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Research paper

Experimental investigation of sandwich panels supported by thin-walled beams under various load arrangements and number of connectors

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Abstract: In the paper there the laboratory tests of interaction between thin-walled beams of the Z cross-section and the sandwich panels with PIR foam core are presented. The different numbers of connectors (0, 4, and 8) were used to connect the sandwich panels with the thin-walled beams. Furthermore, the parallel and perpendicular to the longitudinal axis of the thin-walled beam load arrangement was analysed. The research provides a qualitative and quantitative comparison of the mentioned experiments using the ultimate capacity, the deformation capacity, and the stiffness. In the second part of the paper, the numerical analysis of the thin-walled beam was also performed. The beam was modelled as a shell element and loaded in two ways, which corresponded to the loading scenario during laboratory tests (uniformly distributed and concentrated loads). The results of the numerical calculations of the beam without lateral stabilization were compared with the laboratory results of the beam stabilized by the sandwich panels.

Keywords: failure mechanisms, imperfections, laboratory experiment, nonlinear analysis, sandwich panels, thin-walled beams

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1. Introduction

The interaction between cold-formed thin-walled beams and cladding elements has become a permanent part of the process of designing steel industrial halls. The claddings made of corrugated (trapezoidal) cold-formed sheets are formalized in Eurocode 3 [1] by introducing three construction classes. These construction classes define the level of interaction between the cladding element and the main structure (main columns and rafters) or the secondary structure (purlins and side rails). It should be emphasized that the level of interaction is directly related to the connection provided between the corrugated sheets and structural elements.

The recent research indicates that a similar approach can be used for the other cladding elements such as sandwich panels. In [2] the authors pointed out that the high in-plane stiffness of the sandwich panels can provide lateral-torsional stabilization similar to those which can be obtained by the means of bar elements. In that paper, the literature review related to the determination of the in-plane stiffness and strength was discussed. Moreover, the importance of the connections in such a structural system was also depicted. The continuation of this research can be found in [3], where the detailed investigation of the mechanical connectors used to join the sandwich panel with thin-walled beam elements was discussed, which resulted in the mechanical model of the fasteners. In [4] the authors conducted research related to the behaviour of the free flange of the cross-section of the beam stabilized by sandwich panels. The authors focused on the concept of the notional linear spring placed to that free flange. The research was based on the roof system's full-scale laboratory test, which consisted of the Z thin-walled section and the sandwich panels. In conclusion, the results from these laboratory tests enabled us to apply the simplified procedures from EN 1993-1-3 [1] more practically and directly by supplementing the areas with absent information in code provisions. The influence of the uplift load on the lateral restrain of the thin-walled beam by sandwich panels was investigated experimentally in [5,6]. Another research area was connected with the diaphragm behaviour of the sandwich panels, see [7,8]. In [7] the research covers the investigation of the pin-base frames braced by sandwich panels. It is considered how this structural system can dissipate seismic actions. In that paper, the nonlinear dynamic analysis was used to verify the hypothesis of the behaviour of the sandwich panels as shear diaphragms in seismic areas. In [8] the research covers the influence of the various parameters on the shear diaphragm behaviour of the sandwich panel. The research is based on small scale laboratory tests. The authors also proposed and investigated full-scale laboratory tests of various joint reinforcement methods. In [9] the authors in the experimental approach (full-scale tests) indicate that the number of the fasteners has a significant influence on the capacity of the stabilized by sandwich panel thin-walled beam. The finite element analysis complements this research. The connection stiffness between the sandwich panel and the thin-walled beam element considering the number of mechanical fasteners was investigated in a small-scale test in [10]. The above-presented research papers investigated the interaction between sandwich panels and the cold-formed thin-walled elements. Nevertheless, also the hot-rolled sections are commonly used in the case of steel industrial halls. The interaction between the sandwich panels and the hot-rolled purlins was investigated in [11]. The presented research reveals that special emphasis should be placed on fasteners. The mechanical connectors' problems also appear in other modern composite structures such as aluminium-timber [12, 13] or aluminium-laminated veneer lumber [14].

