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Investigating the impact of thermal stresses on blistering effects in sandwich panels

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Abstract

Lightweight steel constructions made of sandwich panels are an economical solution for wall and roof claddings, especially in industrial construction. The panels consist of two thin sheets of steel and a core with thermal insulating properties. In the mounted state and at high temperatures on the outer face of the panel, damage to the components may occur due to blister formation. In a current research project, the influence of defects in sandwich panels with a PIR-foam core is examined. This article presents the results of experimental tests regarding the influence of various parameters, such as face temperature, production defects and design of the longitudinal joint on blistering in sandwich wall panels with a PIR-core. The aim is to identify the necessary conditions for the occurrence of blisters. Using an optical strain measuring method (Digital Image Correlation), the temperature-induced deformations and strains in the covering nose of sandwich wall panels with hidden fastening are measured and will be analyzed with regard to blistering. First results reveal a significant dependence on the geometry and design of the covering nose.

Keywords

Lightweight steel constructions, sandwich panels, PIR-foam core, hidden fastening, blistering

1 Introduction

In the last decades, lightweight steel constructions made of sandwich panels have been established as an important branch of structural engineering, especially in industrial construction. Due to the low construction weight combined with a high load-bearing capacity, the positive structural-physical properties as well as the high rate of prefabrication, sandwich panels are an economical solution for wall and roof claddings. The panels consist of two thin sheets of steel and a core with thermal insulating properties. For several years now, polyisocyanurates (PIR) have increasingly been used as the core material instead of polyurethane (PUR) [1], whereas both materials are foamed between the face sheets.

However, when exposed to high temperatures on the outer face of the panel, the PIR-containing components may be damaged by blister formation in the mounted state. This describes an outward warping of the face sheet (Figure 1), which is accompanied by delamination between the core and the face. In addition to impairing the appearance of the façade, this may lead to a reduction in the load-bearing capacity. However, as a result, there might be claims against the manufacturers of the panels. Since the implementation of PIR, the occurrence of blisters has been increasingly noted in practice [1].

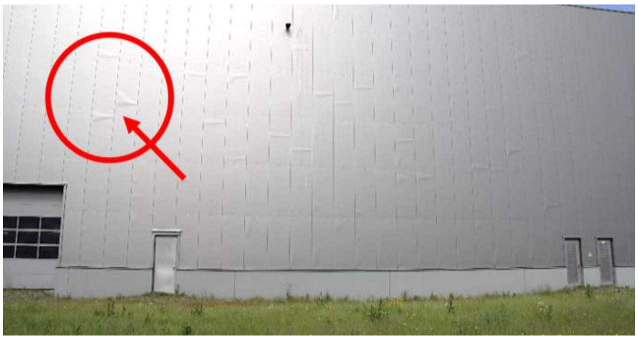

Figure 1 Blisters of different sizes on the outside of the façade.

The analysis of several internal expert reports with cases of damage caused by blisters in practice has shown this problem being an issue for all manufacturers and may occur in both wall and roof panels. Furthermore, the formation of blisters is observed for all common panel thicknesses, profiling types and thicknesses, as well as colors of the face sheets, and seems not to be influenced by the static system. The blisters can be of different sizes, from the size of a palm to half of the panel width (Figure 1). As a special case, in wall panels with hidden fastening, the blisters occur predominantly at the longitudinal joint on the covering nose [1]. Nevertheless, receding blisters were also observed in practice with changing

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environmental conditions (e.g. cooling).

Several aspects of blistering in sandwich panels have already been investigated in previous research (Section 2.1). However, there exist neither holistic considerations nor adequate approaches to solve the problem. This results in a great potential for further and more profound investigations.

In this study, preliminary experimental investigations are carried out to gain fundamental knowledge about the phenomenon of blister formation in sandwich wall panels. The research focuses on the influence of various parameters, such as face temperature and production defects as well as material characteristics of the foam core. The aim is to identify the necessary conditions for the occurrence of blisters and to describe their effects on the load-bearing capacity of the panels. This research will promote an efficiency-optimized production of sandwich panels, as the number of claims and the associated reproduction can be reduced, decreasing the long-term costs and consumption of resources in the production.

