Shear Failure of Sandwich Panels Subjected in Bending

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Abstract. The paper describes the behaviour of the sandwich panels in bending. Two panels of the same dimensions are tested. The panels differ only in the layout of the inner thermal insulation layer. The thermal insulation layer is made of separate mineral wool slabs. The graphs of the strain development in the external sheets, the displacement between the layers and mid-span displacement are presented in the paper. The nature of the failure shows that only separate internal thermal insulation slabs resist the shear force. Therefore, the complete width resistance cannot be evaluated. The views of the failure are also presented.

1. Introduction

Light-weight sandwich panels are important structural elements. These panels serve as the wall or roof structures, providing the desired thermal insulation. The construction is fast and there is no need for a finishing layer while the cross section of the major structural elements is reduced. The loading and its action on these panels depend on their design purpose. If the board is used for making the external walls, the main load and its effect are associated with the wind and the temperature difference. If the board is used in the roof, the main loads include the mounting load, the wind and snow loads and the effect of the temperature difference. Such actions as lifting, transporting and installation must also be considered. Various limit states of sandwich panels made of a soft internal layer and thin external layers are possible. The European standard EN 14509:2013 [1] specifies the critical cases for sandwich panels. The thin external steel sheets can buckle during bending. Moreover, wrinkling of the compressed external steel layer can be observed. It is also possible that steel yield can occur. The internal thermal insulation layer must be checked for local compression (at the point of loading and supporting), as well as for shear force resistance. The most common failure of the continuous sandwich panels is associated with the core shear, crushing failure or buckling failure of the external sheet [2]. In the experimental research of Herranen [3], all the tested sandwich panels failed due to shear. The core of the sandwich panels in the research of Herranen [3] was made of polyvinyl-chloride foam. In the work of Gnip [4], the compressive, tensile and shear tests of mineral wool were performed. The mean square deviations of the modulus of elasticity or shear modulus predicted by Gnip [4] could reach 100 % and more. This shows that the dispersion of these mechanical properties is very high and may decrease the reliability of the considered structures.

The calculation of these panels allowed for determining that their inner layer was solid and the mechanical properties were the same across the width. The stresses in each layer were calculated
according to the principle of superposition [5]. In the design process, it is common to evaluate the whole width of the panel. For example, the resistance for shear is calculated for the whole width. In the manufacture of sandwich panels, the inner thermal insulation layer can be made of separate thermal insulation slabs. If the inner layer is solid, it can resist the shear force over the whole width of the panel. If the inner layer is made of separate thermal insulation slabs, the attached edges of separate slabs do not resist the shear force. These local zero-stiffness zones reduce the load-bearing capacity of the panel and increase their deflection. Sandwich panels are produced as a continuous product, which is then cut into separate panels of the required length. The arrangement of the slabs of the thermal insulation layer is random. Figure 1 presents the random layout of the slabs of the thermal insulation, where the slabs are laid out with an overlap. When cutting the panels, the inner layer with zero-stiffness accidentally falls into the range of the critical load distribution locations. Therefore, the purpose of this research is to determine the impact of the considered random layout of thermal insulation on the load-bearing capacity of the panels.

2. Samples and testing
The tested panels were manufactured at the factory. The panels were manufactured by using a continuous method. The outer steel sheets were rolled out of the rolls and integrated into the plate’s production line. The gap between the upper and the lower sheets was filled with thermal insulation slabs. The width of the internal thermal insulation mineral wool slabs ranged from 230 mm to 245 mm for panel P1 and from 226 mm to 250 mm for panel P2, respectively. Figure 2 presents the case of the thermal insulation slabs in the production line. Only the top and the bottom surfaces of thermal insulation slabs were glued to steel sheets. Steel sheets and thermal insulation slabs were glued with polyurethane adhesive. The widths of the produced sandwich panels P1 and P2 were 1205 mm and 1196 mm, respectively. The lengths of the cut-off plates were 3400 mm. The distance between the outer steel sheets was 95 mm. The thickness of the outer steel sheets of the sandwich panels was 0.5 mm. Figure 3 presents the internal view of the sandwich panel, presenting the external steel sheets, the internal thermal insulation layer made of separate mineral wool slabs and polyurethane adhesive on the bottom steel sheet and the top surface of thermal insulation.

![Figure 1](image1.png)

**Figure 1.** The random layout of thermal insulation slabs during the production process of sandwich panels.

![Figure 2](image2.png)

**Figure 2.** The formation of the internal thermal insulation layer in the production line.
Figure 3. The internal thermal insulation layer between the external steel sheets. The four-point bending test was performed to test the panel. The arrangement of measuring devices is presented in Figure 4. The test was performed in two different ways. Panel P1 was loaded based on using the load control method, while panel P2 was loaded by applying the displacement control approach. The maximal vertical displacement should not exceed 10% of the panel thickness per minute. Therefore, the first panel was loaded based on using the load control method. The obtained results demonstrated that the plate deflection increment was higher. Therefore, the displacement control method was chosen for the second plate. Because of the high loading capacity of the testing machine (1000 kN) and the low panel stiffness, the displacement control method had not been chosen from the beginning of the test. The load for all panels was transferred by 100 mm-wide wooden supports.

Figure 4. The schematic view of the tested sandwich panel and the arrangement of measuring devices. Vertical displacement of the panel was measured by the displacement transducer D1. The displacement between the layers was measured by using the devices D2 and D3. The devices were fixed on the top steel layer and the supporting plate was attached to the lower sheet. The strains in the tensioned external steel layer were measured with the tensometers T1; T2 and T3. The strains in the compressed external steel layer were measured with the tensometers T4; T5; T6.