In [15] the aspect of the shape and mutual orientation of thin-walled beams on the interaction efficiency with sandwich panels was presented. In that paper, the Z and C cross-section shape was investigated. The nine orientations of the sections were investigated, see Fig. 1. It can be noticed that the orientation set-up was in some cases symmetrical ($ZZ-S1$, $ZZ-S2$, $CC-S1$, $CC-S2$) and asymmetrical ($ZZ-A$, $CC-A$, $ZC-A1$, $ZC-A2$, $ZC-A3$). Moreover, the mixed and non-mixed section setup was used.

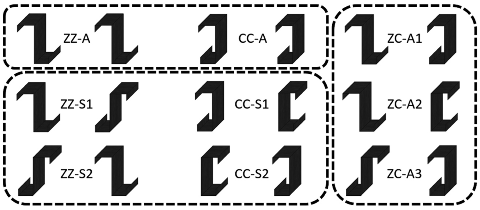


Fig. 1. Cross-sections orientation according to [15]

In that research, the authors pointed out that the investigated cross-sections (Z, C) are characterized by different geometrical properties that influence the sensitivity to lateral-torsional buckling. On the one hand, the position of the shear centre in the case of the Z section is favourable because is significantly closer to the load plane than the shear centre of the C section. It means that the torsional shear stresses will be smaller for the Z cross-section. On the other hand, the principal central axes of the Z cross-section are more rotated concerning the load plane than in the case of the C cross-section. It means that in the case of combined bending the bending about the minor axis will be larger in the case of the Z than the C cross-section. In [15] the influence of the shape and orientation of the cross-section was investigated numerically, using the model validated in previous authors' research [9].

The present paper is a continuation of the research presented in [15] namely, the most reasonable orientation and shape from the practical usage point of view in structural building engineering i.e. the ZZ-A case (see Fig. 1). The full-scale laboratory tests were executed in order to investigate the influence of the various load arrangement on the behaviour of thin-walled Z-beams stabilized by sandwich panels. Moreover, the influence of the number of connectors used to join beams with sandwich panels was considered.

2. Testbed setup

In Figure 2 the scheme of the testbed is depicted. The tested structural system consisted of two sandwich panels attached to the two Z cross-section thin-walled beams (orientation ZZ–A presented in Fig. 1). The sandwich panels were made of a softcore made of polyisocyanurate foam (PIR) and two steel facings with a thickness equal to 0.545 mm for the upper facing and 0.491 mm for the bottom one. The sandwich panel was 1100 mm in length, 650 mm in width and 80 mm in nominal thickness.

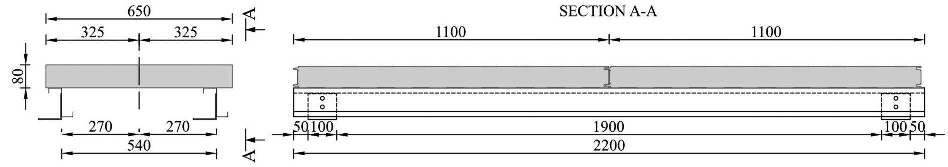


Fig. 2. The geometry of the testbed

The beam cross-section, see Fig. 3, was cold-rolled from the steel sheet with a thickness equal to 1.5 mm. The structural system component elements' material properties corresponding to the data obtained during the laboratory test presented in the authors' article [15].

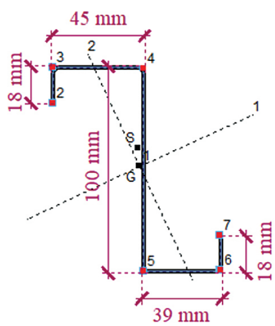


Fig. 3. The thin-walled cross-section geometry (S and G represent the shear and gravity centre respectively)

The thin-walled beams were supported by angle cleats with lengths equal to 100 mm. This kind of support was used to avoid the local compression of the thin-walled beam web. The angle cleats were fastened to the special supports, which allow rotation around the beam's local y-axis. The pictures of the used support are shown in Fig. 4.