2 Blistering in sandwich panels

2.1 State of the art and research

The problem of blistering in sandwich panels with a foam-forming core layer (like PUR/PIR) used in civil engineering is known and has been described relatively frequent in the literature [1-7]. However, in most cases, there are mainly observations and conclusions on the formation of blisters and rarely a quantitative and holistic view of the problem. Regardless of the type of panel, Davies [2] identifies the rapidly increasing internal cell pressure in the core material as the cause for the occurrence of blisters, which is triggered by a rapid increase in temperature. The high internal cell pressure results in the gases inside the core migrating to weak spots or imperfections in the sandwich panel. This might be, for example, a defective cell structure or voids in the core. The formation of a blister may occur when the core first delaminates locally from the face sheet. This can happen if the shear or tensile stresses in the joint between the face and the core become too high or if there is a production-related defect (adhesion imperfection) from the outset. In [3] it is also postulated that the gas pressure alone is not sufficient to form a blister at face temperatures of up to 80°C.

These observations refer to sandwich panels with a PUR-core. It is not clear whether this applies to PIR foam systems as well. Nevertheless, this observation points to the importance of production defects in the investigation of the blistering problem, as in practice blisters can also be seen at lower face temperatures. Adhesive imperfections can be related to faulty production conditions whilst not being visible on the outside of the panels [4].

A numerical, thermal-mechanical study to examine blistering in sandwich wall panels with hidden fastening is carried out in [1]. There, the main cause for blister formation is identified as the deflection of the covering nose and the associated stresses due to the one-sided heating of the face.

Requirements for self-supporting metal faced sandwich panels are regulated in EN 14509 [5]. In addition to procedures for testing the mechanical properties, the standard also contains requirements for the durability of the panels. The problem of blistering is limited here to the durability of the panels, as only the external appearance is visually controlled. Annex B.7 describes the thermal shock test, a testing method for observing the formation of blisters in sandwich panels. In this test, several panels of full and half width are mounted on a steel frame as a two-span beam. The outer face of the panel is then heated in 10°C increments in several cycles up to a maximum temperature difference between the inner and outer face of 60°C, whereas the inner face of the panel is kept at a constant temperature of 20°C. After each temperature cycle, the panels are abruptly cooled by spraying them with cold water. Afterwards, it is documented whether visible damage, such as blistering, wrinkling, or delamination, has occurred.

Chapter 5.2.12 of the European recommendations for sandwich panels [6], describes another test method in the context of quality assurance. In this case a visual inspection also takes place after the panels have been heated to a defined temperature. In this so-called “blistering test” the outer face of a sandwich panel with a minimum length of 1 m and the full panel width is heated to a uniform temperature of 85°C. The temperature has to be maintained for two hours.

In both tests the focus is exclusively on temperature effects and only the durability is considered. On the effects of blistering on the load-bearing capacity of the panels, only a few investigations have been carried out in the past. A first attempt to evaluate the influence of imperfections on the wrinkling stress by experimental and numerical investigations can be found in Wolters et al. [7]. Here, the effects of adhesive imperfections and voids in the core are investigated. The test showed that both types of imperfections lead to a decrease in the wrinkling stress of the panels. For adhesive imperfections there was also a difference between longitudinal and transverse imperfections. Nevertheless, the results obtained did not lead to any exploitable conclusions for the structural design or production of sandwich panels.

2.2 Evaluation of survey reports

In order to provide a foundation for further investigations, the problem of blistering is first analyzed from a building practice perspective. For this purpose, a total of 79 confidential expert reports on cases of damage with blisters or delamination in sandwich wall and roof panels with a PU-foam core were evaluated. These expert reports, which were prepared between the years 2006 and 2021, deal with sandwich panels in the thickness range between 30 and 200 mm, produced by 11 different manufacturers. This analysis aims to gain knowledge about the occurrence of blisters in practice. It is of interest when and at which position the blisters occur and of which size they are. An additional focus is set on the reason for the occurrence of blisters according to the expert opinion.

