ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
UDC/UDK 624.073.5:620.172.2]:519.61

FINITE ELEMENT ANALYSIS OF SANDWICH PANELS WITH LONGITUDINAL JOINTS AND LARGE OPENINGS

Metod Čuk, Silvo Štih, Boris Jerman

Original scientific paper

Lightweight structural sandwich panels made of two thin steel facings, which are bonded to a relatively thick and light insulating mineral wool core, are often used for wall claddings. The sandwich panel clad structures are frequently weakened by cut-outs and openings for doors, windows, and in other cases. If the resistance of remaining cross-section of a weakened panel is not sufficient an additional load-bearing support of adjacent panels through the longitudinal joints must be activated. The paper concerns effects of large openings on load-bearing capacity and structural stiffness of sandwich panel claddings. Since it is not possible to give generally acceptable rules to evaluate their complex structural behaviour at the present time this research project was conducted using finite element models to study the local and global behaviour for a certain sandwich panel product and a certain design examples. Firstly, a finite element model of double interlocking tongue and groove joint between neighbouring panels was built to study behaviour of the panel-to-panel connection. Secondly, finite element models of two typical design examples of sandwich panel claddings with large opening and load transfer from weakened sandwich panel through the longitudinal joints to the adjacent panels were built and analysed numerically. And thirdly, the laboratory experiment of two studied design examples was also conducted. The results obtained from the experiment were reasonably agreeable to support the finite element analyses results.

Keywords: *buildings, finite element method, load-bearing capacity, longitudinal joints, mineral wool, panel interconnection, structural analysis, structural sandwich wall panels, testing, window openings*

Metoda konačnih elemenata u analizi sendvič-panela s uzdužnim spojevima i velikim otvorima

Izvorni znanstveni članak

Lagani konstrukcijski sendvič-paneli izrađeni od dvije tanke čelične obloge, spojene s relativno debelom i laganom jezgrom od izolacijske mineralne vune, često se koriste za zidne obloge. Konstrukcije obložene sendvič-panelom često su oslabljene isklopnicima i otvorima za vrata, prozore, te u drugim slučajevima. Ako otpornost preostalog presjeka oslabljenog panela nije dovoljna, mora biti aktivirana dodatna nosiva potpora susjednih panela preko uzdužnih spojeva. Članak se bavi utjecajima velikih otvora na nosivost i krutost konstrukcije sendvič-panel obloga. Budući da nije moguće dati općenito prihvatljiva pravila za sadašnju procjenu njihovog složenog strukturnog ponašanja, ovaj je istraživački projekt proveden pomoću modela metode konačnih elemenata za proučavanje lokalnog i globalnog ponašanja za određeni proizvod od sendvič-panela i određene primjere dizajna. Prvo, napravljen je model konačnih elemenata dvostrukog sigurnosnog spoja na pero i žlijeb između susjednih ploča kako bi se pratilo ponašanje spoja dviju ploča. Drugo, izrađeni su i brojčano analizirani modeli konačnih elemenata dvaju primjera tipičnog dizajna sendvič-panel obloge s velikim otvorom i prijenosom opterećenja s oslabljenog sendvič panela kroz uzdužne spojeve na susjedne ploče. I treće, proveden je laboratorijski eksperiment dvaju proučavanih primjera dizajna. Rezultati dobiveni pokusom prilično su dobro podržavali rezultate dobivene analizom konačnih elemenata.

Ključne riječi: *konstrukcijski zidni sendvič-paneli, međupovezivanje panela, metoda konačnih elemenata, mineralna vuna, nosivost, prozorski otvori, strukturna analiza, testiranje, uzdužni spojevi, zgrade*

1 Introduction

Structural sandwich panels consist of three main structural components: two flat or lightly profiled thin faces are bonded to relatively thick light core. The strong and stiff thin steel faces provide flexural load bearing capacity and rigidity of the panel. The low density and flexible thick core made of mineral wool with adequate shear strength and stiffness transfers shear loads between the two faces while also providing thermal insulation. The result is a composite structural element with relatively high load-bearing capacity and bending stiffness, thermal and sound insulating capacity, and environmental (rain, snow and wind) and fire resistance [1].

Structural sandwich panels used for wall claddings need to have construction cut-outs and openings for doors, windows, HVAC (heating, ventilation and air conditioning) ducts and pipes and other penetrations. The openings may vary in shape and size, per location and by span direction (horizontal, vertical) [2]. Any opening in a structural sandwich panel represents weakening by decreasing the effective area of faces and core that reduces bending, shear and tensional rigidity and resistance of panel cladding [1].

The existing European standard EN 14509 does not provide design and testing procedures for sandwich panels with openings [3]. The "official" technical solution for the openings within sandwich panels is to use a "replacement" in the form of an additional supporting structure. Such reinforcement has to replace the load-bearing capacity which has been removed from the self-supporting sandwich panels by the openings, and transfer applied loads to the spaced frame. But there is also a common practice to use the structural sandwich panels with openings and cut-outs without any additional support. These design solutions are based on design methods provided by some of the sandwich panel manufacturers [2].

The first design rules for sandwich panel walls with window openings were proposed by Höglund [4]. He suggested that properly designed unstrengthen panels with window openings may be used. The design formulae to evaluate the transfer of the load from a panel with openings to the adjacent panels were based on the compatibility of deflections at the midspan of the longitudinal joints of simply supported sandwich panels due to bending moments, shear forces and torsional moments caused by uniformly distributed pressure load and the temperature difference between the inside and outside of the sandwich elements.

Toma and Courage [5] proposed a design procedure for sandwich panels with openings without additional stiffeners based on design rules for sandwich panels without openings by introducing experimentally determined correction factors to calculate strength capacity. Further correction factors based on numerical study taking into account the stress concentrations in the core and the faces around the opening were also introduced.

Berner and Pfaff [2] suggested common solutions and introduced a supporting reinforcement within the range of openings with particularly conceived framework. Firstly, the sufficient load-bearing capacity of the panels with small openings can be achieved by the resistance of the remaining cross-section. Secondly, because of smaller flexural rigidity, the panel with an opening (without reinforcing) supports itself onto the adjacent panels. In this case, two substantial conditions must be present: adjacent panels that are additionally stressed must not have any openings and the transmission of loads into the adjacent panels must be ensured through the longitudinal joints. The activation of load-bearing support of adjacent panels can only be achieved to the extent permitted by shear force capacity of the longitudinal joints. Thirdly, a supporting frame made of special thermally separated aluminium profiles was introduced for reinforcement of the openings. In this case a useful allowable spans may be achieved (even with large openings up to entire panel width) similar to that of not weakened panels without participation of adjacent panels and therefore without an additional stress of the longitudinal joints between the panels. It was suggested, however, that for a final practical application further investigations are necessary.