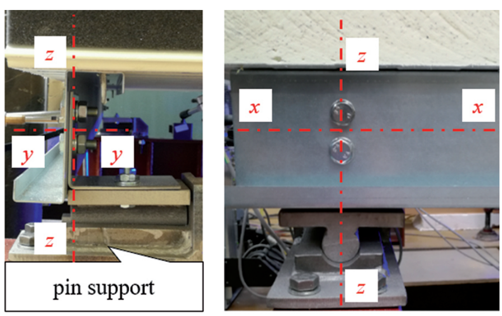


Fig. 4. Support of the structural system

To connect the thin-walled Z-beam with the cladding, the typical self-drilling fasteners for sandwich panels were used. A different number of these fasteners were used to connect the upper flange of the beam with the sandwich panel: 0, 4 and 8. The arrangements of the fasteners are shown in Fig. 5.

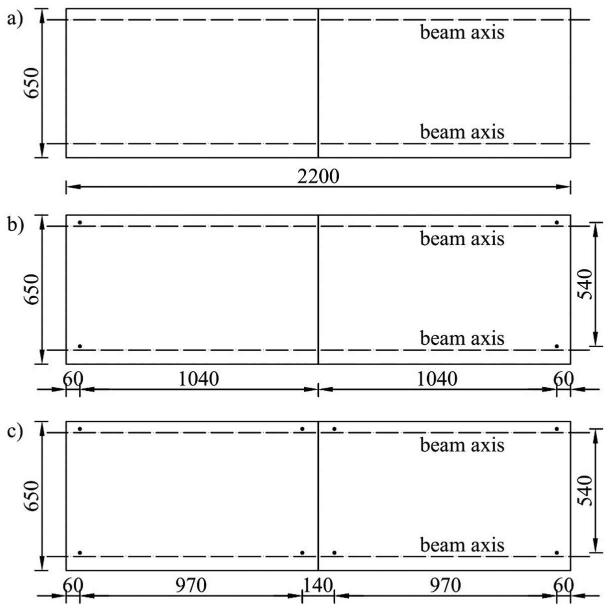
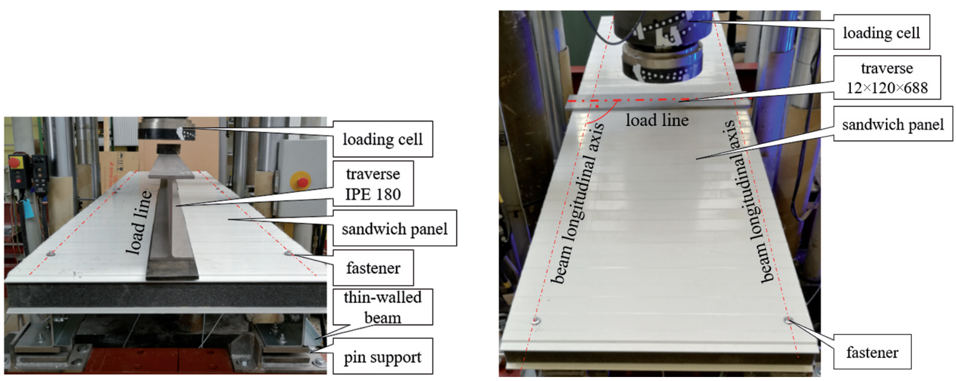


Fig. 5. Fasteners arrangement (view from above): a) 0 fasteners, b) 4 fasteners, c) 8 fasteners

The presented structural system was subjected to two load arrangements: parallel and perpendicular to the beams' longitudinal axis (local x-axis), see Fig. 6a and Fig. 6b respectively. The load was induced by the loading cell displacement with a 5 mm/min velocity.



(a) (b)

Fig. 6. Test bed view: a) U load arrangement, b) P load arrangement

The application of a load parallel to the longitudinal axis of the beam causes that the load is uniformly distributed over its entire length. In turn, the application of the load perpendicular to the axis of the beam causes the transfer of the load in the form of a concentrated load in the middle of the beam span, which can be considered a three-point bending scheme. In the further analysis, the load parallel to the beam axis will be signed with the letter U, while the load perpendicular to the beam axis with the letter P. In Table 1 the nine laboratory tests that were carried out are listed.