2.2.1 Cause of blistering

Due to the complexity of the problem, the actual cause of the blistering cannot be conclusively clarified within the scope of the expert reports. Instead, the procedure corresponds to a principle of exclusion, in which any design or construction error is individually checked and excluded. In the following, based on the expert opinions, it is shown for sandwich wall panels in how many cases a correlation between the formation of blisters and a design or execution error exists. A distinction is made between wall panels with visible and hidden fastening. A clear trend can be noted for wall panels with hidden fastening (Figure 2).

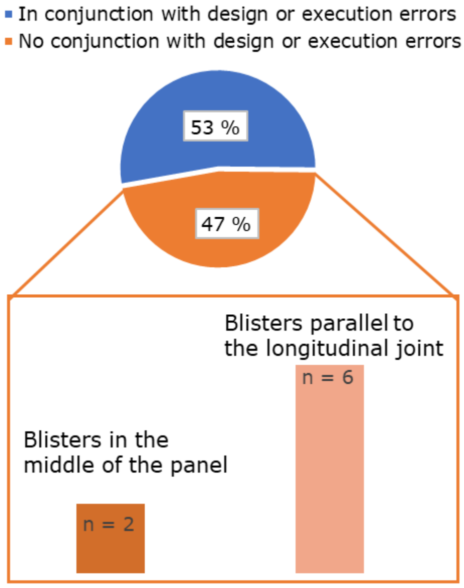


Figure 2 Position of the blisters for sandwich wall panels with hidden fastening.

Here, the percentage of blister defects related to design or execution errors is approximately equal to the percentage without a corresponding relationship. Following, only those blister cases are considered in which no design or execution errors were detected. Here, the blisters were found to occur mainly parallel to the longitudinal joint.

2.2.2 Temporal aspects of blistering

In this category, the period between the installation and the documented occurrence of the blisters is analyzed. Thus, it is considered when the blisters were spotted on the building. Therefore, it is possible that the blisters already existed undetected. It should be noted that blisters are often discovered less frequent in roof panels compared to wall panels. It was found that most blisters (62%) were detected within the first 12 months after installation and assembly of the panel. In 10% of the cases no information is available and in only 28% of the cases the blisters are detected more than a year after installation. Considering the time at which the survey report was prepared, it should be mentioned that most expert reports were prepared after 2017.

2.2.3 Size and position of blisters

For further investigations, it is of particular relevance at which positions the blisters occur within the sandwich panel and how large they usually are. In 89% of the expert reports, the blisters occurred exclusively on the outside of the panel. For wall panels, the position of the blisters can be divided into two categories, either in the center of the panel or parallel to the longitudinal joints. The latter applies in particular to wall panels with hidden fastening. The blisters vary in size, from the size of a palm to half the width of the panel.

3 Experimental investigations

3.1 Tests on the influence of the longitudinal joint under high face sheet temperatures

3.1.1 Experimental program

From the expert reports it emerged that in sandwich wall panels with hidden fastening most blisters form parallel to the longitudinal joints. This issue was initially investigated from a mechanical point of view. For this purpose, two panels with hidden fastening and half panel width were firmly braced together with the help of tensioning belts to interlock tongue and groove (Figure 3). The test specimens had a length of 1000 mm and a PIR core with a density of approx. 37 kg/m³. The profiling and nominal face thicknesses of the investigated panels as well as the total panel thicknesses are shown in Table 1. The design of the covering nose was different in both test specimens. In one specimen, it was fully foamed, in the other specimen, the tip of the covering nose was free, and a sealing tape was inserted.

Table 1 Properties of the tested panels.

no.	Product properties
1	Outer face: steel, t_N = 0.75 mm, lined Inner face: steel, t_N = 0.40 mm, lined Depth: D = 150 mm Covering nose <u>is fully</u> foamed out
2	Outer face: steel, t_N = 0.63 mm, microlined Inner face: steel, t_N =0.50 mm lined Depth: D = 160 mm Covering nose <u>is not fully</u> foamed out

The outer face of the panels was heated to a temperature of approx. 80°C using textile heating blankets. The temperature was continuously measured and recorded by magnetic temperature sensors. The temperature-induced deflections and strains in the core at the cover nose were measured and evaluated using optical strain measurement (Digital Image Correlation, DIC). In addition, it was visually checked whether blistering occurs parallel to the longitudinal joint.