Böttcher and Lange [6] presented a calculation model of wall sandwich panels with openings, which considers the load transfer over the longitudinal joints into neighbouring elements. The global load model of interconnection system i.e. a system of multiple sandwich panels where the panels are inter-supported (in transverse direction) at adjacent edges, is based on a three-dimensional beam theory model. Beam finite elements were used to model the stiffness of panels in transverse and longitudinal direction and the joint stiffness of the longitudinal joint. Presented model provides loads and displacements, while a further local finite element model of single face was used to determine stress distribution in steel sheet near the opening. Experimental investigations were conducted to determine joint stiffness of longitudinal joint of different panel types with polyurethane foam core.

Warmuth and Lange [7], and later Rädel and Lange [8] published reports on the ongoing European research project EASIE, where one of the aims is how to avoid use of additional supporting structure in the case of the openings cut in sandwich panel claddings. The last publication also contains part of the coming ECCS/CIB report "Preliminary European Recommendations for Design of Sandwich Panels with Openings" (based on an updated report [9] that was announced earlier [10]). The ECCS/CIB report completes the directions given in EN 14509 and introduces a possibility to design sandwich panel claddings with openings without additional support if really not needed. In the case of "small opening", where an opening does not meet or cut the longitudinal joint of the panel and the width of the opening is smaller than the width of the sandwich panel, the resistance of the remaining cross-section may be sufficient. The activation of load-bearing support via the longitudinal joints to the adjacent panels is also possible. By use of numerical models of sandwich panel interconnection systems with openings, based on the geometry and the stiffness parameters (bending, shear and torsional rigidity of the panels, shear rigidity of the longitudinal joint) that are obtained by presented formulas or test procedure, an evaluation of the internal forces and deflections with software for 3D beam structures can be made. Recent experimental investigations performed by the same authors have however showed, that suggested formulas overestimate the torsional stiffness for sandwich panels in the case of panels with eccentric point loads and that additional axial stresses caused by torsional moment that were measured in the faces of the panels cannot be neglected.

Rädel and Lange [11] have also published a paper on experimental and numerical investigations concerning roof sandwich panels with profiled faces and openings. A computational approach using solid and shell finite elements was introduced. Design formulas for a single sandwich with profiled steel sheet faces, a polyurethane foam core and small opening were proposed based on study results.

The objective of this paper is to present details of finite element analyses of structural behaviour of wall sandwich panels with large openings. A new approach in structural analysis of interconnection sandwich panel systems by detailed modelling of longitudinal joint between neighbouring panels was introduced. The interlocking longitudinal joints were included in finite element models of two typical design examples of sandwich panel claddings with large openings. A structural behaviour of longitudinal panel to panel connection was also analysed using detailed finite element model of the longitudinal joint between neighbouring sandwich panels consisting of the double interlocking tongue and groove connection. The results of simulations were carefully analysed. In addition, a laboratory experiment was carried out for the same two studied design examples. The comparison of the experimental results to the model calculations is also presented.

2 Finite element analysis

Structural behaviour of wall structural sandwich panel cladding with large openings was investigated using ANSYS® simulation software package. Three-dimensional finite element models of panel interconnection systems with openings were built. The models incorporate detailed longitudinal joint between the panels to simulate load transfer from the weakened panel to the neighbouring panels. Even more details were included to the further local model of double interlocking tongue and groove panel to panel connection that was built to study stiffness and load transfer characteristics of the longitudinal joint between neighbouring sandwich panels.

Different finite element arrangements and mesh refinements were studied to determine the most appropriate model configurations. The models presented in this paper were modelled using shell elements (SHELL181) for the faces and solid elements (SOLID45) for the core. The used shell elements are well suited for large strain nonlinear applications while the used solid elements have large deflection and large strain capabilities [12]. Bonded connections between steel faces and a mineral wool core were modelled using duplicate nodes for the face and the core that were coupled in all three displacement directions (*UX*, *UY* and *UZ*). Surface-to-surface contact elements (CONTA173 and TARGE170) were employed in the contact area of interlocking tongue to groove joints. No contact friction was assumed. A steel face sheets were assumed to be isotropic and a bilinear isotropic hardening material model was used while an anisotropic bilinear plastic material model (uniaxial bilinear tension and compression stress-strain curves in three orthogonal directions and shear stress-engineering shear strain curves in the corresponding directions [12]) was employed to solid elements of mineral wool core. It has to be noted that the applied material model is a good approximation of the mineral wool material properties when the global sandwich panel behaviour is investigated, whereas in the case of investigations of local phenomenon even a more precise description of the complex mechanical characteristics of the mineral wool would be preferred. The material properties of steel face sheets and mineral wool core based on data provided by the sandwich panel manufacturer are shown in Tabs. 1 and 2. The coordinate directions used in Tab. 2 are consistent with the coordinates used in all presented finite element models: *X* coordinate defines direction parallel to the width of the panel, *Y* coordinate defines direction parallel to the panel thickness and *Z* coordinate defines direction parallel to the length of the sandwich panel. It should also be noted that all mechanical properties of mineral wool core, which is made of lamellas cut from mineral wool plates, may vary depending on manufacturing process and thickness of the plates of mineral wool. The values of some mechanical properties may even vary in a wide range by batch to batch from the same manufacturer.

2.1 Longitudinal joint stiffness and load-bearing capacity

For the effective use of the sandwich panels in the wall claddings with openings it is necessary to consider the load transfer through longitudinal joint between the neighbouring panels.

A joint along longitudinal edges of adjacent sandwich panels comprises interlocking tongue and groove between both inner and outer faces providing a structural panel to panel connection. In the case of weakened panels due to an opening, the transmission of the loads must be ensured through the longitudinal joints to the not weakened adjacent panels. This means that a sufficient shear force capacity of the longitudinal joints must be available. A calculation of shear force capacity is (because of nonlinear characteristics and complicated geometry of tongue and groove joint) not a simple procedure and is probably feasible only via finite element analysis as shown in this paper. In addition, such finite element analysis can also be used for further study of local phenomena that cannot be accomplished by any other research tool.

In order to determine the load-bearing characteristics of longitudinal joint of typical sandwich panel cladding as used in the two analysed design examples presented later in this paper, a relatively small and simple model of longitudinal joint was built as shown in Fig. 1 with fine quadrilateral mesh, which is further refined in proximity of the interlocking joints.

The model of longitudinal joint consists of two complementary segments of neighbouring panels with double interlocking tongue and groove. To minimize the effect of bending in the resulted deflections, a nominal width (size in *X* direction) of modelled segment of each neighbouring panel equates a half of the sandwich panel thickness. As the geometry of longitudinal joint does not vary along the joint (*Z* coordinate), the problem was effectively reduced from 3D to plane strain problem using single layer of 3D finite elements (parallel to *XY* plane). Symmetry boundary conditions (not plotted in Fig. 1) were applied to all nodes to implement plane strain conditions. On both left and right outer surfaces symmetry boundary conditions were also applied to induce slider support (with a single degree of freedom in *Y* direction) to each of two panel segments. Zero displacement conditions in *Y* direction were imposed on the nodes in the bottom left corner and load *F* was applied on the nodes in the top right corner of the model. Model was solved numerically including large-displacement effects.

