Stabilization effect on portal frames given by stressed skin action of sandwich panels

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ABSTRACT: Previous research studied the influence of the diaphragm effect on the behaviour of pitched roof portal frames, having Z purlins and corrugated sheeting as cladding. Research results emphasized the stabilizing effect on portal frames by taking into account the lateral constraints ensured by a typical cladding system – Z purlins with one layer of sheeting panels. Further studies are focusing to extend the knowledge on different cladding systems. Present study is dedicated for roofing system with Z purlins and sandwich panels. The purpose of the paper is to simulate in 3D portal frame models with the stabilizing effect given by sandwich panel covering. In the proposed methodology the diaphragm stiffness of the sandwich panels was determined analytically, in order to create an equivalent plate diaphragm, which could be implemented in the 3D structural model. The simulations show clearly the effect of the roof diaphragm on the lateral stiffness increase of the internal frames, which can affect the design of the frame components or the integrity of the cladding system.

1 INTRODUCTION

The popularity of using sandwich panels for exterior cladding is in a constant rise since they serve as a barrier against weathering effects, while also providing the necessary thermal insulation at the same time. Besides the typical technological advantages, such as quick erection time, they can also carry substantial loads through their planar surface (Koschade 2002), which is completely disregarded in the current day-to-day design procedures. By acknowledging the load carrying capabilities in design, the sandwich panels become load-bearing structural components, not just secondary envelope elements. This means that special considerations must be taken in the construction phase as well as the maintenance phase of the structure.

The term stressed skin effect is often used when considering the diaphragm behaviour of the steel sheet cladding, the study of stressed skin design dating back to the early 1950s. Over the years, a multitude of design procedures were developed to quantify the positive effects of the steel sheet cladding, such as calculation procedures published by Davies & Bryan (1982), European Recommendations for the Application of Metal Sheeting acting as a Diaphragm – Stressed Skin Design (ECCS Technical Working Group 7.5 1995) and the Romanian code provisions NP 041 (2001). However, the abovementioned calculation procedures are developed by considering diaphragms built up of only corrugated (trapezoidal) steel sheeting and are not suitable for stressed skin design using sandwich panels.

The stabilizing effect of sandwich panels on single steel structural elements, like beams and columns was extensively studied in relevant literature, but the effect on the global structure as a whole was rarely considered. In the study conducted by Lindner & Gregull (1989) the calculation procedure for the torsional restraint coefficients provided by sandwich panels were presented for beam members. In more recent years, the European research project EASIE (Ensuring Advancement in Sandwich Construction through Innovation and Exploitation), which was carried out between 2008 and 2011, focused among other things on the development of a design model to determine the stabilizing effect of sandwich panels on single structural members, as well as the shear stiffness and load bearing capacity of a single diaphragm (Käpplein & Misiek 2011). Later on, this work was at the basis of the European Recommendations on the Stabilization of Steel Structures by Sandwich Panels (ECCS Technical Working Group TWG 7.9 & CIB Working Commission W056 2014), prepared by the European Joint Committee on Sandwich Constructions. A journal article by Jayasinghe et al. (2004) proposed a design methodology in which 3D structural modelling was combined with the results of an experimental program, according to which the sandwich panels could be modelled by equivalent diagonal members. Among other experimental investigations of the sandwich panel diaphragm rigidity, the studies carried out by Georgescu et al. (2014) and Kunkel & Lange (2015) could be mentioned.

2 METHODOLOGY

2.1 *Procedure*

The aim of the research was to implement the calculated sandwich panel diaphragm stiffness of a single panel in the design of a global structure, in order to observe the stressed skin effect. This way the traditional bracing systems of the structure could be replaced partially or even totally by accounting on the stabilizing effect of the roof cladding in the design phase of a structure.

The stiffness and the corresponding shear angle of the diaphragm composed only of the sandwich panels was determined by using the methodology developed during the EASIE project (Käpplein & Misiek 2011) and also presented in the European Recommendations on the Stabilization of Steel Structures by Sandwich Panels (ECCS Technical Working Group TWG 7.9 & CIB Working Commission W056 2014). Two major assumptions were considered in the calculation procedure, according to which the seam fastenings between the sandwich panels were completely disregarded and the overall stiffness of the diaphragm was governed by the fastenings between the sandwich panels and the substructure (purlins). The analytically determined stiffness values were used to calibrate an equivalent structural model of the diaphragm, using the structural analysis software Consteel. The diaphragm was replaced in the structural model by a plate element, having the same thickness as the considered sandwich panel and the material model of which was adapted by changing the E-modulus in such a way to obtain the same panel edge displacement as the analytically calculated value, running a first order elastic analysis of the model. The plastic material definition was not of importance, since the analysis was carried out in the elastic domain. The calibrated plate was then incorporated into the 3D structural model, taking into account the fastener distribution between sandwich panels and purlins, as well as purlin and beam connections.

