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Investigations on the Load-bearing Behaviour of Slotted Steel Sections as Substructures in Multi-Shell Facades

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ABSTRACT

Multi-shell constructions in the building envelope offer many advantages in terms of sustainability. Thin-walled steel sections used as one-part substructures for metal facades form a linear thermal bridge. The insertion of slots in the webs of these sections allows for an more energy-efficient design by reducing the thermal bridge effect. Prolonging the heat flow through the slotted web decreases the thermal transmittance of the component. However, the insertion of slots weakens the cross section and reduces the load-bearing capacities. Therefore, a slotted section optimized in terms of structural and thermal aspects has to be developed.
The structural behaviour of slotted steel sections was investigated using numerical simulations of FE-based models. Several loading scenarios were considered representing various construction and installation methods. Different boundary conditions as well as potential simplifications were applied in order to determine a realistic model of the substructure. Thereafter, a parametric study was conducted to evaluate the influence of different geometric parameters on the load-bearing behaviour of slotted steel sections. The reduction in load-bearing capacity introduced by the insertion of slots was quantified with respect to unslotted reference sections.
The preliminary results indicate that depending on the loading conditions a significant decrease of the structural resistance can be observed. However, different parameters exhibit a varying impact on the load-bearing behaviour. Thus, the variation of parameters allows to adjust the structural and thermal performance of slotted steel sections in order to meet the individual requirements of a certain project, resulting in a broad field of potential application scenarios.

Keywords: slotted steel sections, multi-shell facades, lightweight metal constructions

1 INTRODUCTION

Metal facades are a frequently used construction method as part of the building envelope, particularly for industrial buildings. These can be designed as multi-shell constructions with a skeleton structure and an inner shell of liner trays or trapezoidal steel sheeting or with a solid wall as the primary load-bearing system. Thin-walled steel sections are used as substructures in these constructions to create space for thermal insulation. They transfer parallel and vertical loads acting on the building envelope into the primary structure. Thus, they penetrate the layer of thermal insulation and form a thermal bridge. To minimise the thermal bridge effects, slots can be inserted in the web of the steel section to prolong the heat flow through the component and thereby reduce the thermal losses (1). Numerical simulations of the thermal behaviour of slotted spacer sections have shown that a reduction of the heat transfer coefficient of up to 65% is possible (2).
Different kind of forces act on the metal facade due to the effect of wind loads and dead weight of the outer cladding. In order to transfer these loads to the primary structure, a sufficient load-bearing capacity must be ensured. Lightweight steel sections, such as Z-sections, which are often used for this purpose, usually have sufficient load-bearing capacity to withstand the resulting forces. However,

inserting the slots weakens the cross-section and a sufficient resistance must be verified to ensure safe application. Numerical simulations of FE-based models were carried out in order to investigate the structural behaviour of these slotted steel sections.

2 STATIC REQUIREMENTS

Transferring the loads acting on the facade is an essential function of the spacer construction. The acting loads depend on the location and the dimensions of the building as well as the installation situation. Therefore, a distinction is made between forces acting in the direction of the web or transverse to it. In case of a wall construction with Z-sections as a horizontally or vertically installed spacer construction, as shown in Fig. 1, wind pressure and wind suction result in forces in direction of the web, which cause compressive or tensile stresses respectively in the cross-section. The dead load of the building envelope results in additional bending and transverse shear for horizontally installed sections or longitudinal shear for vertically installed sections. However, these forces only occur if the components act as fixed points for the outer cladding.

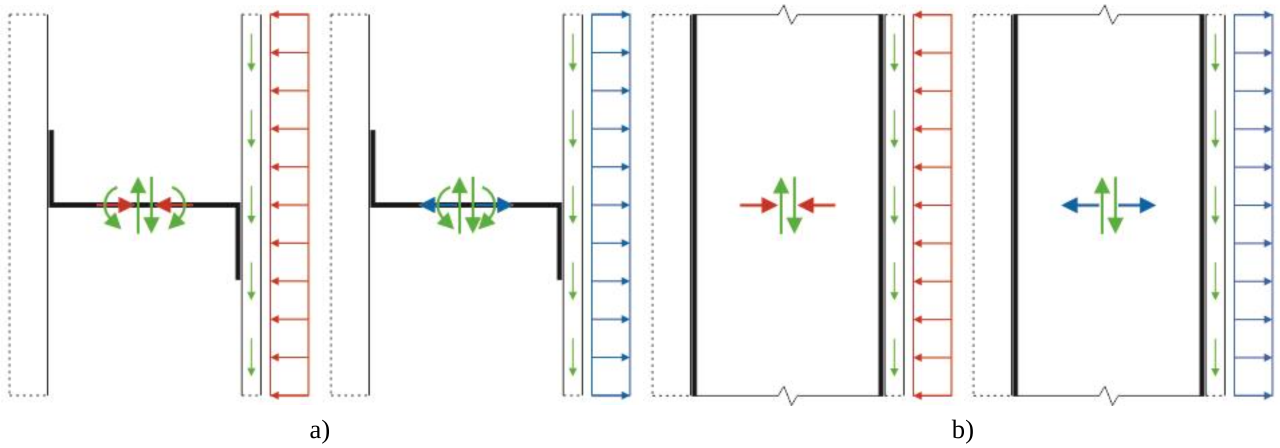


Fig. 1. Loads acting on a horizontally (a) or vertically (b) installed Z-section causing forces within or transverse to the web plane