Table 1 Material properties of steel faces

Density / kg/m^3	Elastic modulus / GPa	Yield strength / MPa	Poisson ratio	Tangent modulus / GPa
7850	210	320	0,3	0,100

Table 2 Material properties of mineral wool core

Density / kg/m^3	Elastic modulus / MPa			Poisson ratio			Shear modulus / MPa		
	X	*Y*	*Z*	*XY*	*YZ*	*XZ*	*XY*	*YZ*	*XZ*
120	0.5	11	45	0	0	0	2,32	5,8	0,4

	Yield strength / MPa			Tangent modulus / MPa		
	X	*Y*	*Z*	*X*	*Y*	*Z*
Tension and Compression	0,033	0,1	0,04	0,01	0,07	0,03
	XY	*YZ*	*XZ*	*XY*	*YZ*	*XZ*
Shear	0,02	0,68	0,02	0,01	0,01	0,01

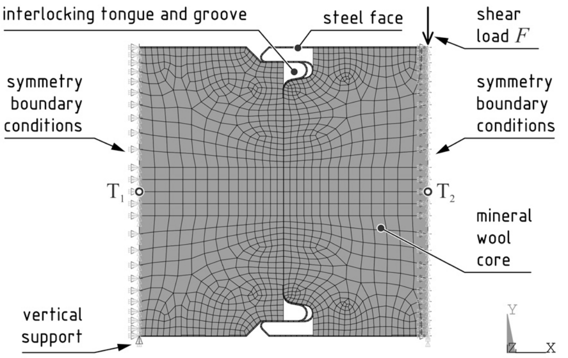


Figure 1 FE calculation model of a double interlocking tongue and grove longitudinal joint with applied load and boundary conditions

Fig. 2 shows shear stiffness characteristics (a relation of vertical shear load per unit length to vertical deflection u_y, which was calculated as the difference of vertical displacements of the outermost points T_1 and T_2 on the panel mid-surfaces of both panel segments) of analysed longitudinal joint across full range of results obtained by numerical solution (maximum shear load is 2,08 kN/m at the vertical deflection of 9,1 mm).

Vertical (shear) loading of joint F is also inducing a horizontal reaction force R_x in the applied slider supports which equates to the force that is needed to keep a horizontally unconstrained longitudinal joint (in real-world applications) closed. Fig. 3 shows a relation of horizontal reaction force per unit length to shear load per unit length. It can be observed that in first part ($F < 200$ N/m) the horizontal reaction is negligible and then increases proportionally to the shear load F. Maximum value of horizontal reaction force obtained is 697 N/m at the vertical load 1,82 kN/m (and value of 441 N/m is obtained at joint shear capacity 1,16 kN/m).

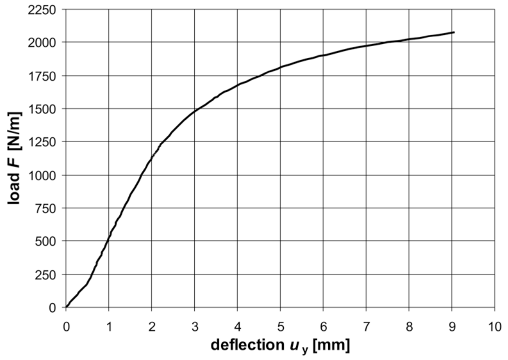


Figure 2 Shear stiffness characteristics of longitudinal joint: vertical (shear) load per unit length F vs. vertical deflection u_y

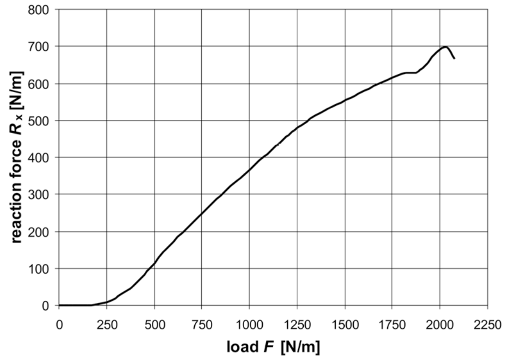


Figure 3 Horizontal reaction force per unit length R_x vs. vertical (shear) load F per unit length F

The shear load-bearing capacity of longitudinal joint was estimated based on analysis of calculated stress and strain distributions in mineral wool core. Normally a structural role of lightweight core is described to be a transfer of shear loads between the two faces but in the case of shear loaded longitudinal joint the mineral wool core at the margin of sandwich panel is used as a tension connection between the two faces in Y direction as can be seen from normal stress and strain distributions σ_y and ε_y in Figs. 4 and 5, respectively. A normal strain of 0,04 (4 % deformation) as proposed by sandwich panel manufacturer was used as a limiting value to dominant strain in Y direction (ε_y) assuming adequate bonding between the steel face and the mineral wool core. The value of shear capacity of longitudinal joint obtained from finite element calculation using this strain-based criterion is 1,16 kN/m (see Fig. 5).

The determined value of shear capacity of longitudinal joint seems very comfortable as theoretically it means that a panel with nominal width of 1 m loaded with uniform surface load of 2,32 kN/m^2 could be supported only by adjacent panels through longitudinal joints. Practically, especially in the case of a sandwich panel with large opening, where the loads acting on the panel and then transmitted through the longitudinal joints are far from uniformly distributed [8] and while the adjacent panels can be additionally stressed only to a certain extent, only a part of the lost load-bearing capacity of sandwich panel with an opening can be regained by activation of load transfer through longitudinal joints to the adjacent panels.

A shear stiffness of the longitudinal joint was established from calculated data (as a slope of linear portion of the curve presented in Fig. 2) to be approximately 650 kN/m^2.