2.2 *Procedure validation*

The methodology presented was tested by comparing the panel edge displacement obtained by the presented methodology with the results of the frame experimental testing conducted by Kunkel & Lange (2015).

The considered frame (6m x 6m) for the methodology validation was composed of two HEB260 beams connected by two HEB140 secondary beams. The substructure for the 60 mm thick sandwich panels consisted in SHS40x4 profiles, which were welded to the top flanges of the frame beams. The external face sheet of the sandwich panel had a thickness of 0.4 mm, while the internal sheet thickness was 0.5 mm. The panels were fastened on the short side to the SHS40x4 profiles by using EJOT JT3 D6H 5.5/6.3 screws in every second valley, at a distance of 175 mm from each other (Kunkel & Lange 2015).

The experimental frame was fixed on one side and testing was carried out in a displacement-controlled manner by using a hydraulic jack, similarly to the schematic deformation representation of a sandwich panel diaphragm depicted in Figure 1.

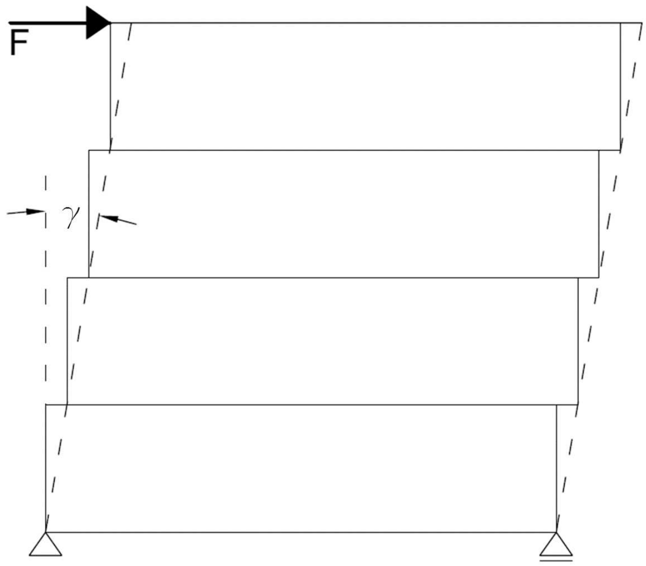

Figure 1. Schematic deformation representation of a sandwich panel diaphragm.

In the first step the stiffness and shear strain of the sandwich panel diaphragm was calculated analytically, then a similarly configured 60 mm thick plate was defined using the structural analysis software Consteel. By defining the plate material E-modulus equal to 12.235 N/mm^2, Poisson factor as 0.3 and defining a finite element size of 100 mm, the obtained deformations at the load application point agreed with the calculated values, as presented in Table 1.

Table 1. Diaphragm displacement comparison.

Applied force	Analytical value	Consteel value
kN	mm	mm
1	4.377	4.378
5	21.886	21.890
10	43.773	43.780
15	65.660	65.670

The second step consisted in determining a similarly configured frame structure as the one used in the Kunkel & Lange (2015) experiment and applying the equivalent plate diaphragm to the frame model, through link elements placed at the position of each screw, in order to account for the vertical eccentricity. The results showed, that the analytical diaphragm stiffness calculation combined with the program assisted structural analysis is a linear approximation, which provides a good estimation of the experimental results in the linear-elastic domain (Fig. 2).

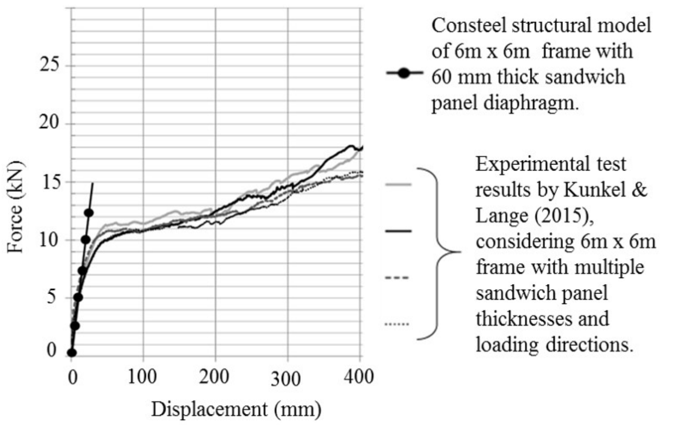

Figure 2. Comparison between the results of the Consteel frame model and the experimental results obtained by Kunkel & Lange (2015).

