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SEGMENTED COMPOSITE SECTIONS WITH WOOD DOWELS

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ABSTRACT: Recent research approaches try to expand the scope of application of timber construction elements. Possibilities to reduce the material consumption and raise the automatization level are also gaining interest to an increasing degree. Segmented sections with wood connectors are predestined for this challenge because of their modular character. Analytical, numerical and experimental investigations are conducted to assess the effects of different geometrical and material parameters. The results provide a strong basis to understand and improve the effectiveness of these sections.

KEYWORDS: segmented sections, elastic composite, modular engineering, robotic fabrication, wood dowels

1 INTRODUCTION

Questions of the consumption of resources, efficient material usage, recyclability and sustainability at large are gaining significant importance within the construction sector. In addition, experts and the public are focusing increasingly on aspects of automatization, modular production and robotic fabrication. Accordingly, civil engineering in general and timber engineering in particular should also take these topics into account. [1]
A current research project at the University of Kassel is being carried out by the Chair for Timber Structures and Building Rehabilitation together with the Chair of Experimental and Digital Design and Construction. The project includes both numerical studies about the effective use of material and experimental studies to develop new types of connections with wood dowels.
The overall objective of this optimization process is to develop new types of slab and wall elements by using beam sections of limited length, which should be taken from reused or recycled materials as far as possible, and addresses all those aspects. Timber engineering can provide here an important contribution to the urgent questions of sustainability and resource consumption. [2]

2 GENERAL SET-UP

The research activities deal with segmented box-type elements. The section is symmetric and composed of two oriented strand board (OSB) panels, forming the upper and the lower layer of the element, and the web beam section, for which structural timber (KVH) C24 is used. Due to the “second-usage approach” of the project, other timber products and different strength classes may also be considered in the future. The connection between the upper and lower OSB panels and the web section is realised by wood dowels. These fasteners can be arranged in several set-ups, including various distances or angles. The general set-up can be seen in Figure 1.

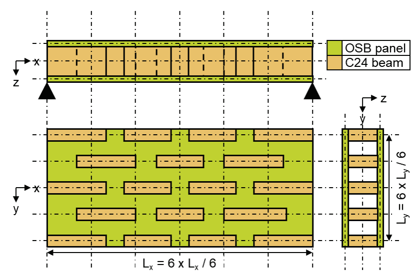

Figure 1: *General set-up*

3 METHODICAL APPROACH AND MODEL DEVELOPMENT

3.1 GENERAL

Both numerical and experimental investigations are part of the research. Whereas the numerical calculations provide the possibility of determining the influences of a huge number of different parameters systematically (e.g. geometry, material combinations, fasteners), the experimental testing should help to validate and calibrate the numerical models.
Analytical methods for composite sections can be found in EC 5 [3]. Several comparative studies with the analytical calculations are performed to check and verify the basic numerical approach. The pros and cons of different types of modelling can be found and assessed by varying the level of composite elasticity (between no and rigid composite). Finally, a numerical model has been developed and validated.

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3.2 SET-UP AND PARAMETERS

As a first step, a construction element with a segmented beam was investigated (Figure 2).

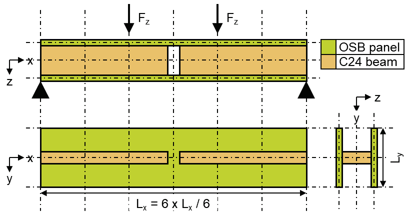

Figure 2: *Set-up for first step*

The materials considered are OSB panels and C24 beams; wood dowels at variable distances and slip moduli are applied for the fasteners. Dimensions and properties are listed in Table 1. The gap length is 2.0 cm.

Table 1: *Geometrical and material parameters*

		OSB	C24
Width	$L_y = b_y$	360 mm	60 mm
Height	$L_z = h_z$	24 mm	200 mm
Moe	$E_{0,mean}$	198 kN/cm^2	1,100 kN/cm^2
Density	ρ_{mean}	600 kg/m^3	420 kg/m^3

The wood dowels have a length of ℓ_{td} = 10.0 cm and a diameter of d_{td} = 1.0 cm; the distance between these fasteners is set to e = 2.0 cm. The static system is a single-span beam with a length of L_x = 2.0 m. The beam is loaded with two vertical forces of F_z = 10 kN. This arrangement represents a four-point bending set-up.