Table 1. List of the performed experiments

<table>
<tr><th>No.</th><th>Sample name</th><th>Number of fasteners</th><th>Load type</th></tr>
<tr><td>1</td><td>$F0 - U\_1$</td><td rowspan="2">0</td><td rowspan="6">uniformly distributed</td></tr>
<tr><td>2</td><td>$F0 - U\_2$</td></tr>
<tr><td>3</td><td>$F4 - U\_1$</td><td rowspan="2">4</td></tr>
<tr><td>4</td><td>$F4 - U\_2$</td></tr>
<tr><td>5</td><td>$F8 - U\_1$</td><td rowspan="2">8</td></tr>
<tr><td>6</td><td>$F8 - U\_2$</td></tr>
<tr><td>7</td><td>$F4 - P\_1$</td><td>4</td><td rowspan="3">concentrated load</td></tr>
<tr><td>8</td><td>$F8 - P\_1$</td><td rowspan="2">8</td></tr>
<tr><td>9</td><td>$F8 - P\_2$</td></tr>
</table>

During the laboratory test, the vertical displacements of the thin-walled beam bottom flange in the middle of its span and vertical displacement of the sandwich panel middle point were measured. The collected measurements were the basis for further comparative analyses.

3. Presentation of the results

According to the presented testbed and the research plan, the results from the experiments will be presented. The conducted research describes the kinematic and mechanical response of the structural system, consisting of sandwich panels and cold-formed thin-walled beams. Please note that the investigated system of sandwich panels and thin-walled beams is understood as one complex structural element where sandwich panels play two roles. The sandwich panels transfer all the loads onto the thin-walled beams as well as provide the lateral restrain for the upper flange of the thin-walled beam to prevent or limit the lateral-torsional buckling. The analysed structural system refers to typical industrial floor systems that are characterized by the beam span (L) to beam spacing (c) ratio (L/c) in the range of 2.5 to 4.0. In the case of the structural system investigated in this article, the beam span ($L = 2.1$ m) to the beam spacings ($c = 0.54$ m) ratio is equal to 3.89.

The designed research aims to show how the stiffness and the capacity of such a structural system change for different load arrangements and a different number of fasteners. As presented in Section 2 the two load arrangements will be investigated. The first load arrangement simulates the situation when the beam supporting the sandwich panel is subjected to a uniformly distributed load – case U; see Fig. 2. The second load arrangement simulates the situation when the beam is subjected to a concentrated load in the middle of the beam's length – case P, see Fig. 3. The latter case can be also considered as three-point bending. Another design parameter refers to the number of mechanical fasteners used to connect sandwich panels to thin-walled beams. For both load arrangements, four and eight fasteners were used. The case with a freely supported sandwich panel, i.e. without fasteners, was considered for the U load case, not for the P load case. It was because of the two phenomena. Firstly, the external edges of the sandwich panels would be significantly lifted. Secondly, below the load line, the panels would be separated. These two phenomena would make it impossible to transfer the load from the sandwich panel to the beam.

3.1. Equilibrium load-displacement paths

Figure 7 shows the equilibrium load-displacement paths. The force values and vertical displacements are measured on the ordinate and the abscissa axes, respectively. The thin-walled beams used in the experiment are of the Z cross-section and the assumed load plane arrangements (U load, P load) do not coincide with both the cross-section shear centre and the cross-section main axes. Therefore, the thin-walled beam's vertical deflection is accompanied by both the horizontal deflection (about the local y-axis) and the rotation of the section (about the local x-axis).

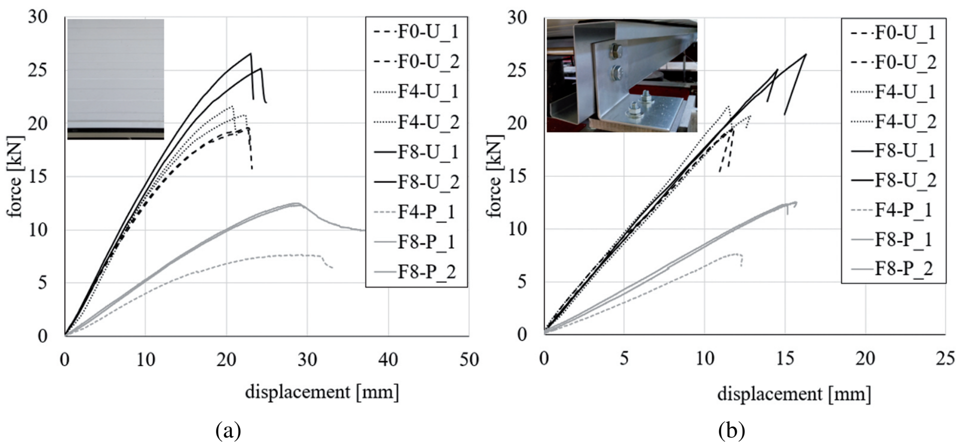


Fig. 7. Load vs vertical displacement equilibrium paths of the investigated structural system: (a) sandwich panel vertical displacement, (b) thin-walled beam vertical displacement