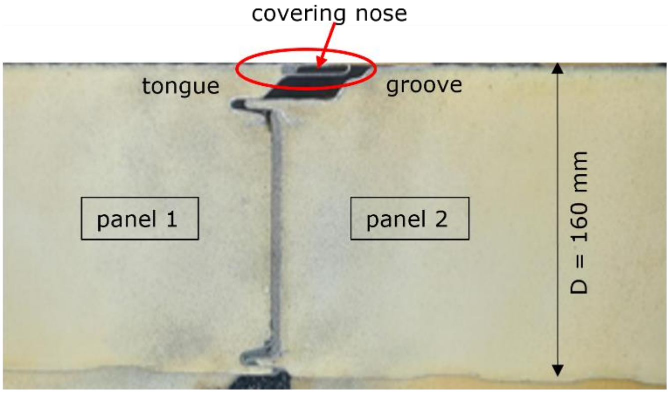
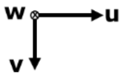


Figure 3 Tests on the influence of the longitudinal joint under high face temperatures – arrangement of the panels of specimens no. 2.

3.1.2 Results

The unilateral heating of the outer face results in deformations of the sandwich panel. The deformations in the sandwich core in the area of the cover nose were recorded during the entire test period. Table 2 shows the measured deformations shortly before the termination of the respective test. The measured face temperature at this stage was approx. 76°C for specimen no. 1 and approx. 84°C for specimen no. 2. Horizontal (*u*) and vertical (*v*) deformations as well as out-of-plane deformations (*w*) were measured for all panels. However, the measured maximum values are in a low range.

Table 2 Maximum values of the measured deformations at the maximal face temperature.

	Specimen no. 1	Specimen no. 2
Max. Deformation *u* in mm	0.13 mm	0.33 mm
Max. Deformation *v* in mm	0.32 mm	0.10 mm
Max. Deformation *w* in mm	0.37 mm	0.51 mm

Comparison and evaluation of the occurring deformations reveal quantitative differences between the test specimens. When the joint is not fully foamed out (specimen no. 2), the horizontal and out-of-plane deformations reach significantly higher values than in the case of the fully foamed out joint. Hence, there seems to be a dependence on the joint design and geometry, or more precisely on the degree of foaming.

Figures 4 and 5 show the course of the deformations (*u*, *v,* and *w*) as a function of temperature for both specimens. Here, the averaged deformations over the entire evaluation area are considered.

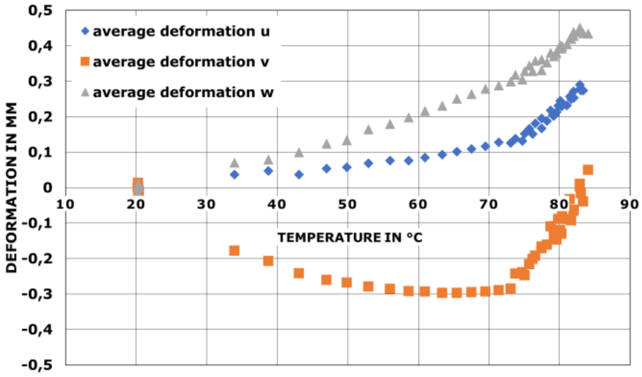


Figure 4 Course of the averaged deformations in specimen no. 2.

The diagrams illustrate the horizontal and out-of-plane deformations increase in both specimens with rising temperature. A different trend can be observed with regard to the vertical deformations. In both test specimens, both negative and positive vertical deformations arise in dependence on the face temperature. This means an upward and downward deformation of the covering nose.