3. The results
The performed experiment has shown that the loading manner influenced the results. Firstly, the maximal load-carrying capacity of the sandwich panel P1 was 4.0 kN·m, while that of the panel P2 was 3.33 kN·m. As mentioned above, the panel P1 was tested by using the load control method and test duration was 8 minutes. However, the panel P2 was tested by using the displacement control test, the duration of which was 28 minutes. For the panel P1, the maximal stresses in the top and the bottom steel sheets at the maximal load were \( \sigma_{\text{s.top}} = \frac{\sigma_{\text{c}} E_s}{205 \cdot 10^9} = -54.8 \text{ MPa} \) and \( \sigma_{\text{s.bot}} = \frac{\sigma_{\text{c}} E_s}{205 \cdot 10^9} = 55.8 \text{ MPa} \), respectively. For the panel P2, the maximal stresses in the top and the bottom steel sheets at the maximal load were \( \sigma_{\text{s.top}} = \frac{\sigma_{\text{c}} E_s}{205 \cdot 10^9} = -54.9 \text{ MPa} \) and \( \sigma_{\text{s.bot}} = \frac{\sigma_{\text{c}} E_s}{205 \cdot 10^9} = 50 \text{ MPa} \), respectively. Meanwhile, the same stresses were found in panel P1 at the maximal load level of panel P2: \( \sigma_{\text{s.top}} = \frac{\sigma_{\text{c}} E_s}{205 \cdot 10^9} = -45.2 \text{ MPa} \) and \( \sigma_{\text{s.bot}} = \frac{\sigma_{\text{c}} E_s}{205 \cdot 10^9} = 45.7 \text{ MPa} \), respectively. The compression and tensile stresses in the panel P1 were by 18 % and 9 % lower than those in the panel P2. The deflection of the panel P1 at the same load level was by 10 % lower.
The measured strains in the top and the bottom sheets are presented in Figure 5. The development of the strain until failure had shown that the external steel sheets’ work was elastic. The comparison of the normal stresses in the panel P1 had shown that they were similar. Thus, the neutral axis is located at the centre of the cross section height. The comparison of the panel P2 stresses had shown that the compressive stresses were larger than the tensile stresses. In this panel, the neutral axis was moved away from the centre.

Figure 5. The strains in the tensioned and compressed external steel layer; (a) denotes the strains in panel P1; (b) shows the strains in panel P2.

The observed difference in the stresses and the location of the neutral axis can be accounted for by the elasto-plastic strain development in the internal thermal insulation layer and the displacement of the external layer. In fact, the plasticity of the inner thermal insulation layer resulted in the considered stress distribution. The longer loading time led to the development of plastic strains. Therefore, in the panel P2, premature displacement between the external layers could be observed. Figure 6 presents the development of the displacement between the external layers. In the panel P1, a considerable displacement was recorded when the limit load was reached.

Figure 6. The displacement between the external steel layers; (a) shows the displacement in panel P1; (b) demonstrates the displacement in panel P2.

The increment of the mid-span displacement characterizes its linear nature until the failure. Then, the panel was loaded according to the load control method. It can also be mentioned that the displacement between the external layers was zero. Theoretical deflection of sandwich panels consists of two parts: the deflection caused by loading and the deflection produced by shear. The displacement between the external layers in panel P2 and the deflection at the higher load level developed following the parabolic trajectory. Mid-span displacements of the panels P1 and P2 are presented in Figure 7.
After the experiment was accomplished, a part of the external sheet was hand-peeled at the place of failure. In this way, the internal thermal insulation layout structure was uncovered. The uncovered area and the layout structure are presented in Figures 8 and 9 (the cross-marked trajectory denotes the non-bonded edges). It was found that the failure trajectory of the internal layer matched that of the vertical non-glued edges of the internal thermal insulation slabs. In both cases, the failure trajectory chose the way where there were three (the maximal number for the tested panels) non-glued transverse edges. There is no connection between the thermal insulating slabs at the edges, which can intercept vertical internal shear stresses. The friction between the edges is not a good criterion for assessing resistance. Three stripes of thermal insulation resist a shear force in the case of two transverse edges. Two stripes of thermal insulation resist a shear force in the case of three transverse edges. The resistance of two stripes is lower than that of three stripes and the failure trajectory chose the way where there were three non-glued transverse edges. Figures 10 and 11 present the failure and the trajectory of failure in the uncovered area.

Figure 7. Mid-span displacements of the considered sandwich panels.

Figure 8. The uncovered top steel sheet layer and the structural layout of the internal thermal insulation, the trajectory of failure, P1.
Figure 9. The uncovered top steel sheet layer and the structural layout of the internal thermal insulation, the trajectory of failure, P2.

Figure 10. The failure of the sandwich panel near the support, P1.

Figure 11. The displacement of the internal thermal insulation layer, P1.
4. Conclusion
The panel loaded according to the load control method demonstrated higher stiffness and load-carrying capacity. The panel loaded based on using the displacement control method had shown lower stiffness and lower load-carrying capacity. The longer testing time influenced the development of plastic deformations and the neutral axis moved away from the centre of the cross section, therefore, the compressive stresses in the panel P2 were 1.2 times higher than the compressive stresses in the panel P1 at the same load level.
Non-glued edges of the thermal insulation slabs influenced the decrease in the load-bearing capacity. All the tested panels failed in the region of the shear load action. After peeling the steel sheets, it was found that their resistance depended on the separate (not glued at the edges) thermal insulation insert. During their production, the inner edges must be glued. Then, a single inner layer will be formed.

References
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