3.3 SELECTED RESULTS AND DISCUSSION

The deformation curve was determined numerically for each variation of the set-up. The results are shown in Figure 3 exemplary for K = 15.00 kN/cm. The curve for a non-segmented element is included as a reference. The other curves represent the three parts of the cross-section.

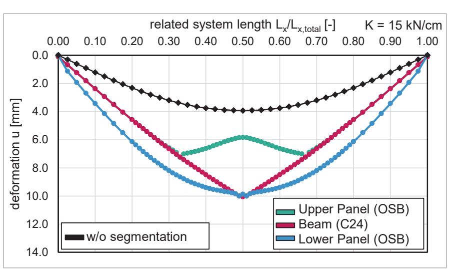

Figure 3: *Selected results*

The points where the load was applied ($L_x/L_{x,total}$ = 0.33; $L_x/L_{x,total}$ = 0.67) can easily be identified because of the contact between the upper panel and the beam. The upper panel separates itself from the beam between these points; the transmission of tensile forces through the dowels was deactivated for this numerical calculation. The deformation curve of the beam – actually, due to the gap, there are two beams – is linear, but it shows a discontinuity at midspan. This discontinuity is caused by the segmentation which is located here. Regarding the lower panel, it can be seen that the curve is not linear. The beam and the lower panel do not act as a composite cross-section because of the deactivated tensile forces. The ends of both beams push against the lower panel at midspan, which initiates the detachment of the lower panel.

Table 2: *Deformation in midspan*

		deformation u	
		absolute	related
Reference		3.938 mm	100 %
Upper panel	*OSB*	5.834 mm	145 %
Beam	*C24*	10.059 mm	255 %
Lower panel	*OSB*	9.869 mm	251 %

The segmentation leads to deformations that are more than 2.5-times higher in relation to the reference curve. The numerical results in midspan can be found in Table 2.

3.4 FURTHER EVALUATIONS AND PARAMETRIC STUDY

In addition to the investigation of construction elements on a macro level, single components were also evaluated on a micro level, for example, the behaviour and load factor of the dowels. As part of this, the optimization of the arrangement of these components was conducted. Effects of inclined dowels, which are about to transfer tension forces, were considered.
The results of these experimental tests and more detailed information are published by Brieden et al. [4]. Against this background, the slip moduli of the different configurations of fasteners was selected for the further investigations.
Investigations into modified set-ups were conducted; in particular, the impact of multisegmented web beams was evaluated. Other types of constructions will be considered to grasp effects such as the warping of the upper layer,.
The approach described previously was transferred to the general set-up. Thus, the opportunity to evaluate different combinations and variations of segmented sections with elastic composite is enabled. The influence of missing web segments at different locations will be determined to outline different effects – such as the rearrangement of the load transfer from web to covering layer – within this step.

4 DESIGN OF TEST SPECIMENS

4.1 GENERAL

Three major layouts are considered to assess the influence of the different configurations.
The arrangement of the fasteners – total number, properties, inclination, distance, *inter alia* – are constant for all layouts. The loads applied are also constant.

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4.2 DESIGN PARAMETERS

4.2.1 Geometry and elements

Each layout consists of two OSB panels and five C24 beams; the dimensions can be found in Table 3. The beams are arranged in five axes, all identical.

Table 3: *Dimensions of components*

		dimension [mm]		
		length L_x	width L_y	height L_z
Upper panel	*OSB*	4,600	1,250	25
Beams [x)]	*C24*	4,600	60	200
Lower panel	*OSB*	4,600	1,250	25

[x)] L_x for refence variation; otherwise segmented

As described in the previous sections, wood dowels are used to realise the connection between the different elements. The wood dowels have a length of ℓ_{td} = 10.0 cm and a diameter of d_{td} = 1.0 cm.

Table 4: *Slip moduli of fasteners*

	slip modulus K [kN/cm]	
	compression	shear
Perpendicular dowel (1 dowel)	1.25	9.00
Inclined dowel (2 dowels)	5.00	12.50

The slip moduli of the wood dowels depend upon the arrangement (perpendicular or inclined) and the particular direction (tension or shear), see Table 4.