The series of laboratory tests presented in Fig. 7 refers to the various laboratory arrangements listed in Table 1. They should be read in the following way: the first part refers to the number of mechanical fasteners: $F0$ – without fasteners, $F4$ – four fasteners, $F8$ – eight fasteners. The second part refers to the load distribution along a thin-walled beam: U – uniformly distributed, P – concentrated load in the middle of the bam. The third part refers to the consecutive number of tests in the series. In Table 2 the data presented in Fig. 7 are listed, where $F_{\max}$ represents the ultimate force applied to the investigated system, U and P represent load type, $u_{z,SP}$ represents the vertical deflection of the sandwich panel at the ultimate force, $u_{z,B}$ represents the vertical deflection of the thin-walled beam vertical deflection at ultimate force, $F_{L,SP}$ represents the maximal linear force for the sandwich panel, and $F_{L,B}$ represents the maximal linear force for the thin-walled beam concerning the vertical displacements.

Table 2. Selected data from the experiments

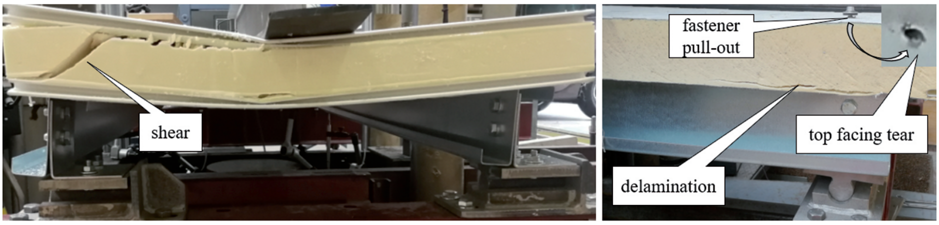
Test name	$F0-U$	$F4-U$	$F8-U$	$F4-P$	$F8-P$
Type of a load along beam	uniformly distributed load			concentrated load	
Number of fasteners used	0	4	8	4	8
Location of failure mechanisms	SP	SP	SP	B	B & SP
$F_{\max}$ [kN]	19.5	21.2	25.8	7.7	12.4
U [kN/m]	4.64	5.05	6.14	–	–
P [kN/m]	–	–	–	3.85	6.2
$u_{z,SP}$ [mm]	22.6	25.3	28.8	33.0	35.2
$u_{z,B}$ [mm]	11.8	12.2	15.4	11.9	15.5
$F_{L,SP}$ [kN]	11.3	12.2	17.7	5.5	10.2
$F_{L,B}$ [kN]	17.6	20.0	21.3	7.3	11.7

Please note that the thin-walled beam also deflects horizontally ($u_{Y,B}$) and there was a different horizontal displacement of the top and the bottom flanges. These displacements were not measured during the experiments, but it is expected that the resultant mechanical understood as force vs. resultant displacement response will not be so linear as presented in Fig. 7b. In Table 2 the location of failure mechanisms is also presented where *SP* refers to the failure of the sandwich panel, *B* refers to the thin-walled beam failure.

3.2. Failure mechanisms

The data presented in Table 2 depicted that the load arrangement for the considered structural system influences the location of the leading failure mechanism. It was observed that in the case of the U load (load perpendicular to the sandwich panel span and parallel to the beam length), the core shear failure of the sandwich panels limited the overall capacity of the structural system, see Fig. 8a. Simultaneously the thin-walled beams manifested only the elastic bow deformation. The bow deformation was realized in two directions e_z (vertical i.e. along the local z-axis) and e_y (horizontal i.e. along the local y-axis). The U

load arrangement also reveals that the four mechanical fasteners' occurrence causes both the delamination between the bottom facing and the core along sandwich panel length and the pull-out of the edge fasteners, see Fig. 8b. Further increase in the number of fasteners (eight fasteners), causes the exceeding of the plastic bearing resistance of the top sandwich panel facing in the vicinity of the edge fasteners (the top facing tear was noted).