The loading scenarios depicted in Fig. 1 result in various possible types of failure:

- *flexural buckling*
- *tension failure*
- *shear failure*
- *excessive bending*
- *failure of fasteners*

These failure cases require a limitation of the deflections and the design of the fasteners in addition to the cross-sectional design. However, this paper focusses primarily on the load-bearing behaviour of the slotted section.

3 MODELING FOR NUMERICAL SIMULATIONS

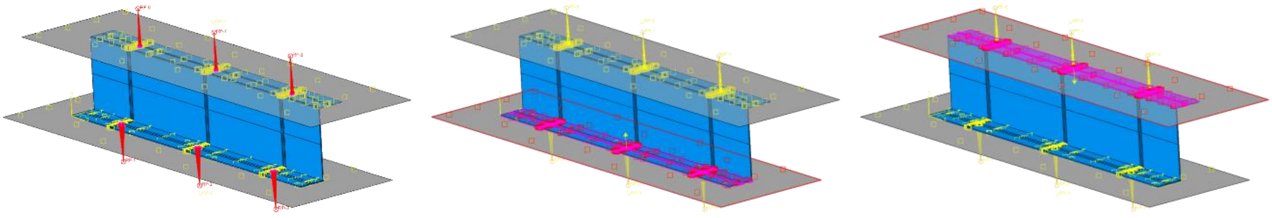
As an alternative to time-consuming and material-intensive experimental tests, numerical simulations allow for the investigation of multiple different parameters with less additional effort and therefore lower costs. For the numerical investigation of the steel sections, a parameterized model was created in SIMULIA ABAQUS to simulate the load-bearing behaviour for different section properties and loading scenarios. The three-part model consists of an inner shell, the steel section itself and an outer shell. These parts are connected to each other by various interaction conditions. By determining suitable boundary conditions, a calculation-optimized, fully parameterized and realistic model of the lightweight steel section was created. The applied conditions will be discussed below. The assembled model is shown in Fig. 2.

3.1 Inner and outer shell

The substructure, which can be profiled sheeting or a solid wall, is modelled as a rigid inner shell connected to a reference point to which the boundary conditions are applied. All degrees of freedom of the reference point are removed, thus, the inner shell can neither translate nor rotate. The outer cladding is also modelled as a rigid shell with a reference point and cannot be rotated. The displacement is either fixed or free depending on the load case.

3.2 Spacer sections

The spacer construction is defined as a Z-section and can be modelled with a slotted web or unslotted, the latter one acting as a reference. The dimensions of the section and the slot geometry are fully parameterized and can be can be defined through an input mask. The inner and outer fastening points are modelled as reference points, to which the boundary conditions are applied. The number and spacing of these points depend on the chosen component length and spacing between fasteners. The reference points are constrained to the inner or outer flange respectively. The boundary conditions of the fasteners correspond to the boundary conditions applied to the inner or outer shell. The contact between the shell and the section parts is defined by an interaction property. Thus, the lateral and rotational movement of the flanges are restrained.