3 CASE STUDY

3.1 *Structural configuration*

Three structural configurations were considered from a structural analysis point of view in order to observe the stressed skin effect, one without any roof bracings or sandwich panels (Fig. 3), one with only flexible roof bracings (Fig. 4) and one with only equivalent plate diaphragm, representing the sandwich panel cladding (Fig. 5). The sandwich panels were assumed to be fastened to the substructure by EJOT JT3 D6H 5.5/6.3 screws (Fig. 6). The dimensions of the considered structural members were as follows:

- Columns: 2xC250/3
- Beams: 2xC250/3
- Eave rafters: SHS80x4
- Ridge rafters: SHS100x4
- Wall bracings: Ø30
- Roof bracings: Ø20
- Purlins: Z200x66x74/2
- Sandwich panel: TeraSteel IsoAc5 – 60 mm

The structure had a span of 6 m and three bays of 3 m each, reaching a total length of 9 m. The height was considered as 2.6 m at the eave and approximately 3 m at the ridge. In all cases the column ends were considered as hinged.

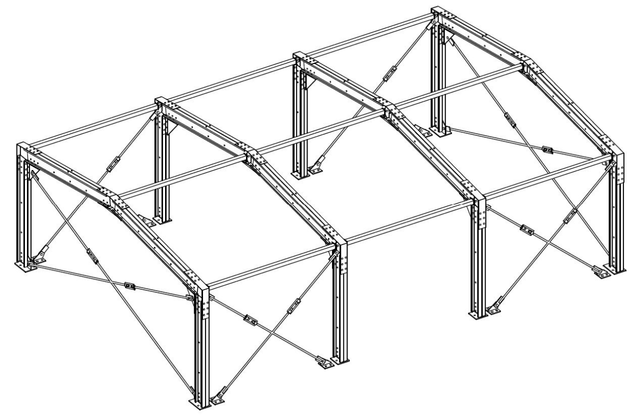

Figure 3. Plain structure: Structure without roof bracings, purlins and sandwich panel cladding.

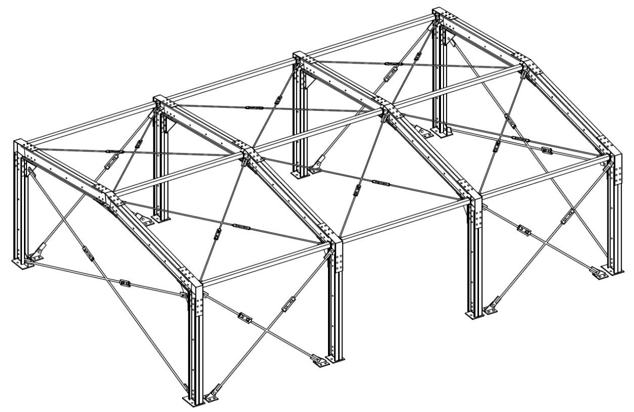

Figure 4. Braced structure: Structure with roof bracings and without purlins and sandwich panel cladding.

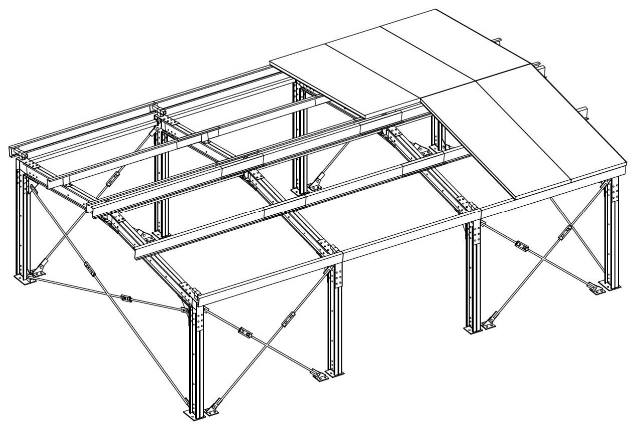

Figure 5. Cladded structure: Structure with purlins, sandwich panel cladding and without roof bracings.

