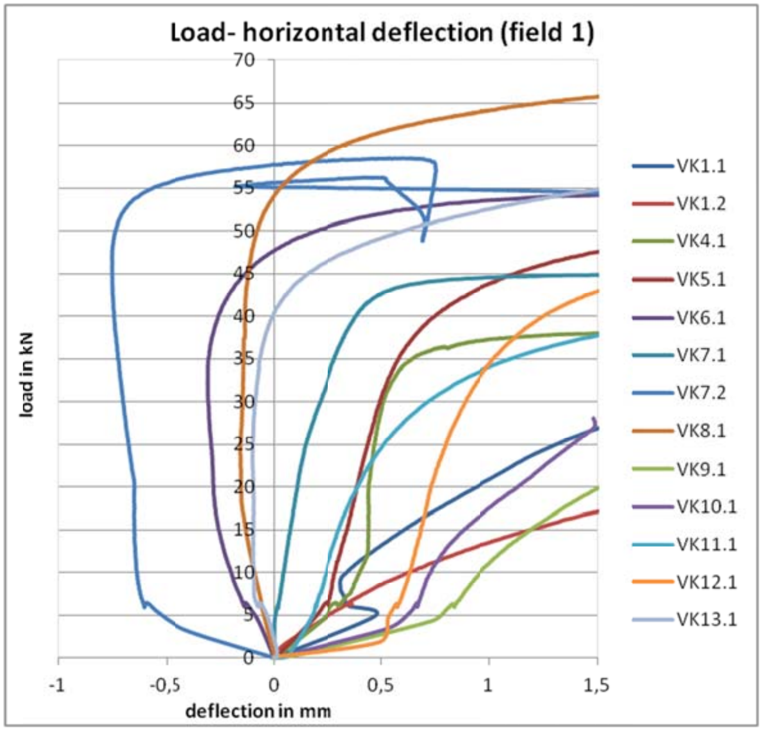


Figure 19: Horizontal deflection shear field 1

In the tests it can be seen that the structured plate has a higher stiffness than the planar web. That means that the buckling behavior of a girder with a structured web is much better than the girder with a flat web. Fig. 20 shows the different tension fields from test VK4.1 - VK13.1. It can be observed that the comb structure does not exist partially.


Figure 20: Tension fields of some tests

5. Analytical Results

The ultimate load is achieved when the load does not increase anymore and only the deformation accelerates.

Table 7: Comparison of test and analytical results

[1]	[2]	[3]	[4]	[5]	[6]	[7]
Specimen	$F_{u,exp}$ [kN]	$F_{cal,ec3}$ [kN]	$F_{cal,dast15}$ [kN]	$F_{cal,Zem}$ [kN]	[2] / [3]	[2] / [4] - [2] / [5]
VK1.1	92,6	44,5	72,9	X	2,08	1,27
VK1.2	93,8				2,11	1,29
VK2.1	67,5	47,7	39,8	X	1,41	1,69
VK2.2	65,1				1,36	1,63
VK3.1	78,5	68,5	X	43,9	1,14	1,79
VK3.2	69,3				1,01	1,29
VK3.3	74,2				1,08	1,69
VK4.1	89,2	X	X	X	X	X
VK5.1	89,8					
VK6.1	91,4					
VK7.1	91,8					
VK7.2	87,4					
VK8.1	95,0					
VK9.1	95,62					
VK10.1	96,62					
VK11.1	91,83					
VK12.1	89,98					
VK13.1	86,67					

Table 7 contains the measured load for all types of girders. Furthermore for the first girders it was possible to calculate the ultimate load according to [DIN1993 2010], [DASt015] and [Zeman 1999]. In adaption of [Aschinger 1991] it should be possible to find a design method of girders with structured web.

In all girders with planar and structured web after shear buckling, a tension field developed (=post- buckling) and later plastic hinges were formed (=frame effect). A difference between the flat and structured web was observed: Parallel to the forming of a tension field, the comb structure was lost.

There was one difficulty in finding the comparable values for the definition of shear and tension load from [DASt015] for the experiment and the FE method. The buckling load was defined as a load, which corresponds to the horizontal displacement of the web of 1,5 mm. It was difficult to recognize, when the frame effect started during the experiment. That’s why the tension effect was given by an approximate value. In Table 3 are only shown the complete ultimate loads from the tests and the analytical analysis.