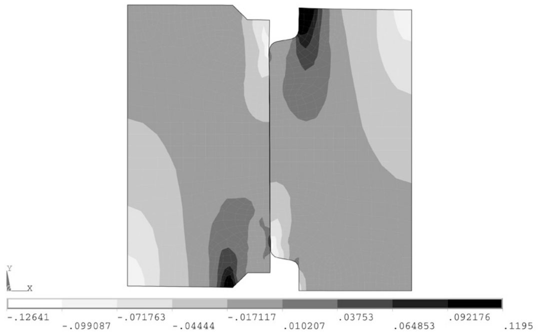


Figure 4 Calculated normal stresses σ_y (MPa) in mineral wool core of a longitudinal joint (at load F = 1,16 kN/m)

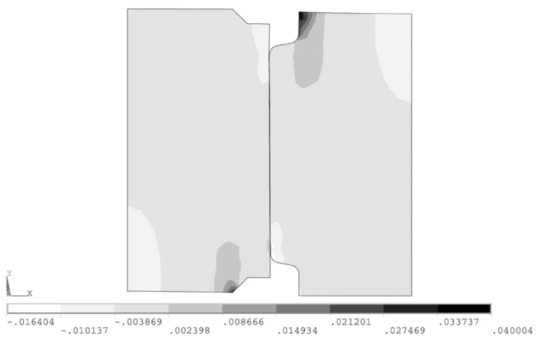


Figure 5 Calculated normal strains ε_y in mineral wool core of a longitudinal joint (at load F = 1,16 kN/m)

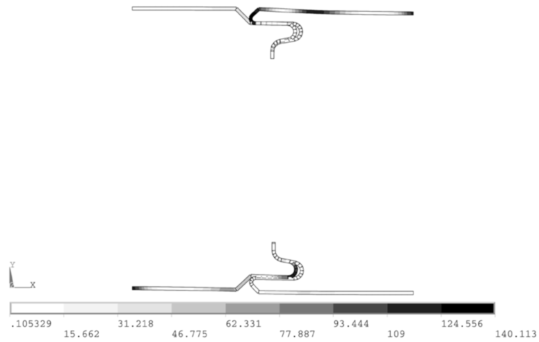


Figure 6 Calculated von Mises equivalent stresses σ_{eqv} (MPa) in steel faces of a longitudinal joint (at load F = 1,16 kN/m)

Figs. 4 and 5 show stress and strain distributions in the mineral wool core in the area of longitudinal joint in Y direction, σ_y and ε_y, respectively, at vertical load F value of 1,16 kN, i.e., longitudinal joint shear capacity. The two areas with maximal compression stresses σ_y down to –0,126 MPa are directly above vertical support in the left panel segment and directly below applied vertical load F in the right panel segment. Areas with maximal tension stresses up to 0,120 MPa are located in lower right corner in the left panel segment and in upper left corner in the right panel segment. The areas of peak values in stress distribution σ_y directly correspond to the areas of peak values in strain distribution ε_y. The (absolute) strain peak ε_y values in tension (although in very small region), however, are almost three times greater to those in compression (0,0400 vs. –0,0164).

The von Mises equivalent stress distribution σ_{eqv} in steel faces is shown in Fig. 6. The maximum values reach up to 140 MPa which is well bellow 320 MPa, the yield strength of steel sheet as noted in Tab. 1.

2.2 Panel interconnection systems with large openings

A study of two specific design cases of the interconnecting systems with a large opening was conducted: firstly, an interconnection system of four sandwich panels and large window opening of size 0,8 × 0,8 m which is positioned centrally across two inner panels as shown in Fig. 7, and secondly, an interconnection system with three sandwich panels and large window opening of size 1 × 1 m where opening width equates to entire width of the inner panel as shown in Fig. 8. The modelled panels have a thickness of 120 mm, nominal width of 1000 mm and total length of 3800 mm.

The numerical study of the activation of the load-bearing resistance of neighbouring panels in the panel interconnection systems with large opening was carried out using finite element models. Due to double symmetry across two perpendicular planes for both analysed systems one quarter symmetry models were built as shown in Figs. 9 and 10. It has to be noted that symmetry across longitudinal vertical midplane can only be introduced by assumption that there is no significant difference in structural behaviour between the two panel-to-panel connections at each side of sandwich panel (double groove-to-tongue connection on one side and double tongue-to-groove on the other side). In the case of the model of interconnection system of four sandwich panels (Fig. 7) a further assumption was made that due to the supposed symmetry across longitudinal vertical midplane right through the supposedly symmetrical longitudinal joint between the two inner panels, there is no interaction between middle panels via the joint and no symmetry boundary conditions were applied at the plane of symmetry. The models were designed by the use of very same finite elements and same principles as used in the above model of longitudinal joint. In addition to the solid, shell and contact elements used for mineral wool core, steel sheets and the joints, linear compression-only elements (LINK10) were used to simulate simple supports at both ends of interconnection system.

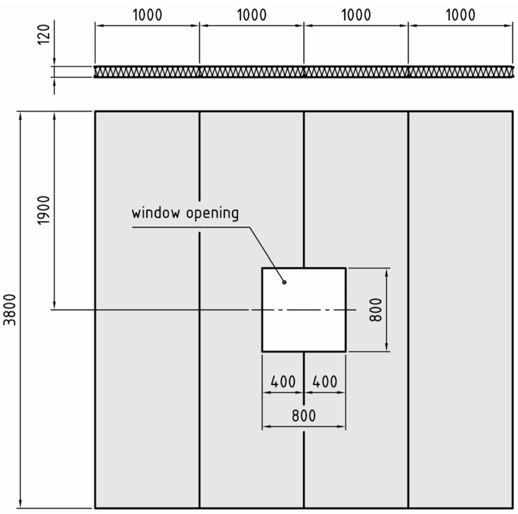


Figure 7 Interconnection system of four sandwich panels with large window opening positioned centrally across two inner panels

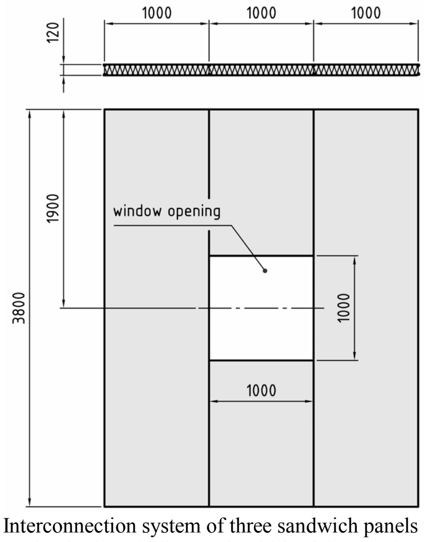


Figure 8 Interconnection system of three sandwich panels with large window opening in the middle panel (width of the opening equates to entire width of the panel)

The wind action simulation was performed by applied pressure load on upper face of the panels as shown in Figs. 9 and 10. The pressure loading on the area of the opening was uniformly distributed on the 40 mm wide marginal area around the opening, which corresponds to the load application at laboratory experiments (see Figs. 11 and 12). For the same reason a dead load of sandwich panels was also applied by specified gravitational acceleration of 9,81 m/s^2 in Y direction.

The models above were solved numerically including large-displacement effects. In addition to the principal analysis (FE Calculation A) an alternative analysis (FE Calculation B) was conducted for each of the two examples to demonstrate the influence of material properties of mineral wool core on structural behaviour of sandwich panel interconnection systems with openings, where values of all material properties of mineral wool (as presented in Tab. 2) have been decreased by 10 %.

The results obtained by numerical solution and their comparison to the results obtained experimentally are presented later in this paper.