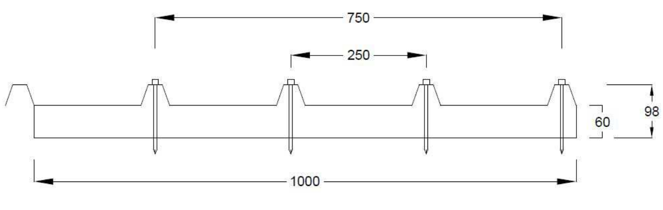

Figure 6. Schematic configuration of TeraSteel IsoAc5 sandwich panel and screw positions.

The essential details for the ridge, respectively for the eave nodes are presented in Figures 7-8. During the analysis phase, two cases were considered, one when the nodes were assumed to be completely rigid and a second case, when the nodes were considered as semi-rigid. In the case of the semi-rigid joints, the stiffness values of the joints were introduced in the Consteel model, as determined for the similar type of joints by Fodor (2014):

- Ridge joint rigidity: 2948 kNm/rad
- Eave joint rigidity: 2062 kNm/rad

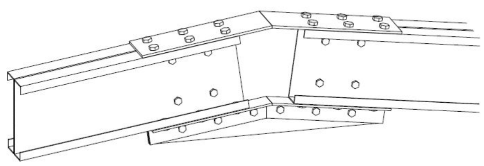

Figure 7. Ridge joint detail.

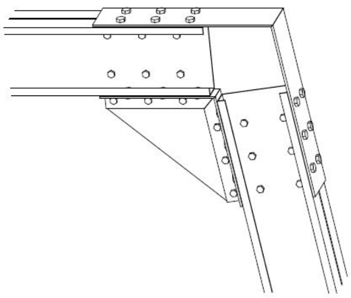

Figure 8. Eave joint detail.

3.2 *Purlin connection calibration*

The purlin to beam connections were calibrated in order to account for the connection flexibility. The Z profile purlins at the eaves and at the ridge were fixed with the help of a UPN65 profile (Fig. 9a), while the middle purlin was connected by an L200x100x5 profile (Fig.9b), which proved to be more flexible than the UPN65 connection.

The calibration was performed in three steps:

Step 1: Develop shell models in Consteel of the two connection types (Fig. 10).

Step 2: Application of a unitary load on the upper flange of the purlin, in order to account for the connection flexibility and the Z profile distortion.

Step 3: Defining an equivalent purlin connector, using bar element, which would produce the same deformation for a unitary load as the model from Step 2 (Fig. 11). The Z purlin remained modelled as shell element and the length of the equivalent connector was considered as the distance from the beam axis to the last screw, in order to include the vertical eccentricity. The line on the Z purlin web, where the connector element was placed was defined as a rigid body.

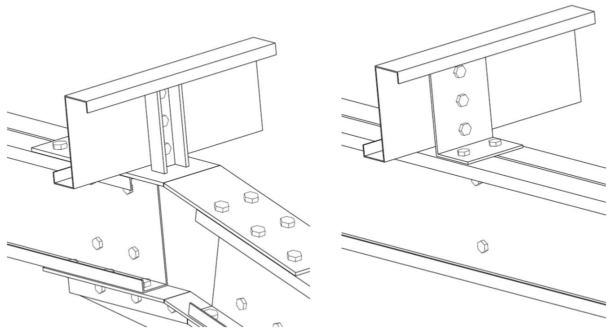

Figure 9. Purlin connection detail a) at ridge and eave with a UPN65 profile b) with an L200x100x5 profile.

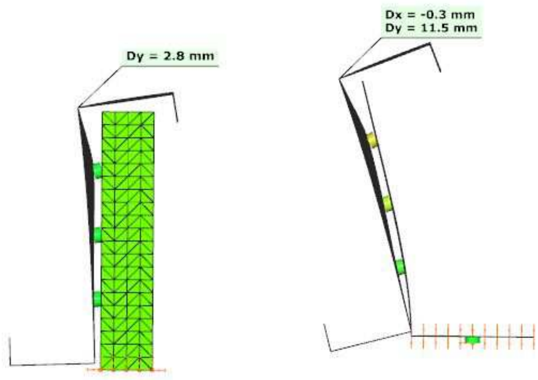

Figure 10. Purlin connection shell models, subjected to a unit load on upper flange of Z purlin.