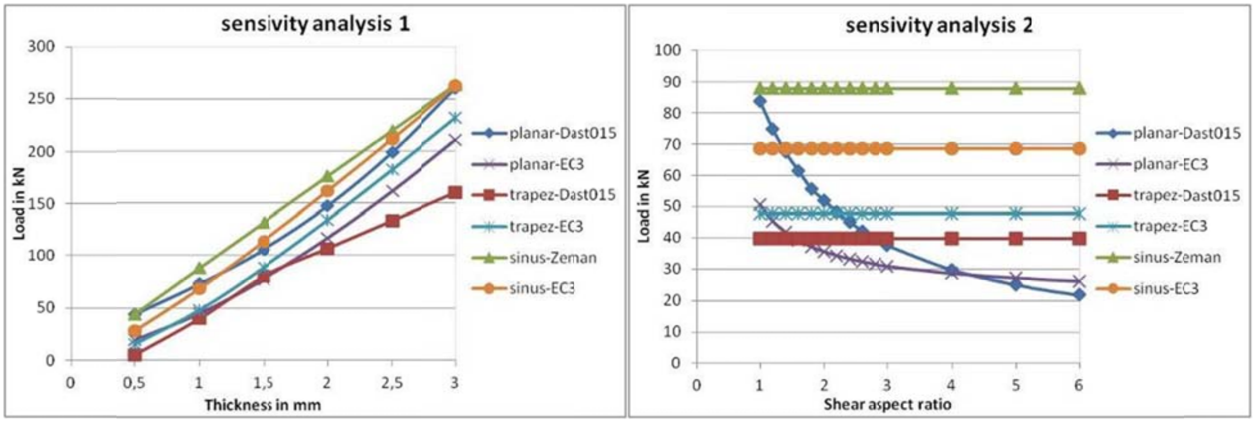


Figure 21: Load over shear aspect ratio and thickness- analytical results 1 and 2

In Fig. 21 and Fig.22 the comparison is shown considering the influence of the parameter thickness and shear aspect ratio. The thickness is directly linear to the ultimate load, as shown in sensivity analysis 1. The overview of the differences in the sensitivy analysis is given in Table 4.

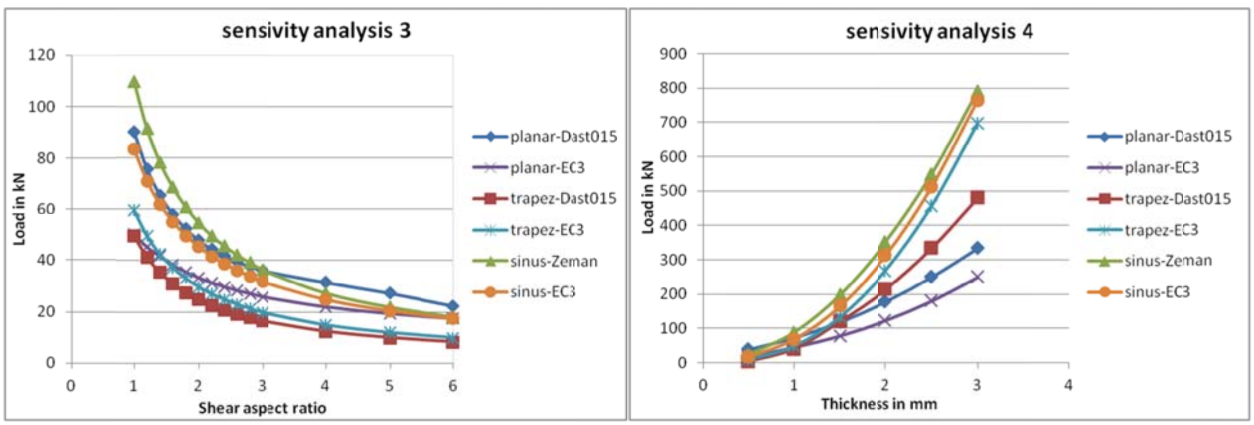


Figure 22: Load over shear aspect ratio and thickness- analytical results 3 and 4

The highest value for loads are calculated for a girder with a sinusoidally web. In the diagram for the sensivity analysis 2 has 4 graphs with the same value of load for different shear ratio aspects. More over the obtained results show, that the shear aspect ratio for analysis 3 is indirectly proportional to the ultimate load and the thickness is more than linear directly proportional to the ultimate load (analysis 4).

6. Conclucions

The stiffness of the sandwich element is higher than the flat plate. The ultimate loads of girders with planar and structured webs are comparable. The buckling behavior of the girder with a structured web is depended on the orientation of the combs. Sin girders give the highest ultimate load.
The design model is being developed according [Aschinger1991], [DASt1990] and [DIN1993 2010]. The further refinement of structured web-model with geometry and material properties is necessary.

Acknowledgments

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