(a) (b)

Fig. 8. The failure mechanism for the load type U: (a) core shear; (b) bottom facing-core delamination, fastener pull-out, and top facing tear

In the case of the P load (load parallel to the span of the sandwich panel and perpendicular to the beam length), for four fasteners, the weakest link was the thin-walled beam which has bow deformation coupled with local instability of the section under the applied load, see Fig. 9. In Figure 6 one can notice that additionally, for four fasteners, an edge connection between the panels was open at the bottom. The same failure of thin-walled beams was obtained for eight fasteners nevertheless, the fastener's pull-out was also observed as well as the core crushing under the applied load.

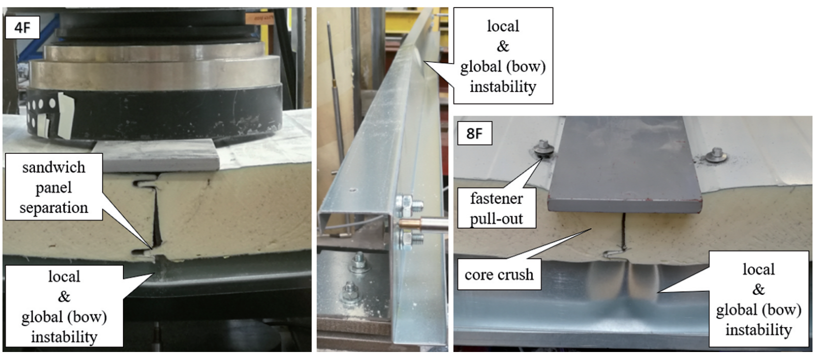


Fig. 9. The failure mechanism of the load type P with four and eight fasteners

4. Discussion of the results

The results of laboratory research of the structural system that consists of two thin-walled beams and two sandwich panels with PIR foam core depicted that both the resistance and the failure mechanisms are dependent on the load arrangement. In the case of the U

load type, the resistance of the structural system was depended on the shear capacity of the sandwich panel core. On the contrary, in the case of P load type, the resistance of the structural system was dependent on the local buckling of the web of the thin-walled beam. Additionally, in both load arrangements, the thin-walled beam global bow deformation was observed. This bow deformation in the case of U and P load was elastic and plastic respectively. Nevertheless, it was observed that, for both load arrangements, the increasing number of fasteners had increased the resistance of the structural systems. For U load the resistance increases by 9% (four fasteners) and 32% (eight fasteners) with respect to the situation of zero fasteners. For P load the resistance increases by 61% (eight fasteners) with respect to the situation of four fasteners.

To find the influence of the sandwich panel on the increase of the capacity of the thin-walled beam, numerical simulations were done. Therefore, the shell finite element model in AxisVM software was created. The boundary conditions were set up providing the free rotation about the local y-axis ($R_{yy} = 0$ kNm/rad) and constraining the other degrees of freedom ($R_x = R_y = R_z = 10^{10}$ kN/m; $R_{xx} = R_{zz} = 10^{10}$ kNm/rad). The elastic-plastic model of the steel grade S320GD was assumed, see Fig. 10. Two load scenarios were considered namely, concentrated forced applied in the middle of the top flange $P = 3.85$ kN and uniformly distributed loading applied along the top flange $U = 5.05$ kN/m. Both loads were 10 mm in offset from the cross-section web, see Fig. 12 and Fig. 13.

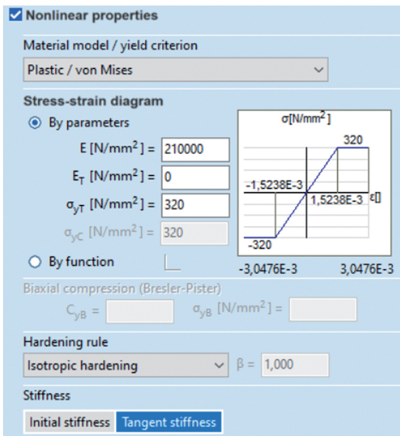


Fig. 10. Definition of the material nonlinearity: elastic-plastic model

The two-stage finite element analysis was performed. In the first stage, the linear buckling analysis was used to find the first local and the first global buckling mode shape. Then based on Eurocode 3 [1] the magnitude of the local and global imperfection was determined. The local imperfection magnitude was established for the wall without ribs i.e. $e_{0,L} = b/100 = 100$ mm$/100 = 1.0$ mm. The global bow imperfection was established as for the lateral-torsional buckling i.e. $e_{0,G} = 0.5 \times L/100 = 0.5 \times 2100$ mm$/100 = 10.5$ mm. In Figure 11 the introduced imperfections into the analytical model are depicted.