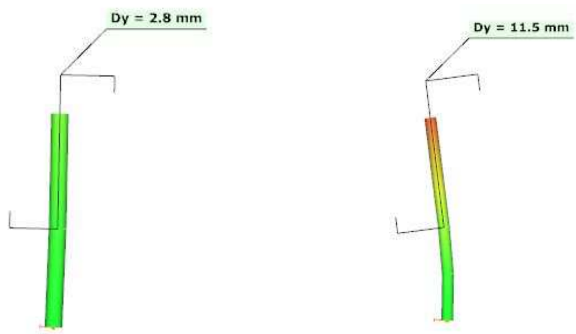

Figure 11. Equivalent purlin connection models, subjected to a unit load on upper flange of Z purlin.

3.3 *Structural model and results*

The diaphragm panels were calibrated in a similar manner as for the experimental validation phase. Two 3m x 9m diaphragms were considered, which were divided by the ridge. The displacement produced by a unit load for the sandwich panel diaphragm according to the analytical evaluation was 4.431 mm, displacement which was also obtained in the Consteel model of a 60 mm thick equivalent plate, having the same dimensions as the diaphragm. The displacement of the equivalent plate was calibrated by defining the material E-modulus as 134.5 N/mm2 and finite element size of 100 mm. The calibrated plate was then incorporated into the 3D structural models, by connecting it to the purlin upper flange, via link elements disposed at the position of each screw (Fig. 12).

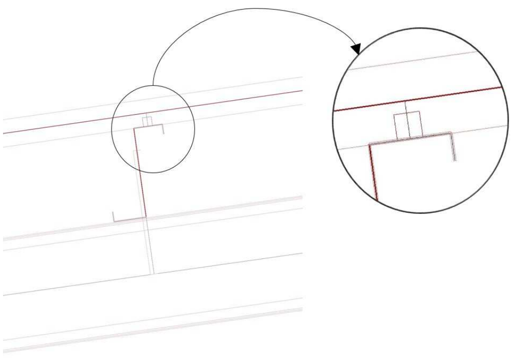

Figure 12. Connection of the equivalent plate to the purlin upper flange, via link elements.

Considering the 3D structural models, the Z purlins were modelled as shell elements, while everything else was modelled as bar element. The self-weight of the purlins and sandwich panels were included in the analysis. The capacity of the plain structure with rigid joints was reached by loading the intermediate frames with point loads of 40 kN, as shown in Figure 13. Thus, this loading was applied for each analysed structure. The structural displacement at the point of load application and the axial force in the end frame wall bracings were checked and recorded.

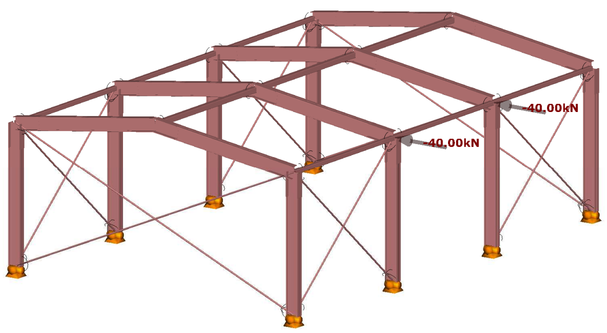

Figure 13. Consteel model of plain structure, showing the applied load of 40 kN on the two intermediate frames.

3.3.1 *Rigid joints*

The displacement and the axial force in the end frame wall bracings in tension for the three considered structural configuration types and rigid beam to beam and beam to column connections are presented in Table 2, while the displacement in the direction of the loading for the cladded structure can be seen in Figure 14.

The maximum utilization percentage for the plain structure was evaluated to 98.4 % at the intermediate frame beam, which reduced to 26.1 % after adding the equivalent plate and to 22.1 % in the case of the braced structure.

Table 2. Structural model displacements and axial forces in wall bracing in the case of rigid joints.

Structure type	Displacements	Axial force in bracing
	mm	kN
Plain structure	33.6	11.1
Braced structure	5.0	37.1
Cladded structure	9.3	32.9

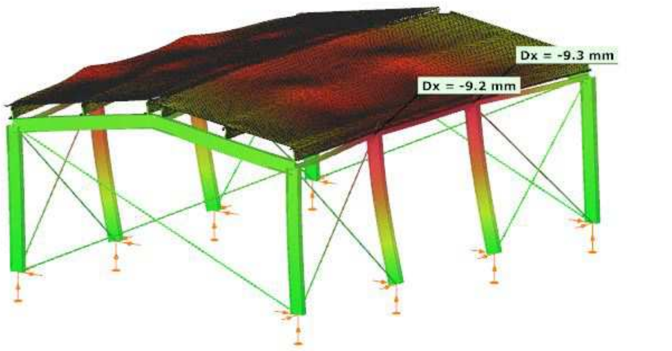

Figure 14. Magnified displacement results of cladded structure from Consteel.