Table 5: *Distance between fasteners*

		distance e [mm]	
		Axes I / III / V	Axes II / IV
Frist segment	X	50	50
	O	3×100|2×150|3×100	4×125
	X	125	125
	total	9 fasteners	5 fasteners
Second segment	X	125	125
	O	4×125	4×125
	X	125	125
	total	5 fasteners	5 fasteners
Third segment	X	125	125
	O	4×125	4×125|3×100|4×125
	X	125	125
	total	5 fasteners	12 fasteners
Fourth segment	X	125	125
	O	4×125	4×125
	X	125	125
	total	5 fasteners	5 fasteners
Fifth segment	X	125	125
	O	3×100|2×150|3×100	4×125
	X	50	50
	total	9 fasteners	5 fasteners

The total number of fasteners for each variation is 326, of which 100 are inclined. The position of the inclined fasteners results from the specimen's layout; they are located at the beginning and end of each single segmented beam and inclined by α = 15°. The detailed distribution can be found in Figure 4 and Table 5.

The distances between the particular dowels varies between e = 5.0 and 12.5 cm and can be found in Table 5. The inclined fasteners here are labelled "X", while the perpendicular ones are named "O". Moreover, the number of fasteners for the particular segment is listed.

More information concerning the wood dowels can be found in Brieden et al. [4].

4.2.2 Loads and load cases

A total of g_k = 1.0 kN/m² is considered for the self-weight of the elements. Furthermore, an additional self-weight, for example, floor construction because of vibrations, thermal or acoustic aspects, of Δg_k = 2.0 kN/m² is taken into account. Regarding the live load, p_k = 2.0 kN/m² is considered.

Two load cases are evaluated. A total load of $q_d^{ULS} = 1.35 \cdot (1.0 + 2.0) + 1.50 \cdot 2.0 = 7.0$ kN/m² is applied for the evaluation of the ultimate limit state, whereas the total load in the serviceable limit state is $q_d^{SLS} = 1.0 \cdot (1.0 + 2.0) + 1.0 \cdot 2.0 = 5.0$ kN/m².

Table 6: *Loads and load cases*

		load [kN/m²]	
		USL	SLS
Self-weight	g	1.35	1.00
Add. self-load	Δg	2.70	2.00
Live load	p	3.00	2.00
Total	q_d	7.00	5.00

Table 6 summarises the loads and load cases.

4.3 REFERENCE ELEMENT

A construction with two OSB panels and five C24 beams is considered for the reference element. An overview of this variation is presented in Figure 4.

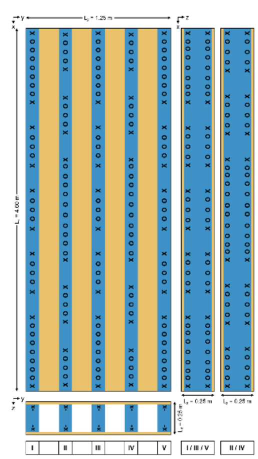

Figure 4: *Reference specimen*

The inclined fasteners in the figures are illustrated as "X" while the perpendicular ones are marked as "O".

The length of the beams is identical for all five axes – L_x = 4.60 m.

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4.4 GAP SEGMENTED ELEMENT

The gap segmented element consists of two OSB panels and five segmented C24 beams. An overview of this variation is presented in Figure 5. A pair of inclined fasteners are applied ("X") at the beginning and end of each particular beam. The other (inner) fasteners are arranged perpendicular to the board surface ("O"). The gap between the single segments has a width of 5 cm.

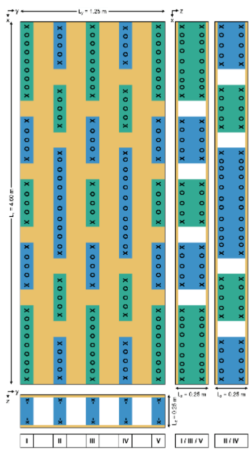

Figure 5: *Gap segmented specimen*

4.5 NOTCHED SEGMENTED ELEMENT

Furthermore, an element with two OSB panels and five notched segmented C24 beams is considered. An overview of this variation is shown in Figure 6. It is already known that a pair of inclined fasteners are applied ("X") at the beginning and end of each particular beam. The other (inner) fasteners are arranged perpendicular to the board surface ("O").