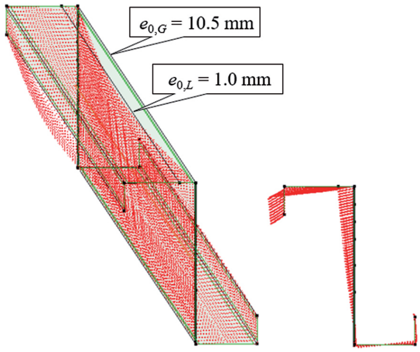


Fig. 11. Local and global imperfections introduced into the analytical model

The global analysis was performed using Geometrically and Materially Non-linear Analysis with Imperfections included (GMNIA). The considered thin-walled beam was meshed using triangular shell finite elements with average mesh elements size of 2 cm. Reducing the mesh size does not cause the results. In Figures 12 and 13 the results of

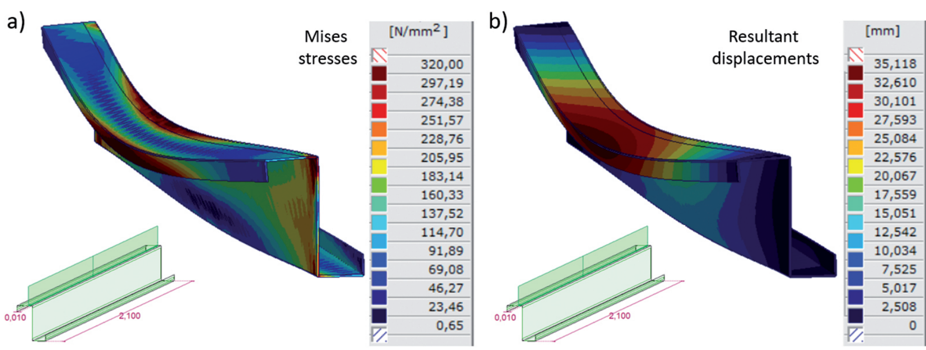


Fig. 12. Thin-walled beam with uniformly distributed load U: U = 50% from 5.05 kN/m = 2.52 kN/m

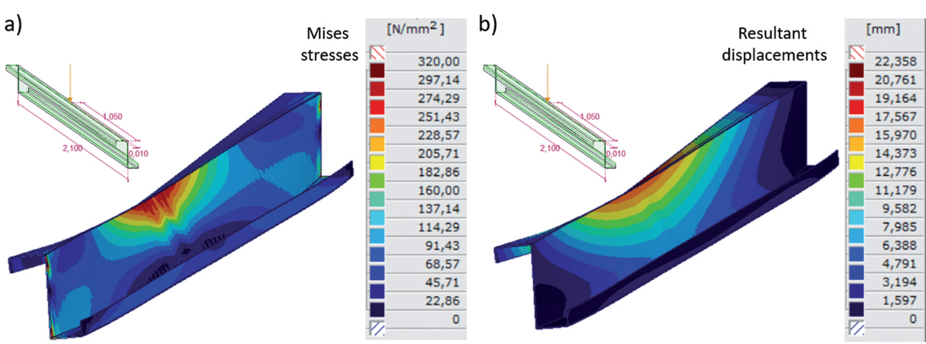


Fig. 13. Thin-walled beam with concentrated load P: P = 60% from 3.85 kN = 2.31 kN

GMNIA analyses are depicted. Due to the lack of convergence of the nonlinear analysis 50% and 60% of the load were applied in the case of the U and P load respectively.