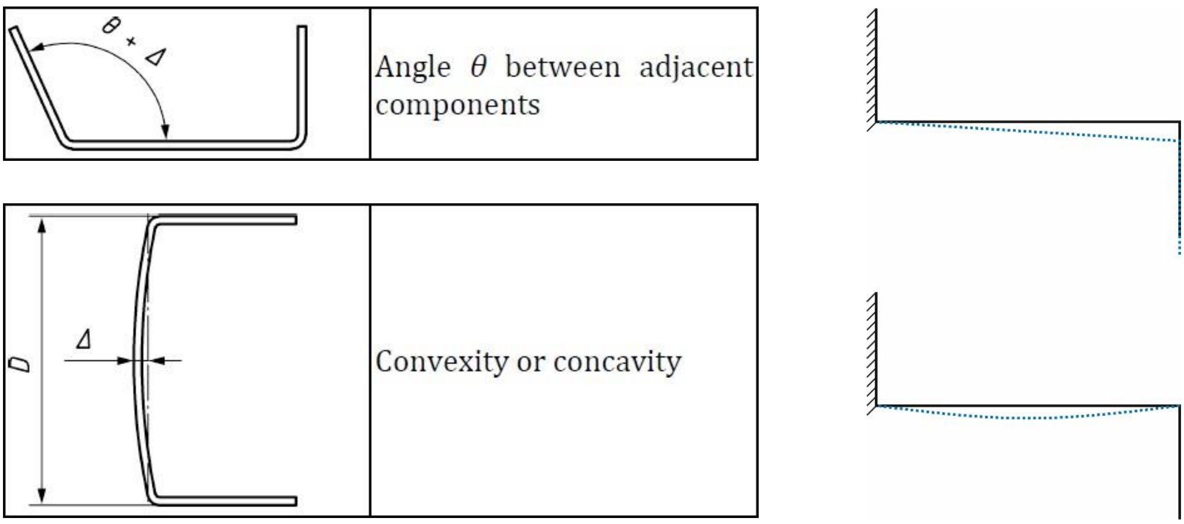


a) b)

Fig. 2. a) Boundary conditions and b) Interaction properties for the assembled model

3.3 Implementation of initial imperfections

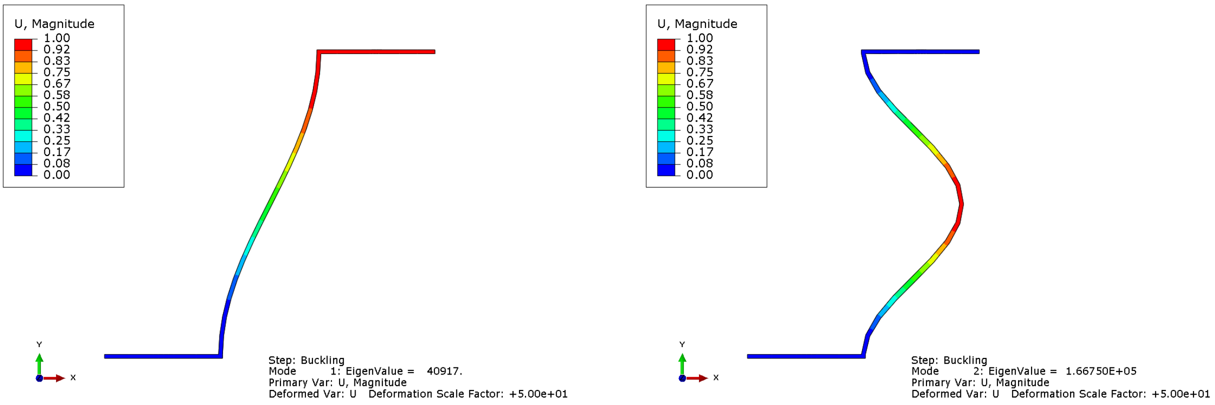
Imperfections usually occur in cold-formed sections within the production process. These initial imperfections, in particular for flexural buckling, can have a great impact on the load-bearing behaviour. Imperfections must therefore be considered in the design. Fig. 3 shows two major types of imperfections that can be derived from manufacturing tolerances according to EN 1090-4 (3).



a) b)

Fig. 3. a) Manufacturing tolerances (3) and b) Resulting imperfections

The potential imperfections are incorporated by the implementation of a preceding buckle analysis with fully constrained flanges. The desired imperfection figures result from the first two eigenmodes as seen in Fig. 4. These represent an initial sway or bow imperfection. The imperfection factor can be used to scale the extent of the imperfection. The effect of imperfections and the relevant eigenmode for each loading scenario are explained in more detail in section 4.



1. eigenmode (sway imperfection) 2. eigenmode (bow imperfection)

Fig. 4. First two eigenmodes resulting from buckle analysis with scale factor 50

3.4 Component length

Substructures are usually installed as components, that are several meters long. However, modelling the steel sections of this length leads to very long calculation times. As part of the model creation, a preliminary study was conducted to verify that a reduction of the models' lengths does not affect the length-normalised load-bearing capacities. It was concluded that for tension, compression and transverse shear loading a minimum model length of 750 mm is sufficient when applying symmetrical boundary conditions in the longitudinal direction at the lateral edges to represent the investigated section as a segment of a longer component. As the symmetrical boundary condition prevents deformation in this direction it cannot be applied for longitudinal shear loading, instead a length of 1500 mm is used for this load case.

3.5 Load application

All loads are applied displacement-controlled to the reference points representing the fasteners and are thus transferred to the flanges. The load-bearing capacity for tension or compression in the web plane is examined by applying a displacement in the y-direction, for transverse shear by a displacement in x-direction and for longitudinal shear in z-direction. The outer shell is subjected to the same displacement to ensure steady contact and thus torsional restraint of the flanges. The applied loads result from the reaction forces in the reference points that occur due to their displacement, and are then normalised to the component length to obtain the load-bearing capacities.