3.3.2 *Semi-rigid joints*

The displacement and the axial force in the wall bracings in tension in the case of semi-rigid joints are presented in Table 3. The axial force in the end frame wall bracing for the cladded structure can be seen in Figure 15.

Table 3. Structural model displacements and axial forces in wall bracing in the case of semi-rigid joints.

Structure type	Displacements	Axial force in bracing
	mm	kN
Plain structure	66.0	22.3
Braced structure	5.9	41.1
Cladded structure	11.3	39.3

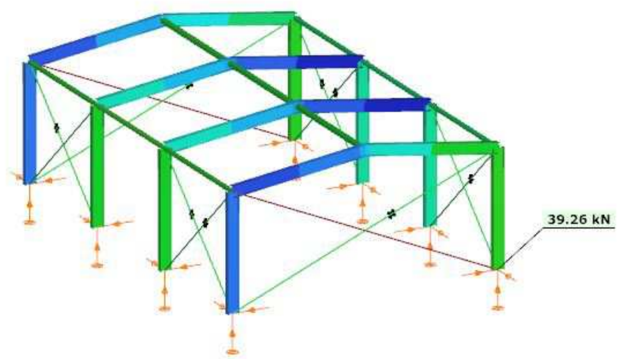

Figure 15. Consteel axial force in end frame wall bracing for the cladded structure.

By including the connection stiffnesses of the main joints a more realistic structural model is obtained, having larger deformations and lower member utilization percentages. The maximum utilization percentage for the plain structure was of 83 %, which was lowered to 24.1 % by adding roof bracings and to 17.7 % by considering the sandwich panel roof cladding.

4 DISCUSSION AND CONCLUSIONS

The presented methodology showed good correlation with the experimental results of Kunkel & Lange (2015), which means that the methodology could be used as an approximative and relatively fast procedure, running linear elastic analysis in order to include the stressed skin effect of the sandwich panels in the currently used structural design procedure, combining analytical calculations with the capabilities of a structural analysis software. However, it should be noted, that the sandwich panels can provide the evaluated stressed skin effect, only while they are in elastic stage, this effect disappearing once the connections between the panels and the substructure fails. Also, if the stressed skin effect is considered in the design phase, then the sandwich panels should be regarded as main structural elements, while also maintaining their original purpose. This would mean, that no structural modifications should be performed on the sandwich panels, that could weaken the diaphragm effect after the erection of the structure, such as additional openings, and that the connections to the substructure should be periodically checked and maintained.

Having frames with rigid or semi-rigid joints and braces placed in the gable end, it is clear that the plain structure will interact with the sandwich panel cladding, giving a similar effect as the roof bracings, reducing the displacements and distributing the loads to the stiffer members, in the current case to the braced end frames, which can be observed by the increase of axial force in the bracings. This effect will exist until the roof diaphragm capacity is reached, then the 3D structure will start to perform as the plain structure, due to the cladding damages. As can be observed from the analysis, there is a very important difference between the two stages. The load carrying capacity of the roof diaphragm can be controlled by increasing the number of fasteners between the sandwich panels and the purlins, using sandwich panels with thicker face sheets and thicker purlins, or by combining the cladding system with an adequate roof bracing system. If the horizontal displacement limit is not met due to joint flexibility, this could be also improved with stressed skin action or roof bracings. Combining roof braces with the stressed skin, the effect of the sandwich panels will be reduced, creating a structural redundancy, increasing the cost of the structure, while the sandwich roof playing only the cladding role. Neglecting the stressed skin effect and including the connection stiffnesses into the model, roof braces will be compulsory. Inadequate stiffness of the bracing system will make the sandwich panel cladding to have great influence on the lateral displacements, but with damage possibilities of the cladding system.

Due to the assumptions of the analytical calculation procedure the stiffness of the sandwich panel diaphragm is highly dependent on the type and number of used screws, as well as the sandwich panel face thickness, yielding an approximate stiffness value, which could be improved. Since the seam fasteners were disregarded in the analytical evaluation, further research should be carried out in order to observe their influence on the diaphragm stiffness and develop a more refined calculation procedure.

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