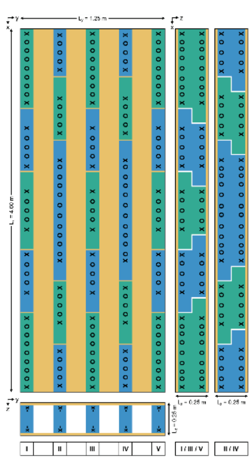

Figure 6: *Notched segmented specimen*

The gap between the single segments has a width of 5 cm, while the length of the notch is 10 cm.

5 NUMERICAL MODELLING

5.1 GENERAL

A numerical model of each variation was created for the investigations. The software RFEM 6 was used [6].
The OSB panels and the C24 beams were modelled as four node shell elements, whereas beam elements were used for the fasteners. An element size of 5.0 cm was chosen for the quadratic elements.

5.2 MODELS

5.2.1 Reference

Figure 7 shows the numerical model of the reference element without the upper panel for a clearer illustration. The support can be seen in addition to the five beams and the lower panel. The support was modelled with steel plates and should help to reduce local stress peaks.

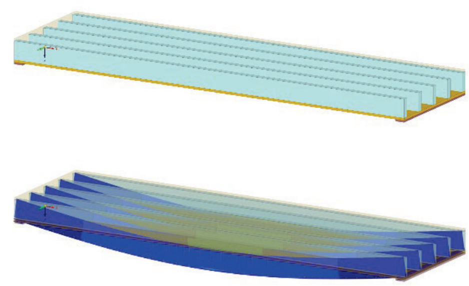

Figure 7: *Reference – model and deformations*

The second part of the figure shows the deformed model for the serviceable limit state (SLS).

5.2.2 Gap segmented

The model of the gap segmented variation is shown in Figure 8 in the same way as described previously. Here, the gaps within the five beams can be seen very well.

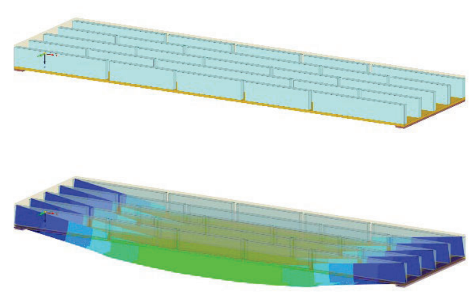

Figure 8: *Gap segmented – model and deformations*

The deformation can also be found in the figure. The relative deformation between the lower panel and the beams can also be seen for the outer edges. As the colours indicate, the deformation is higher for this variation.

5.2.3 Notched segmented

Finally, the numerical model for the notched segmented variation can be found in Figure 9. The notches are also depicted.

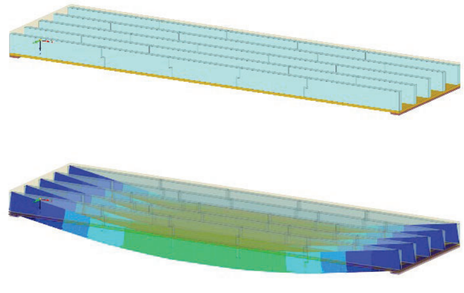

Figure 9 *Notched segmented – model and deformations*

An illustration of the deformed element for the SLS is shown in the second part of the figure.

5.3 RESULTS

5.3.1 General

As mentioned in section 4.2.2, two cases are considered. For the first one – the ultimate limit state – the stresses occurring (bending stress, shear stress and connection force) for the different components of each element are determined and compared. Exemplary, the bending stress in midspan and the connection force are presented in the following. In order to investigate the SLS performance, the deformations of the panels are considered and discussed later on.

5.3.2 Ultimate limit state

Cross-section

The distribution of axial stresses at midspan (L_x = 2.30 m) is illustrated in Figure 10 to Figure 12. The diagrams show the stress as a function of the element height L_z. The different colours of the lines represent the particular axes as labelled in Figure 4 to Figure 6; the axes indicate the position in the y-direction (Axis I: L_y = - 0.625 m to Axis V: L_y = + 0.625 m).