4 SIMULATION OF DIFFERENT LOADING SCENARIOS

According to the different installation situations shown in Fig. 1, four different loading scenarios with different boundary conditions are examined in the simulations. For each case, the relevant initial imperfection needs to be determined. Their influence is analysed by simulating a reference section with the parameters shown in Fig. 5. To obtain comparable results, the same imperfection factor was applied for both imperfection figures. Load-displacement-curves are plotted for each simulation to compare the results.

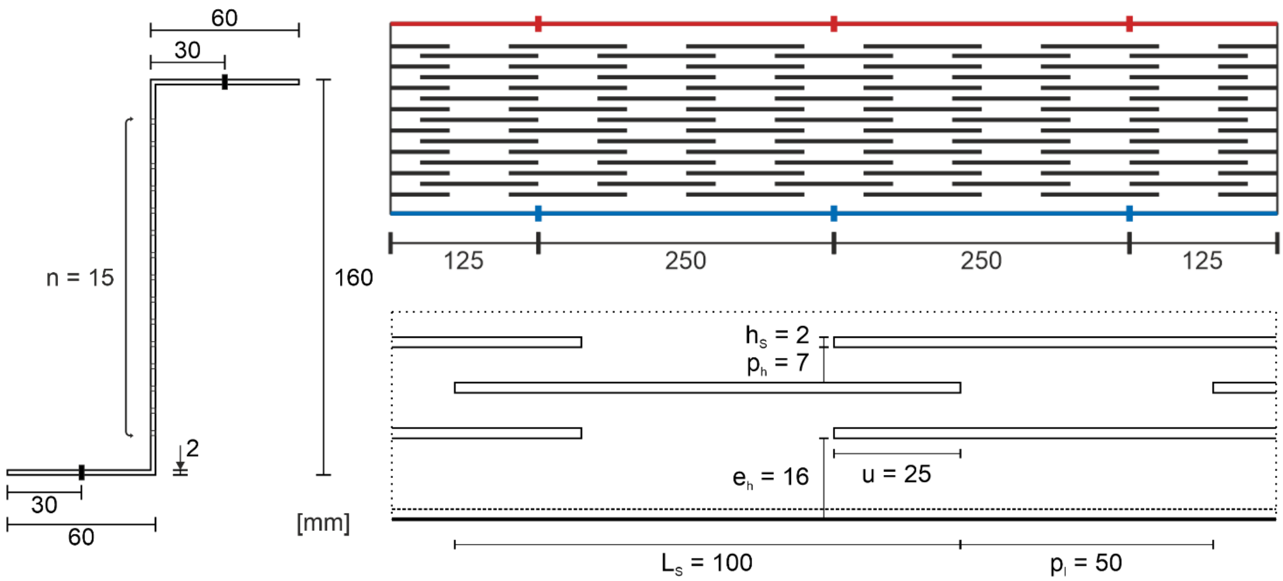


Fig. 5. Geometric parameters of the reference section [mm]

4.1 Compressive loading

In case of compressive loading, flexural buckling governs the failure of the web and thus of the whole section. The resulting deformations depend on the applied boundary conditions regarding the possibility of displacements transverse to the web in x-direction. Fig. 6 a) shows the load-displacement-curves for the two cases analysed, each of which was simulated with both eigenmodes. If no boundary condition is applied, the section can freely deform in x-direction. In this case an initial sway imperfection represented by the first eigenmode is relevant, as lower load-bearing capacities can be reached. In case of a fixed x-direction, an initial bow imperfection is relevant. It can be seen that overall lower loads can be applied if a deformation in the x-direction and thus in direction of the initial sway imperfection is possible.

4.2 Tensile loading

Similarly, two different boundary conditions are investigated for tensile loading and the relevant imperfection is obtained by the simulation of each combination. The results are shown in Fig. 6 b). It can be seen that neither the applied boundary condition concerning the possibility of deformations in x-direction nor the initial imperfections have a considerable influence on the load-bearing capacities of the sections. Up to a displacement of 5 mm the load-displacement curves show an almost linear correlation. After this point, plastic deformation occurs within the web, resulting in a non-linearity. Nevertheless, the applied forces increase steadily up to a displacement of 20 mm. Afterwards, only slight load increases with large displacements can be observed.

4.3 Transverse shear loading

The load-displacement curves for transverse shear in Fig. 6 c) (top). show that large displacements already occur at small forces. This can be explained by a small bending stiffness of the slotted web. The load-bearing behaviour is significantly influenced by the occurrence of tensile stresses and plastic deformations in the web, as deformations in the y-direction are not possible due to the structural design of the multi-shell facade. Thus, the displacement in load-direction is always accompanied by an elongation of the web. As an initial sway imperfection favours an earlier onset of this behaviour, its implementation leads to slightly higher load-bearing capacities. Thus, an initial bow imperfection is relevant for this load case.