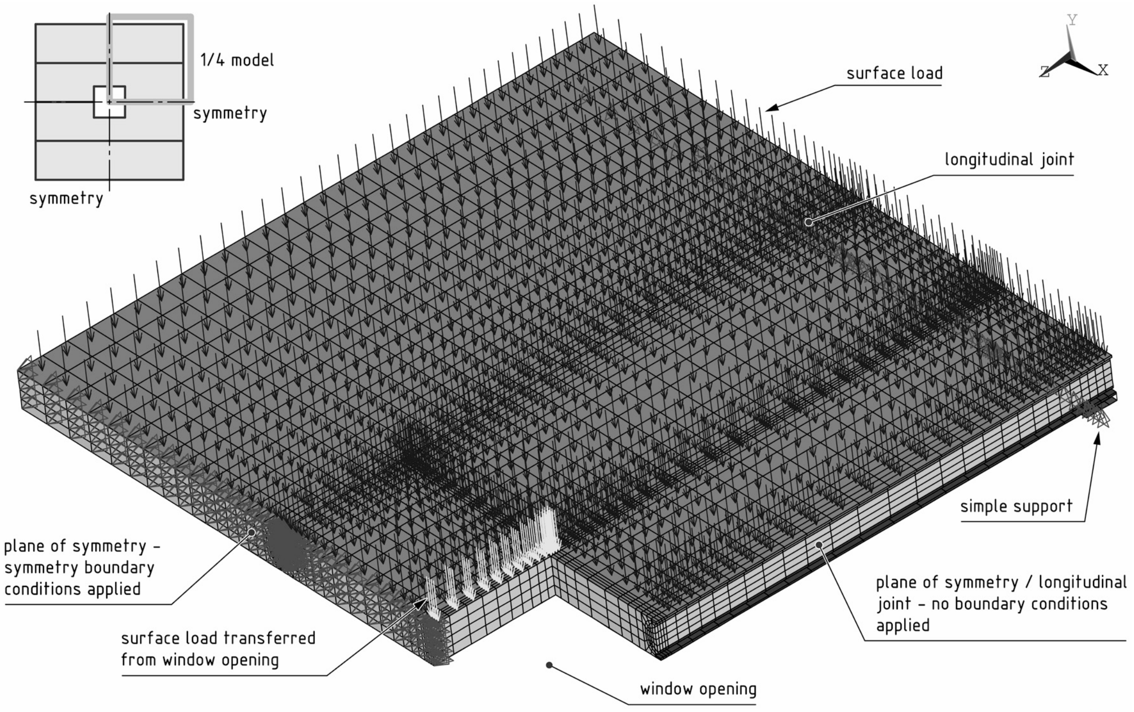


Figure 9 A quarter symmetry FE model of interconnection system with four sandwich panels and large window opening positioned centrally across two inner panels

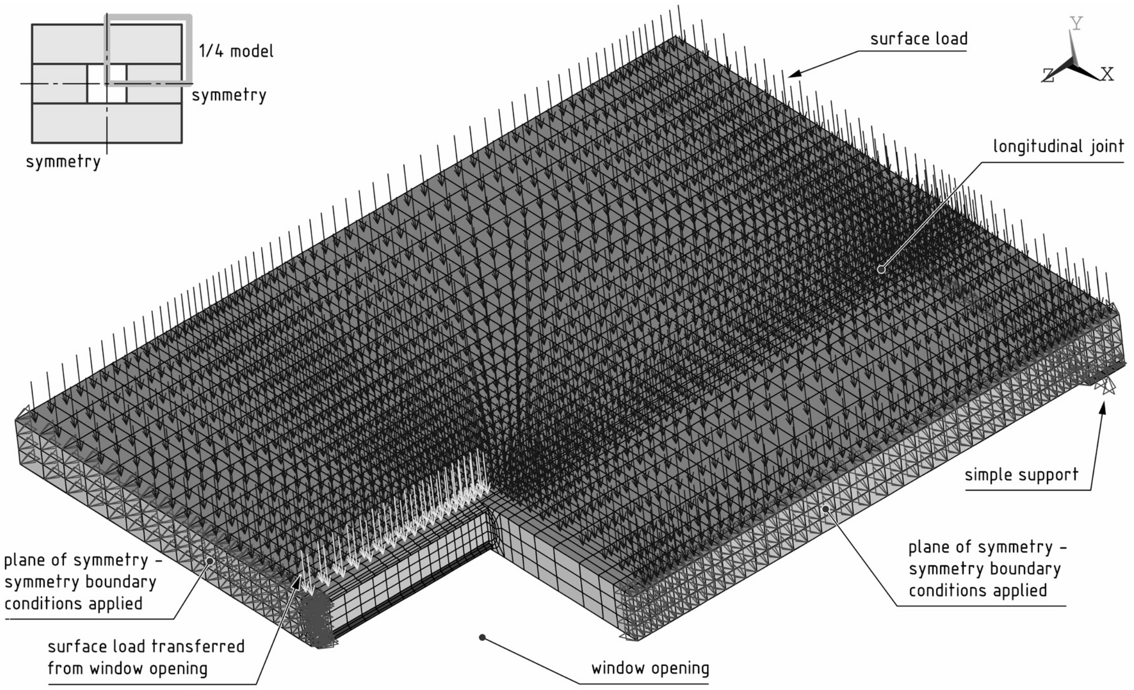


Figure 10 A quarter symmetry FE model of interconnection system with three sandwich panels and large centrally placed full-width window opening in the middle panel

3 Experimental investigations

To verify the numerical investigations, a laboratory experiment was conducted for the same two specific design cases shown in Figs. 7 and 8 that were analysed numerically. Test setups of these two analysed design examples are shown in Figs. 11 and 12. Sandwich panels of tested configuration were simply supported by two girders, one at each end. Centrally placed window openings of size 0,8 × 0,8 m and 1 × 1 m, respectively, were covered with oversized wooden board (thickness: 22 mm, 40 mm overlap on all sides) to create an effect of window frame by transferring loads applied on the window to the corresponding parts of the panels.

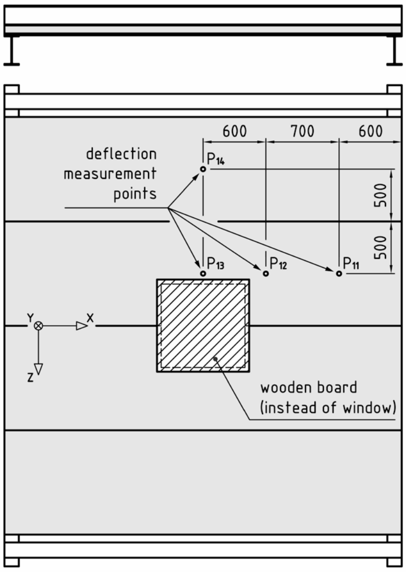


Figure 11 Test setup of interconnection system with four sandwich panels and large window opening positioned centrally across two inner panels.