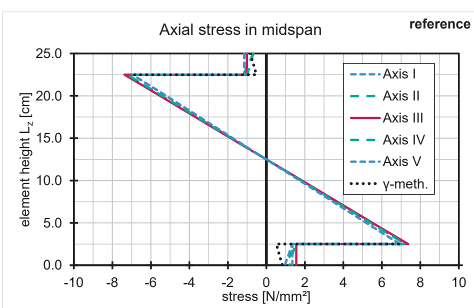

Figure 10: *Ultimate limit state (ULS) – reference – bending stress in midspan*

The different parts of the cross-section, i.e. upper panel, beam, lower panel, can be identified by their dimensions and orientations. The lower panel is located at the bottom of the diagrams (L_z = 0.0 … 2.5 cm); the upper panel can be found at the top of the diagrams (L_z = 22.5 … 25.0 cm); the results for the beams can be seen in between (L_z = 2.5 … 22.5 cm).

In addition, the corresponding bending stresses, which have been determined analytically with "Gamma Method" according to EC 5 [3], are shown for the reference model in Figure 10.

As the diagram illustrates, the stress at the different axes for the reference model only differ very slightly. The maximal stress comes up to $\sigma_{max}^{panel} \approx 1.3$ N/mm² for the panels, and $\sigma_{max}^{beam} \approx 7.4$ N/mm² at the joints (L_z = 2.5 and 22.5 cm) between the panels and the beams for the beams.

Concerning the comparison with the analytical results, some deviations can be found. Regarding the panels, for example, the values do not fit completely. These differences might be caused by the assumptions and simplification that are necessary for the analytical calculation – for example, a homogeneous fastener distance of e = 12.5 cm has been assumed for the "Gamma Method" in contrast to the distances applied for the numerical investigation (see Table 5).

Nonetheless, the agreement between the analytical and the numerical results is obviously good.

Figure 11 shows the stresses occurring for the gap segmented variation. Compared to the reference variation, the stresses in midspan for the beams are significantly lower, while it is vice versa for the panels. This is because of the different load transmission caused by the segmentations of the beams. Considering the illustration in Figure 5, it can be seen that the beam segments in axis I, III and V in midspan are shorter than the ones in axis II and IV. This leads to a higher stress in the latter beam segments, see the green lines in Figure 11. Due to the segmentation of the beams, a load shifting from the beams to the panels occurs.

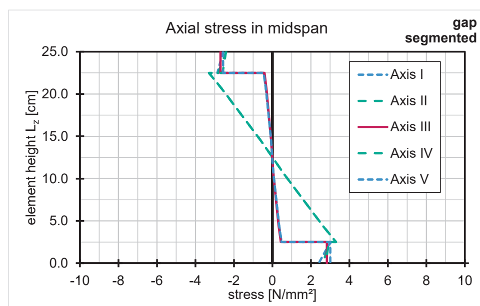

Figure 11: *ULS – gap segmented – bending stress in midspan*

The values of the maximal stress come up to $\sigma_{max}^{panel} \approx 3.0$ N/mm² for the panels, and $\sigma_{max}^{beam} \approx 3.5$ N/mm² at the joints (L_z = 2.5 and 22.5 cm) between the panels and the beams for the beams.

Figure 12 illustrates the axial stresses in midspan for variation notched segmented sections. Again, the load shifting effects can be seen. In comparison with the gap segmented variation, the stress in the panels reduces, whereas for the beams, it increases. Concerning these results, the influence of the notched segmented sections can be seen. The notching of the beams creates a different load transmission.

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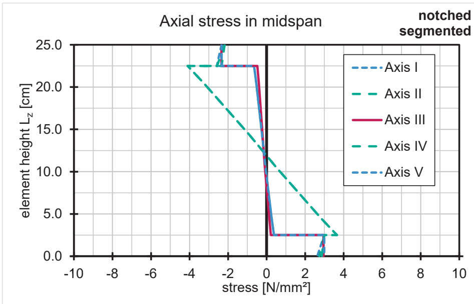


***Figure 12:** ULS – notched segmented – bending stress in midspan*

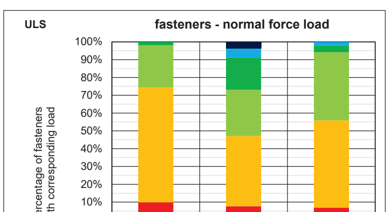
The values of the maximal stress come up to $\sigma_{max}^{panel} \approx 2.5$ N/mm² for the panels, and $\sigma_{max}^{beam} \approx 4.1$ N/mm² at the joints (L_z = 2.5 and 22.5 cm) between the panels and the beams for the beams.

Fasteners

In order to evaluate the performance of the fasteners, in spite of considering each single dowel, the total number and the corresponding load was investigated.