4.4 Longitudinal shear loading

For longitudinal shear, large loads can be achieved with only small displacements applied, see Fig. 6 c) (bottom). The load-bearing behaviour is almost linear until a sudden failure occurs due to distortion of the slotted web. The applied eigenmodes have almost no influence on the load-displacement curves, the obtained maximum load is only slightly lower for an initial bow imperfection as it favours the distortion of the web.

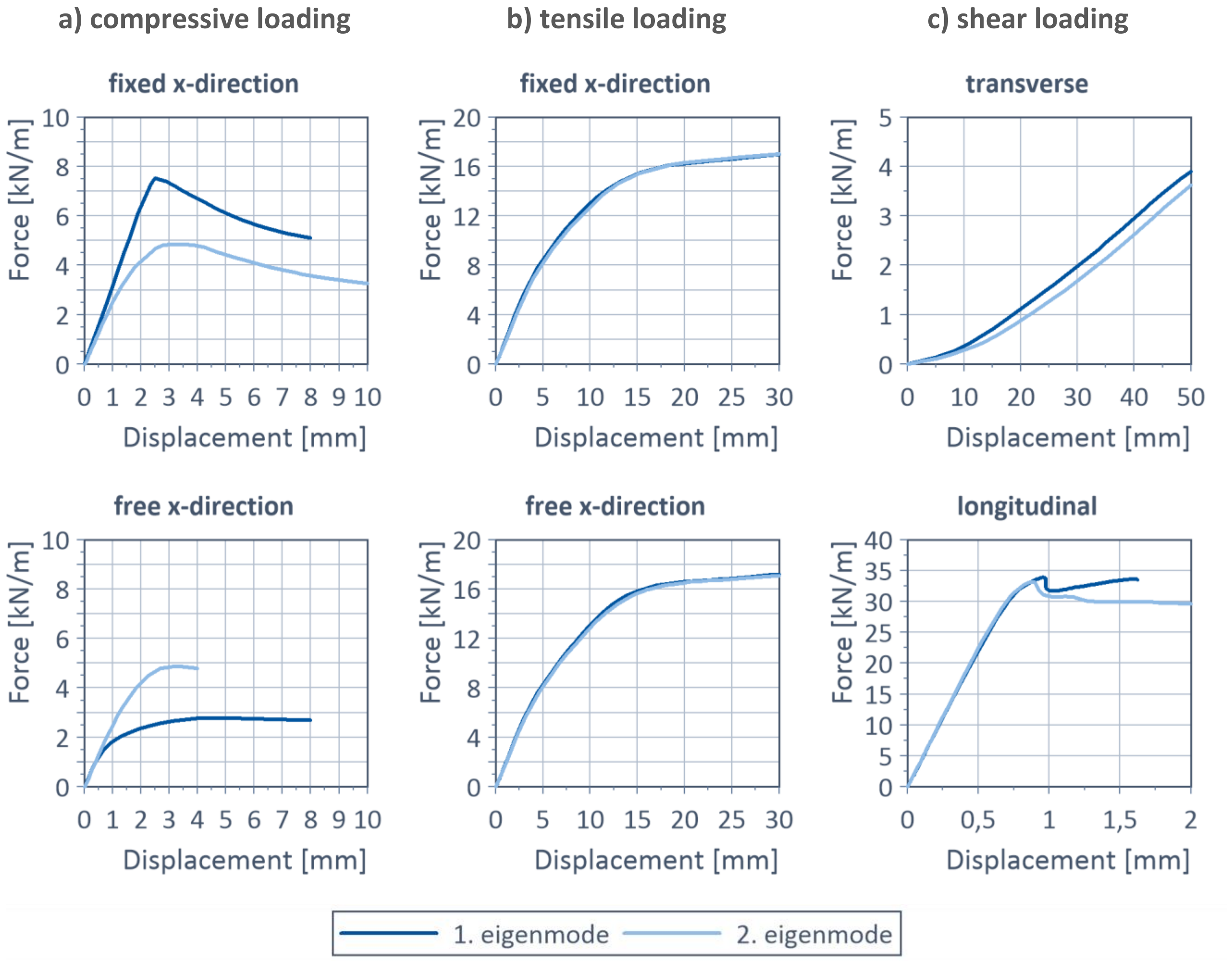


Fig. 6. Load-displacment curves for different initial imperfections applied

5 PARAMETRIC STUDY

Within the parametric study the geometric parameters of the steel section were modified and the impact of each variation was compared to the reference section introduced in the previous section. The same boundary conditions and the relevant imperfection determined for each load case were applied.