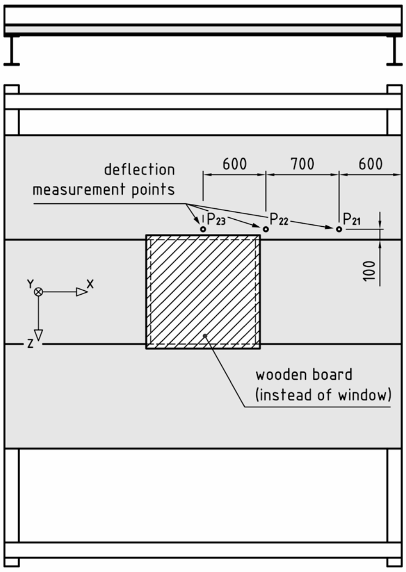


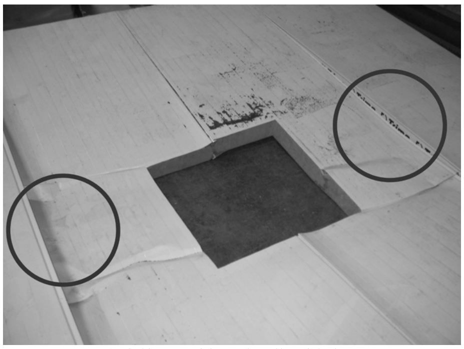
Figure 12 Test setup of interconnection system with three sandwich panels and large window opening (width equates to entire width of the panel) in the middle panel.

The surface load was simulated by placing 25 kg sandbags which were spread evenly in layers on the upper face of panel systems (including wooden board). The load was increased incrementally until failure; an additional layer of sandbags that have been previously weighed was placed at each load step and measurement of vertical displacements at measurement points was conducted manually using a measure. Four measurement points were used for interconnection system of four sandwich panels, i.e., from P_{11} to P_{14} (see Fig. 11), and three measurement points for interconnection system of three sandwich panels, i.e., from P_{21} to P_{23} (see Fig. 12). Dead load deflections at measurement points before the first load step were used as zero reference points. For each of two examples two tests were performed so that fourteen sandwich panels were used altogether.

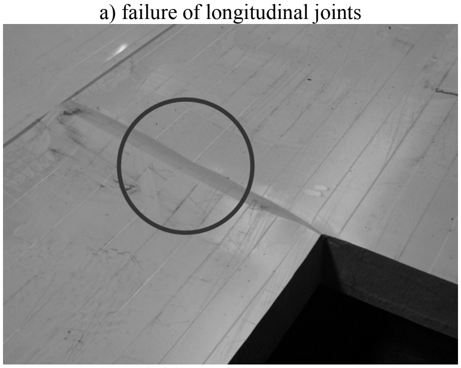
The test results and comparison to the results of numerical simulations are presented below.

4 Results and comparison

In each of the tests the maximum applied surface load before the failure was determined at approximately 2,2 kN/m^2 as presented in Tabs. 3 and 4. For both tested examples similar failure modes were determined between two tests of each system; failure of the systems with four sandwich panels and opening across two inner panels was caused by collapse of two inner panels (wrinkling of inner panels and failure of longitudinal joint) while the system of three sandwich panels with full-width window opening in the middle panel failed by collapse of complete system (caused by collapse of outer panels). Collapse of a tested interconnection system with four sandwich panels is shown in Fig. 13.



a) failure of longitudinal joints



b) wrinkling of the inner panel

Figure 13 Collapse of interconnection system of four sandwich panels with large window opening positioned centrally across two inner panels

In Figs. 14 and 15, the deflection results from the numerical simulation (FE calculation A and B) and the experimental investigation (Test 1 and 2) are presented for both tested design examples.

Fig. 14 shows deflections across load range for the system with four sandwich panels and opening across two inner panels in four measurement points from P_{11} to P_{14}, where a direct proportionality between deflections u_y and loads p can be noticed. A good agreement is observed between both tests, but also between test and calculation results (FE Calculation A) with slightly smaller calculated deflection values. It has to be noted, however, that rather high relative deviations between results of both tests are present especially at the lower half range of loads. A comparison between results of both numerical simulations

(FE Calculation B vs. A) shows that 10 % decrease of values of mechanical properties of mineral wool core (see in Tab. 2) causes 5 % increase in values of deflections at all measurement points.

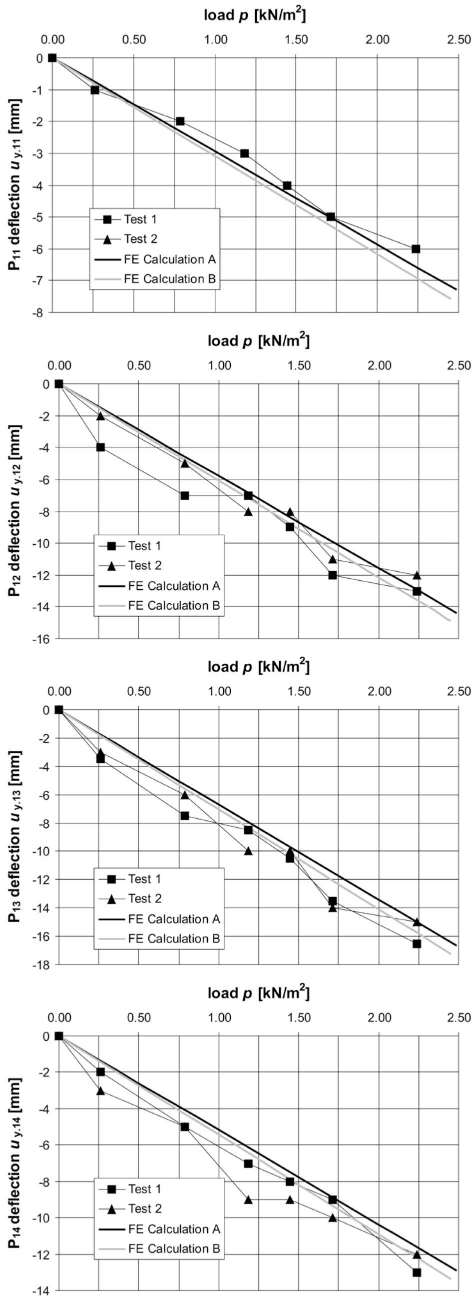


Figure 14 Comparison of experimental and calculated deflections (points P_{11} … P_{14}) of interconnection system with four sandwich panels and large window opening positioned centrally across two inner panels