These results can be found in Figure 13, which shows the load – here, the normal force – of the fasteners grouped for each variation.

Concerning the results, a distinction between fasteners with tensile force and those with compression force is necessary. As the diagram shows, the maximal tensile force is lower than F_t = 0.7 kN, while the compression force goes down to F_c = - 3.0 kN. This means that the relation of the maximal tensile to the maximal compression load is about one to four.



	reference	gap segmented	notched segmented
0.7 kN … 0.5 kN	0%	4%	0%
0.5 kN … 0.3 kN	0%	5%	2%
0.3 kN … 0.1 kN	2%	19%	4%
0.1 kN … 0.0 kN	24%	27%	39%
0.0 kN … -1.0 kN	66%	41%	50%
-1.0 kN … -2.0 kN	10%	6%	7%
-2.0 kN … -3.0 kN	0%	2%	0%

***Figure 13:** ULS – fasteners – normal force*

About a quarter of the fasteners are tensile loaded for the reference variation. Although only 45 % and 55 % of the gap and the notched segmented variation, respectively, are under compression, the majority of the tensile loaded fasteners – 46 % and 43 %, respectively – are loaded with less than F_t = 0.3 kN.

The main part of the fasteners for all three variations was loaded with F_c = 0.0 … - 1.0 kN.

5.3.3 Serviceability limit state

Panels

The results of the investigation of the SLS – here, the total deformation of the panels – are presented as surfaces in Figure 14 to Figure 16.

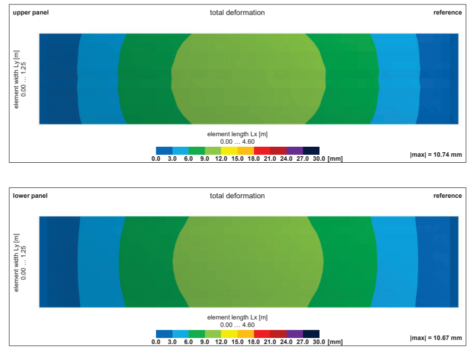


***Figure 14:** SLS – reference – panels – total bending deformation*

The diagrams show the deformation of the upper and the lower panel as well as the maximal value. As expected, the difference between both panels is not significant.

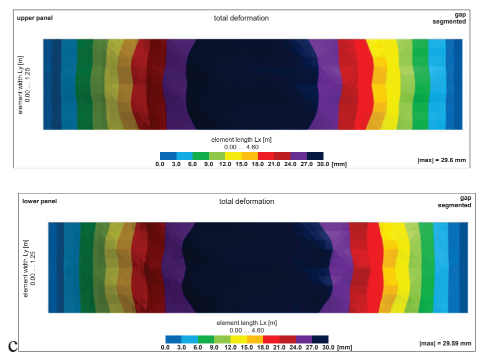


***Figure 15:** SLS – gap segmented – panels – total bending deformation*

As the diagrams indicate, the deformation is maximal for the gap segmented element. The relation between the maximal deformation of the variations is 1.0 to 3.0 to 2.5.

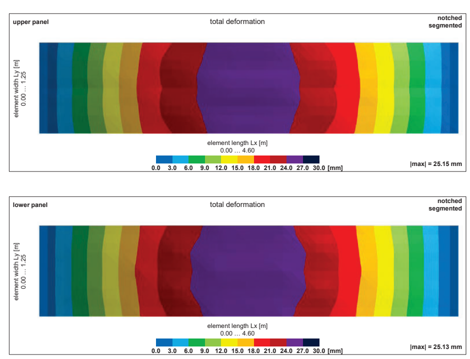


***Figure 16:** SLS – notched segmented – panels – total bending deformation*

6 EXPERIMENTAL INVESTIGATIONS

The results of the numerical investigations indicate that this is a promising approach and experimental testing of macro-scaled specimens is actually conducted and evaluated. These tests and the detailed analysis of the measured and documented results are currently being done at the University of Kassel.

7 CONCLUSIONS AND OUTLOOK

Promising results have been achieved to date. Analytical and numerical approaches for different types of segmented beams were used and compared with good compliance. Further investigations were conducted against this background.

The methodology, development and selected results as well as additional information concerning the further investigations are presented within this paper.

The current results and findings in combination with experimental testing on a micro and macro scale will enable new and further application areas for segmented composite sections.

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