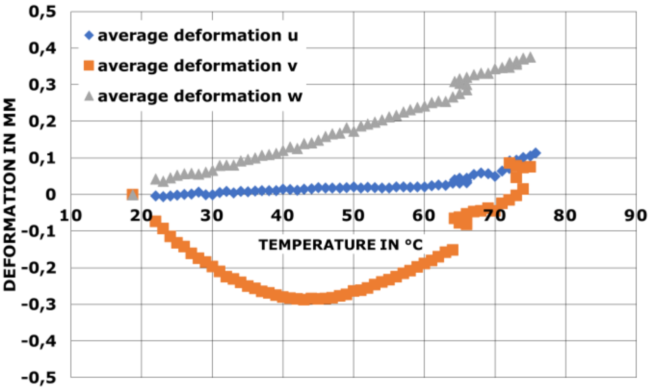


Figure 5 Course of the averaged deformations in specimen no. 1.

After the temperature stress is applied, there is initially a downward deformation until the covering nose contacts the neighboring panel. For test specimen no. 1, this already occurs at a face temperature of approx. 46°C and for test specimen no. 2 at a temperature of about 67°C. This shows the influence of the geometry as well. As the temperature continues to rise, the direction of the deformation changes and the covering nose moves upwards (Figure 6).

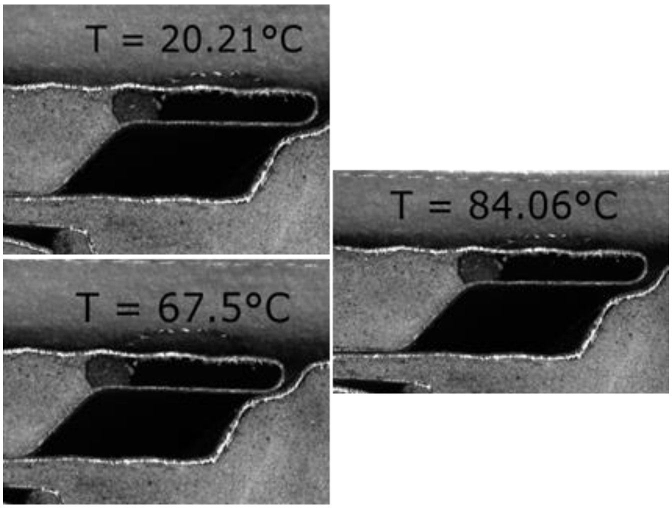


Figure 6 Position of the covering nose (specimen no. 1) in dependence of different face temperatures.

For specimen no. 2, the covering nose lifts off stronger after touching the neighboring panel than for specimen no. 1. Possibly this could be caused by cell gases that accumulate in the air space as the temperature rises and forces the covering nose upwards.

Regarding the blistering, the vertical deformation v and the resulting technical strain ε_{yy} are of particular interest (see also [1]). The distribution of the vertical deformation in both specimens points out that the covering nose behaves like a cantilever. The maximum deflection occurs at the tip, resulting in a strain peak at the base of the covering nose (Figures 7 and 8). The measured strains are maximal at the time of the highest face temperature and not when the covering nose hits the neighboring panel. In quantitative terms, there are also differences between the two tested joint designs.

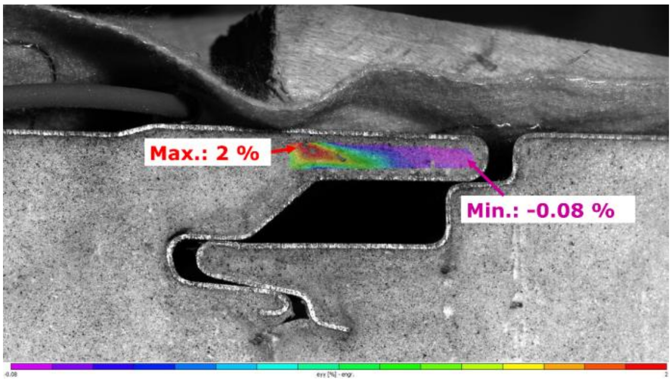


Figure 7 Specimen no. 1: Distribution of technical strain ε_{yy} at maximum face temperature.