5.1 Imperfection factor

The magnitude of initial imperfections can be determined according to geometrical tolerances given in EN 1090-4 (3) and is dependent on the profile height. To investigate its influence different imperfection factors between 0,0 and 3,2 were applied within the simulation of the load-bearing behaviour. In addition, the simulation was carried out without imperfections for each load case to determine whether the load-bearing behaviour is affected at all. It was shown that there is only a dependency on imperfections in case of compressive loading, as these have a significant effect on the buckling behaviour and thus the resulting failure loads. Fig. 7 shows the results for this load case and both boundary conditions. The influence of initial imperfections is clearly visible in both diagrams, whereby their magnitude effects the load-bearing behaviour in case of a fixed x-direction to a greater extent.

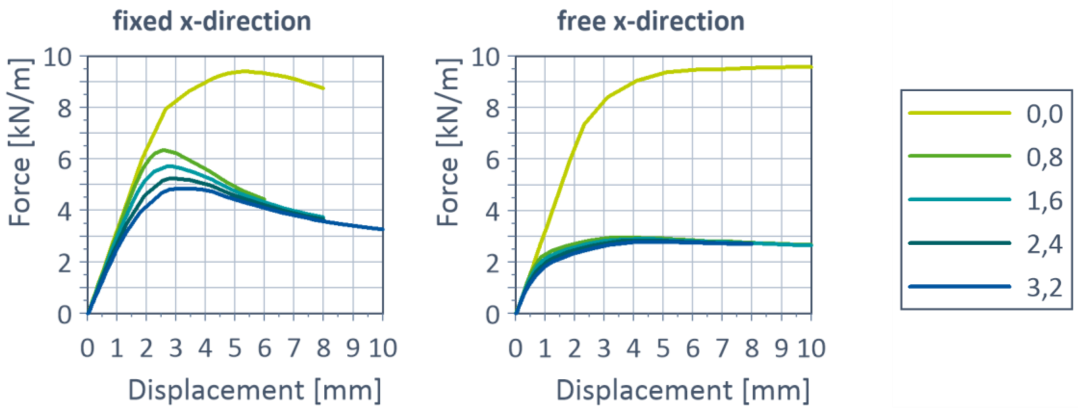


Fig. 7. Influence of initial imperfections for compressive loading

5.2 Profile height

The variation of profile height comes along with the variation of the magnitude of initial imperfections, as these are directly correlated. Three different profile heights were investigated: 100, 160 and 240 mm, whereas a profile height of 160 mm corresponds to the reference section. The number of slot rows n, with constant geometric parameters as shown in Fig. 5, was scaled with the profile height. The resulting load-displacement curves are shown in Fig. 8. It can be seen that the load-bearing behaviour for tensile loading is only slightly affected, whereas compressive and shear loading is considerably reduced with increasing profile height.