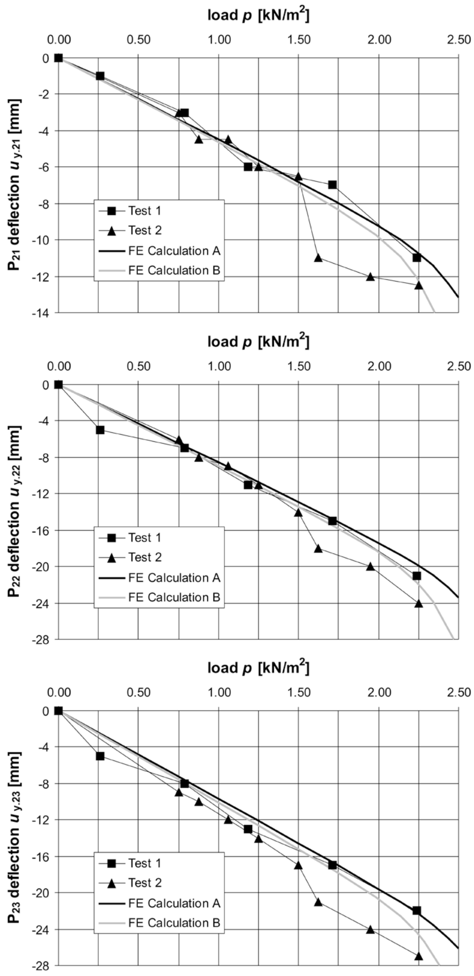


Figure 15 Comparison of experimental and calculated deflections (points P_{21} … P_{23}) of interconnection system with three sandwich panels and full–width window opening in the middle panel

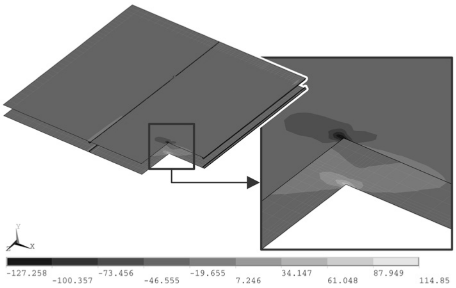
In Fig. 15 where deflections across load range for the system with three sandwich panels and opening across middle panel in three measurement points from P_{21} to P_{23} are presented, similar direct proportionality between deflections u_y and loads p can be noticed, although a significant (nonlinear) increase in deflection is observed at the high end of the load range. Rather high relative deviations of deflection test results (Test 2) noted in the upper half of load range can be attributed to the appearance of wrinkles in the face of outer sandwich panel. A 10 % decrease of values of mechanical properties of mineral wool core (FE Calculation B vs. A) causes from about 4 % (in the middle of load range) up to almost 15 % (at max. load p = 2,2 kN/m^2) increase in values of deflections.

Table 3 Maximum applied loads and failure modes of interconnection system with four sandwich panels and an opening across two inner panels

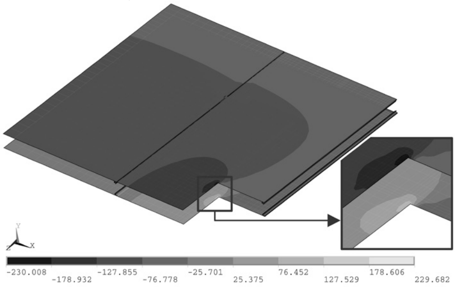
Test	Max. total load (before failure) / kN	Surface load / kN/m^2	Failure mode
1	34,0	2,24	collapse of two inner panels
2	34,0	2,24	collapse of two inner panels

Table 4 Maximum applied loads and failure modes of interconnection system with three sandwich panels and an opening in the middle panel

Test	Max. total load (before failure) / kN	Surface load / kN/m^2	Failure mode
1	25,5	2,24	complete collapse
2	25,6	2,25	complete collapse

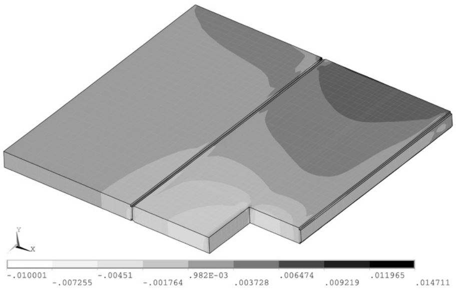


a) normal stress σ_x / MPa

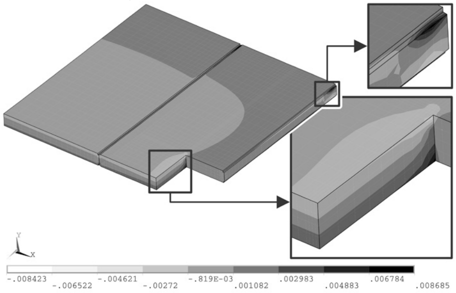


b) normal stress σ_z / MPa

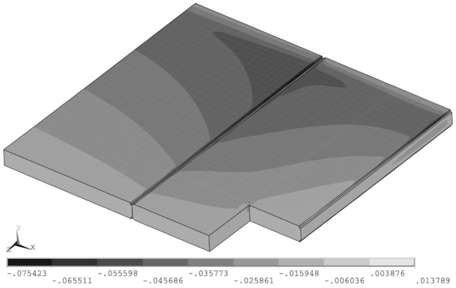
Figure 16 Calculated stress distribution in steel faces of interconnection system with four sandwich panels and large window opening positioned centrally across two inner panels



a) normal stress σ_z / MPa



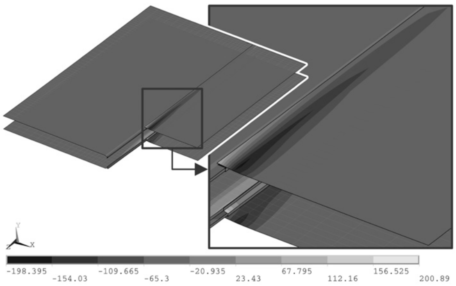
b) shear stress τ_{xy} / MPa



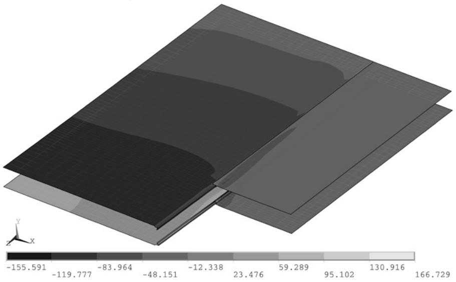
c) shear stress τ_{yz} / MPa

Figure 17 Calculated stress distribution in mineral wool core of interconnection system with four sandwich panels and large window opening positioned centrally across two inner panels

Figs. 16 and 18 show calculated stress distributions σ_x and σ_z in steel faces of both interconnection systems. All stresses are well below specified yield strength (see Tab. 1). In Fig. 16 stress concentrations are observed around corners of window opening. Maximum transverse stresses σ_x are equal to 114,9 MPa (in tension) and 127,3 MPa (in compression), and maximum longitudinal stresses σ_z are equal to 229,7 MPa (in tension) and 230,0 MPa (in compression).