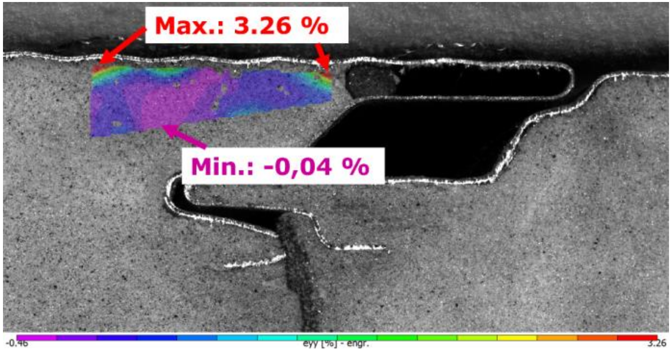


Figure 8 Specimen no. 2: Distribution of technical strain ε_{yy} at maximum face temperature.

After finishing the test, both samples did not exhibit any blisters, therefore the applied temperature stress has not been sufficient. Explanations for this may be, amongst others possible:

- An initial defect or weak point in the structure may be required, but not have been present in the panels examined.
- The applied temperature or load duration may have been too low, lacking sufficient pressure built up in the panel.
- The strains or stresses resulting from the vertical deformations at the base of the covering nose did not exceed the bearable bonding stress, so that the core has not debonded from the face.

3.2 Tests on the influence of production-related defects under high face sheet temperatures

3.2.1 Experimental program

In order to describe the influence of production-related defects on blistering effects, a first experimental attempt was carried out on sandwich wall panels with visible fastening. The two tested specimens had a length of 2.35 m and a 40 mm thick PIR core with a density of approx. 36 kg/m³. One of the tested panels had a provoked defect in the center. As provided in the blistering test (see chapter 5.2.12 of [6]), the outer flat face of the panels was heated up to 85°C using textile heating blankets. The temperature on the outer and inner face was measured and recorded by magnetic temperature sensors for each panel. The temperature profiles in the face sheets of the defective and the intact panel can be seen in Figures 9 and 10.

The average heating rate of the outer face was about 3.5°C/min. The target temperature of 85°C was therefore reached after about 18 min. and was then maintained for 2 h, followed by a visual inspection for blisters.

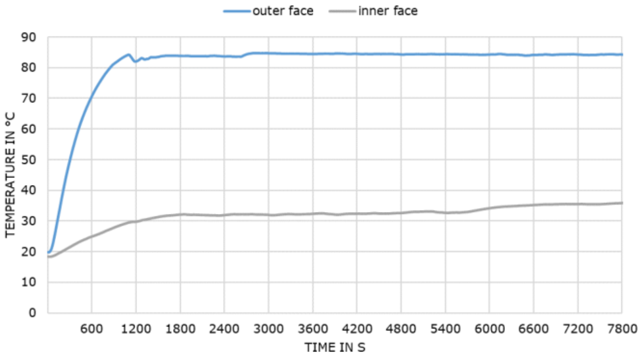


Figure 9 Face sheet temperatures of the defective panel.

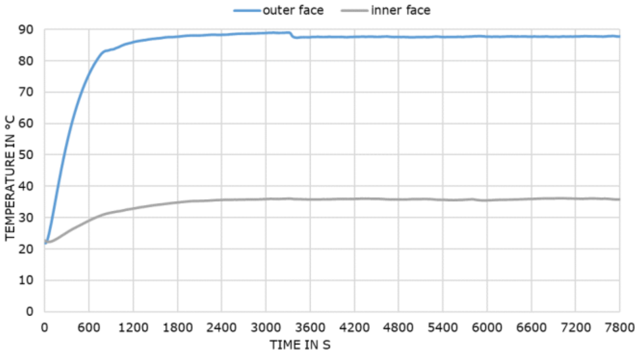


Figure 10 Face sheet temperatures of the intact panel.

3.2.2 Results

The application of a high temperature has led to a clearly visible blister formation on the outer face in both tested panels. In the sandwich panel with the known defect, two elongated blisters, each approx. 10 cm long, have formed on the longitudinal edge (Figure 11).

Consequently, there is no correlation to the defect inserted. It is possible that the defect was not successfully introduced during production and that the desired delamination between the core and the face was not present in the center of the panel.

This is not visible from the outside and, according to the current state of the art, can only be clarified by subsequently removing the face sheet. Until then, it also remains uncertain whether there was an unintentional, production-related defect at the position of the actual blisters.