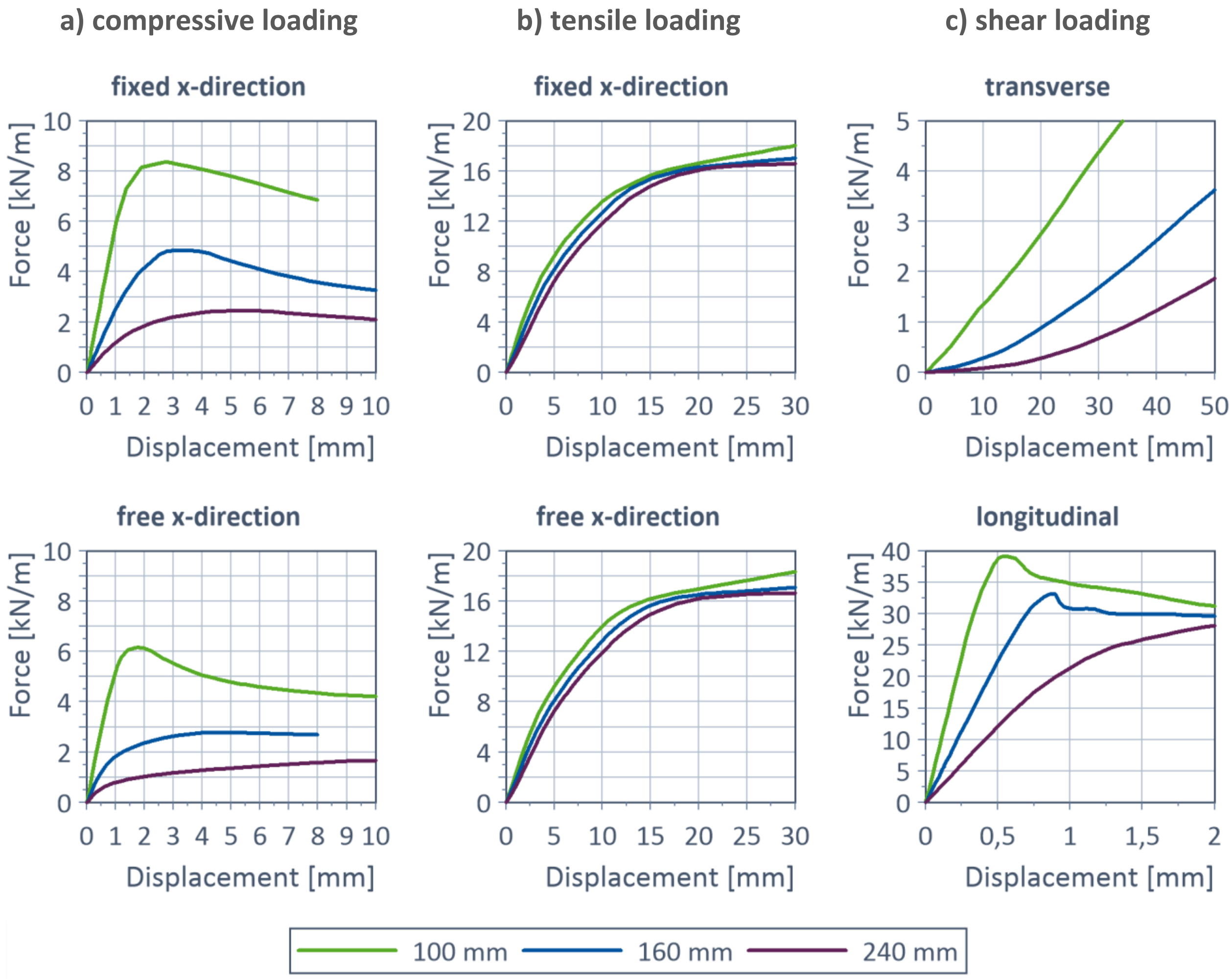


Fig. 8. Influence of profile height on the load-bearing behaviour

5.3 Material thickness

The load-displacement curves in Fig. 9 show the influence of the material thickness of the steel section. The thickness was varied in five steps from 1,0 to 3,0 mm. The load-bearing behaviour is clearly affected for all load cases. As the critical cross-section area in the web is reduced, the tensile, buckling, bending and shear resistance are all decreased to almost the same extent. For longitudinal shear, early failure occurred for a material thickness of 1,0 mm due to distortion of the web plane.