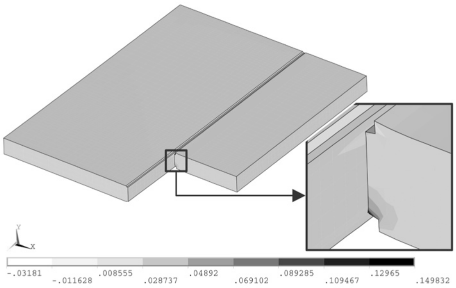


a) normal stress σ_x / MPa

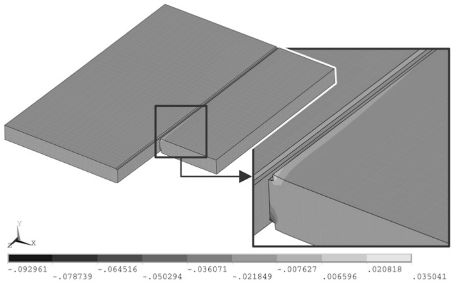


b) normal stress σ_z / MPa

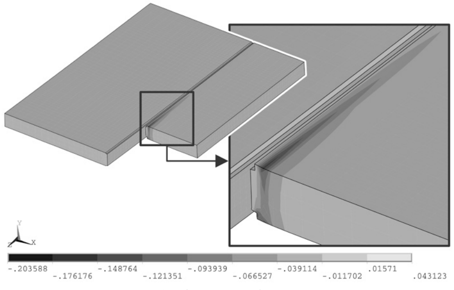
Figure 18 Calculated stress distribution in steel faces of interconnection system with three sandwich panels and large centrally placed full-width window opening in the middle panel



a) normal strain ε_x



b) normal strain ε_y



c) shear strain ε_{xy}

Figure 19 Calculated strain distribution in mineral wool core of interconnection system with three sandwich panels and large centrally placed full-width window opening in the middle panel

The appearance of longitudinal tension stresses σ_z (up to 127,9 MPa) in the upper face of the remaining cross-section of the inner panels is consistent with failure mode due to wrinkling (see Tab. 3 and Fig. 13).

In Fig. 18 areas of high transverse bending stresses σ_x in both faces of middle panel are observed along longitudinal joint up to approximately 200 MPa (in tension and compression). The appearance of longitudinal tension stresses σ_z (up to 155,6 MPa) in the upper face of the outer panels is consistent with failure mode – collapse of outer panels (see Tab. 3).

Fig. 17 shows calculated normal stress distribution σ_z and shear stress distributions τ_{xy} and τ_{yz} in mineral wool core of interconnection system with four sandwich panels. In Fig. 17b stress concentrations are observed in the areas around the window opening and above the support with maximum values up to approximately 0,008 MPa (τ_{xy} in tension and compression) whereas an adequate yield strength is 0,02 MPa (see Tab. 2). All other presented calculated maximum values are also well below yield strength values.

Local effect on behaviour of mineral wool core in the case of overstressed longitudinal joint due to full-width opening in interconnection system with three sandwich panels are presented in Fig. 19. The distinctive strain distributions are shown; transverse and out-of-plane normal strains ε_x and ε_y, respectively and shear strain ε_{xy}.

5 Conclusions

Two numerical studies using finite elements analysis were conducted to examine behaviour of sandwich panels with large openings. The first analysis was focused on structural behaviour of longitudinal joints between the adjacent panels. It was found that shear bearing capacity of longitudinal joint is relatively comfortable although practically only a part of the lost global load-bearing capacity of a sandwich panel weakened by opening can be replaced by load transfer to adjacent panels through longitudinal joint. The second investigation was focused on the two typical design examples of interconnection systems with three and four simply supported panels with one large centrally placed window opening. Finite element models of interconnection systems with included longitudinal joints between adjacent panels were analysed numerically. The results of numerical calculations were compared to the results obtained by experimental study of two analysed design examples. A relatively good agreement between calculated and measured results was found.

6 References

[1] Davies, J. M. Lightweight Sandwich Construction. Blackwell Science, Oxford, 2001.

[2] Berner, K.; Pfaff, U. Openings in sandwich panels. Institute for Sandwich technology, Mainz, 2005.

[3] EN 14509:2006 (E). Self-supporting double skin metal faced insulating panels – Factory made products – Specification. CEN – Comité Européen de Normalisation, Brussels, 2006.

[4] Höglund, T. Load Bearing Strength of Sandwich Panel Walls with Window Openings. // Proceedings of IABSE Colloquium, IABSE Reports, Stockholm, 49, (1986), pp. 349-356.

[5] Toma, T.; Courage, W. Structural detailing of openings in sandwich panels. // Proceeding of Thirteenth International Specialty Conference on Cold-Formed Steel Structures: Recent Research and Developments in Cold-Formed Steel Design and Construction, St. Louis, Missouri U.S.A., 1996, pp. 309-320.

[6] Bottcher, M.; Lange, J. Sandwich Panels with Openings. // Proceedings of the 5th International Conference, Kruger National Park, Berg-en-Dal, Mpumalanga, South Africa, 2004, pp. 722.

[7] Warmuth, F.; Lange J. Openings in Sandwich Elements. // International Conference on Steel & Composite Structures, Sydney, 2010.

[8] Rädel, F.; Lange, J. Calculation model determining mechanical strength of sandwich panels with opening with and without additional internal frame structure. EASIE WP1 Deliverable 1.2, Technische Universität Darmstadt, Darmstadt, 2011

[9] Davis, J. M.; Hassinen, P.; Heselius, L.; Misiek, T. ECCS/CIB Joint Committee on Sandwich Constructions: Recent European Recommendations on Design and Testing. // Proceedings: W056 – Special Track 18th CIB World Building Congress, Salford, UK, 2010.

[10] ECCS/CIB State of the art report for Design of Sandwich Panels with Openings. ECCS, TWG 7.9 Sandwich panels and related structures & CIB, W056 Lightweight Constructions, Brussels/Rotterdam, (may be published as a European Recommendation for the design of sandwich panels with openings in 2012)

[11] Rädel, F.; Lange, J. Tragfähigkeit von Sandwichelementen mit profilierten Deckschichten und Öffnungen. // Stahlbau, 9, 80(2011), pp. 656–661.

[12] Release 11.0 Documentation for ANSYS. Wickens, SAS IP, Inc., 2007.

Authors' addresses

Metod Čuk
University of Ljubljana
Faculty of Mechanical Engineering
Aškerčeva cesta 6
1000 Ljubljana, Slovenia
metod.cuk@fs.uni-lj.si

Silvo Štih
Trimo, d.d.
Prijateljeva cesta 12
8210 Trebnje, Slovenia
silvo.stih@trimo.si

assist. prof. dr. Boris Jerman
University of Ljubljana
Faculty of Mechanical Engineering
Aškerčeva cesta 6
1000 Ljubljana, Slovenia
boris.jerman@fs.uni-lj.si