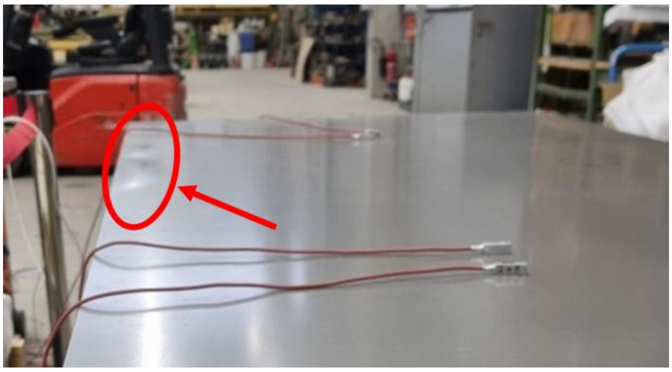


Figure 11 Blistering on the longitudinal joint of the defective panel.

This is supported by the fact that an elongated blister also appeared at the same position, i.e. at the longitudinal edge, on the reference panel of the same production batch. The blister formed here was also approx. 10 cm long. The detected blisters disappeared after the face sheet had cooled down. Nevertheless, this first experimental test reveals the direct correlation of a high face sheet temperature on the formation of blisters in sandwich panels. This influence is found in the literature [1] for PUR cores and can therefore also be assumed for PIR cores. Furthermore, it is shown that the blistering test [6] is a suitable test method for investigating blistering in our study. The influence of an initial defect as well as the heating rate has to be investigated by further studies.

3.3 Effects on the load-bearing-capacity of the sandwich panels

The (experimental) consideration of blistering in the literature and in the standard is limited to the durability of the sandwich panels. Depending on the size and position of the blister, however, this can also result in an impairment of the load-bearing capacity or the load-bearing behavior of the panels. Due to the lack of adhesion between the core and the face, a blister causes a local failure of the bedding of the compressively stressed face. Therefore, effects in the load-bearing behavior are expected as redistributions of strain and stress, which may depend on the size and position of the blister. This assumption is to be verified by experimental bending tests with parallel measurement of the strain state on panels with and without blisters. The experimental setup will be chosen depending on the blister. The aim of the investigation is to examine the load-bearing behavior of sandwich panels with blisters as a function of the mechanical stress.

4 Conclusions and outlook

In this paper, different influences on blistering effects in sandwich wall panels with a PIR core were analyzed and experimentally investigated. The aim of the experiments was primarily to describe qualitative observations concerning the formation of blisters. Therefore, the focus was mainly on the influence of an increased face sheet temperature and partly in dependence of various product parameters. Evaluating expert reports the problem of blistering was also considered from a practical construction perspective.

Based on these investigations, the following conclusions can be drawn:

- In practice, blisters are predominantly detected on the outer face sheet in the first few months after installation;
- There seems to be no dependence on the static system, face geometry or panel thickness;
- Regarding the position of blisters, the evaluation of expert reports shows an influence of the joint design. Wall panels with hidden fastening are to be considered as a special case, as blisters occur predominantly at the longitudinal edge in the area of the covering nose;
- Blistering is directly related to the temperature of the affected face sheet. The blisters become visible by heating the face sheets for a longer period (here: 85°C for 2 h) and may disappear after cooling. This confirms that the observations from studies on sandwich panels with PUR-core are also valid for PIR;
- The heating of the outer face of sandwich wall panels with hidden fastening causes horizontal and vertical deformations as well as out-of-plane deformations and strains in the covering nose. DIC measurements showed these to be in a low range and their maximal shift depending on the geometry and design of the longitudinal joint as well as the degree of foaming of the covering nose;
- The measured horizontal and out-of-plane deformations increase with rising temperature, while the vertical deformations assume both negative and positive values, depending on the face sheet temperature;
- The measured strains are maximal at the time of the highest face temperature.

In summary, the results provide important insight in blistering in sandwich panels. Nevertheless, further extensive experimental studies are necessary to gain fundamental knowledge and to understand especially the influence of (production-related) defects. Subsequently, other relevant boundary conditions are to be successively included.

5 Acknowledgement

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