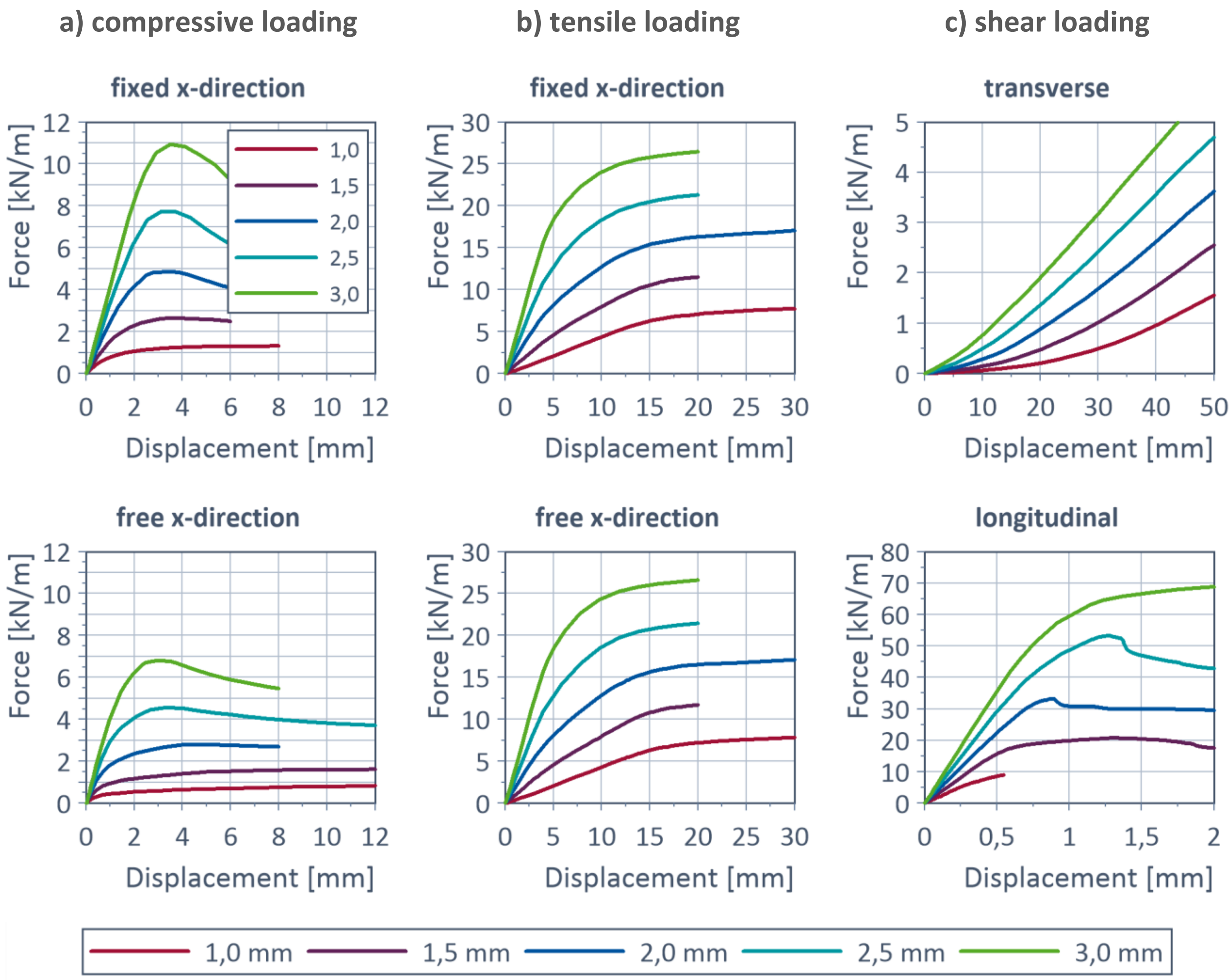


Fig. 9. Influence of material thickness on the load-bearing behaviour

6 REDUCTION FACTORS FOR THE LOAD-BEARING CAPACITIES

In order to determine reduction factors for the load-bearing capacities of slotted steel sections compared to their unslotted versions, all simulations were also carried out for the latter to determine their load-bearing capacities. In case of compressive loading the capacities are obtained from the maximum load, representing a flexural buckling failure. For tensile loading the load-displacement curves show an almost linear correlation up to a displacement of 5 mm, afterwards plastic deformations occur in the slotted web or at the edges between web and flange for unslotted sections. Thus, the load-bearing capacity is defined at a displacement of 5 mm. For transversal shear it is also determined based on the applied displacement, as plastic deformations again occur in the web or in the edges respectively. These emerge at a displacement in load direction of 20 mm, so that the load-bearing capacity is defined at this point. In case of longitudinal shear loading a maximum load can be obtained from the load-displacement curves for slotted sections. However, no such maximum occurs for unslotted sections, therefore, the load-bearing capacity is determined using the linear part of the resulting curve. The resulting load-bearing capacities for the reference section are shown in

Table 1. Finally, the reduction factors represent the ratio of the achieved capacities for slotted and unslotted sections. The range of reduction factors obtained by the variation of parameters within the parametric study is also given in the table. It can be seen, that especially the resistance against buckling under compressive loading is highly affected by the insertion of slots in the web of the steel section. The remaining load-bearing capacities are approx. 5 %. For tensile loading the effect is noticeably smaller with an average reduction factor of 63 %.

Table 1. Load-bearing capacities and resulting reduction factors

Load case		Reference section			Parametric study
		Load-bearing capacity [kN/m]		Reduction factor	
		unslotted	slotted		
compressive loading	fixed	87,67	4,85	0,06	0,05 – 0,09
	free	53,84	2,79	0,05	0,05 – 0,16
tensile loading	fixed	12,61	8,21	0,65	0,60 – 0,66
	free	11,08	8,13	0,73	0,65 – 0,75
transversal shear loading		5,29	0,89	0,17	0,12 – 0,22
longitudinal shear loading		63,13	33,11	0,52	0,29 – 0,71

7 CONCLUSION AND PROSPECT

The presented numerical simulations were carried out on a three-part-model representing a multi-shell facade with a spacer section within the layer of thermal insulation. Different load cases and boundary conditions were applied to simulate multiple installation scenarios. Due to possible manufacturing tolerances, initial imperfections were considered in the investigations. It was shown that these affect the load-bearing behaviour, especially under compressive loading, as this load case is governed by buckling failure. The influence of geometric parameters of the section was investigated by varying the section height and material thickness. These affect the load-bearing capacity to varying extent. To evaluate the load-bearing capacities obtained from the parametric study, the corresponding unslotted version of each simulation was also analysed and the load-bearing capacities compared. It becomes apparent that, depending on the section geometry, a reduction of between 5 and 75 % can be expected. Particularly under compressive loading, the insertion of slots in the web has a great effect.

To validate the FE-model, experimental tests will be conducted and the resulting load-bearing capacities and deformations will be compared with the numerical simulations. Using the validated model, a comprehensive study will be carried out to optimize the section and slot geometry in terms of structural and thermal requirements.

8 ACKNOWLEDGEMENT

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