The performed global analysis (GMNIA) depicted that considered thin-walled beam without lateral restraint provided by sandwich panels is characterized by smaller capacity. In the case of the uniformly distributed load, the unstiffened beam can safely transfer only 50% of the load of the thin-walled beam which is laterally supported by the sandwich panel which is attached via four fasteners. In the case of the concentrated force, the unstiffened beam can safely transfer only 60% of the load of the thin-walled beam which is laterally supported by the sandwich panel which is attached via four fasteners. Please note that the resultant force is significantly higher (66%) in the case of the U load arrangement. This is in agreement with the fact that uniformly distributed load is favourable concerning concentrated load from the point of view of the beams in bending.

5. Concluding remarks

In the paper, the laboratory results of the structural system consisting of thin-walled cold-formed beams and sandwich panels are presented. According to [17, 18] it is assumed that the sandwich panels provide stability to thin-walled beams. The laboratory research revealed that the considered structural system is sensitive to the load arrangement. It was obtained that the load which is parallel to the longitudinal axis of the thin-walled beam allows the transfer of at least a twice higher external load than the load perpendicular to the longitudinal axis of the beam. Furthermore, it was depicted that the different failure mechanisms were associated with the investigated load arrangements.

The research also pointed out that the number of fasteners improves the stabilization of the thin-walled beams and therefore increases the overall capacity of the considered structural system for both load arrangements. Furthermore, increasing the number of fasteners leads to more complex failures localized in different areas of the structural system.

The finite element analysis complements the laboratory research. The finite element simulations investigated the kinematical and mechanical response of the thin-walled beam without any lateral or lateral-torsional stabilization. The obtained results when compared with laboratory data reveal that the interaction with the sandwich panel provides almost twice the capacity of the beam.

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Badania doświadczalne płyt warstwowych opartych na belkach cienkościennych dla różnych wariantów obciążenia i liczby łączników

Słowa kluczowe: analiza nieliniowa, badania laboratoryjne, belki cienkościenne, imperfekcje, mechanizmy zniszczenia, płyty warstwowe

Streszczenie:

W pracy przedstawiono wyniki badan eksperymentalnych układów konstrukcyjnych składających się z płyt warstwowych i belek cienkościennych o przekroju Z ułożonych niesymetrycznie względem

siebie. W oparciu o europejskie rekomendacje oraz wcześniejsze badania autorów zakłada się, że w analizowanym układzie belki są stabilizowane bocznie przez płyty warstwowe. Wykonano 11 badań laboratoryjnych, które różniły się między sobą liczbą łączników oraz sposobem przyłożenia obciążenia. W celu połączenia płyt warstwowych z belką cienkościenną użyto 0, 4 lub 8 łączników. Obciążenie przypadające na układ było przyłożone równolegle do belek cienkościennych powodując obciążenie równomiernie rozłożone a prostopadle do belek cienkościennych powodując obciążenie punktowe.

Przeprowadzone badania wykazały znaczącą wrażliwość układu na sposób przyłożenia obciążenia względem analizowanych układów konstrukcyjnych. Wykazano, że obciążenie realizowane jako równoległe do długości belki podpierającej płytę pozwala analizowanemu układowi na przeniesienie ponad dwukrotnie większego obciążenia niż w przypadku obciążenia realizowanego w sposób prostopadły do długości belki. Dodatkowo omówiono w pracy mechanizmy zniszczenia układu w zależności od sposobu jego obciążenia.

Zbadano również wpływ liczby łączników na całkowitą nośność analizowanego układu. Wykazano znaczący wzrost nośności układu przy zwiększającej się liczbie łączników. Zwiększenie liczby łączników łączących belki cienkościenne z płytami warstwowymi wiązało się również z powstaniem złożonym mechanizmami zniszczenia układu.

Uzupełnieniem przeprowadzonych badań eksperymentalnych było wykonanie symulacji numerycznych belek cienkościennych niestężonych poszyciem. Belki zamodelowane zostały jako elementy powłokowe obciążone na dwa sposoby: obciążeniem równomiernie rozłożonym na pasie górnym belki oraz siłą skupioną w środku rozpiętości belki. Otrzymane wyniki oraz mechanizmy zniszczenia porównano z wynikami laboratoryjnymi belki stężonej płytą warstwową. Wykazano, że belka niestężona płytą warstwową wykazuje prawie dwukrotnie niższą nośność niż belka stężona.

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