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Influence of Temperature on the Behavior of Sandwich Panels

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Abstract

Sandwich panels in the construction industry are used as roof and facade elements and usually consist of two thin face layers of steel and a thicker core of polyurethane (PU) or mineral wool in between. The PU core material is constantly being further developed. In addition to improvements in the physical properties, this further development also leads to changes in the mechanical properties. As a result, the design rules that were established for older foam systems must be reviewed at regular intervals. There is a great need for research into the temperature-dependent behavior of the foam system. As these elements are used as roof and facade elements, they are directly exposed to climatic conditions. High temperatures are generated on the cover sheets due to solar radiation. The PU rigid foam changes its mechanical properties in this temperature range. Tests on small parts and components show a change in the stiffnesses and strengths, as well as the load-bearing behavior under elevated temperature. Consideration of the temperature in the design is therefore of great importance. In view of the continuous further development of the foam system, statements regarding the core material from older research must be reconsidered.

Keywords

Sandwich panels, temperature, rigid polyurethane foam, facade elements, lightweight construction

1 Introduction

Sandwich panels are used in the building industry as roof and facade elements (Figure 1). Here, they offer an economical solution due to their short construction time and the fact that they cover the functions of load bearing, sealing and insulating in one component. In Europe, they are therefore widely used in industrial and hall construction. In 2020 more than 22 million square meters of sandwich panels were installed in Germany. The square meters installed annually are increasing.

Mineral wool and polyurethane foam are the most widely used core materials. Mineral wool is mainly used when high demands are made on fire protection. Otherwise, PU rigid foam is used. In Germany, 90% of the elements produced and installed have a PU rigid foam core.

Figure 1 Industry building with sandwich panels

Due to their use as roof and facade elements, the panels are directly exposed to climatic influences. Depending on the colour of the outer surface layer, temperatures of up to 80 °C are generated in summer due to solar radiation. In winter, on the other hand, temperatures below 0 °C are reached. Within this temperature range, the core material, PU rigid foam, changes its mechanical material parameters. Studies on the behaviour of sandwich panels

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and in particular on the changes in the foam material are part of some past research work. In his work from 1978, Berner [1] showed that adding heat reduces the strength and stiffness of PU rigid foam. A decrease in these material parameters at elevated temperature was shown in the results of tensile, compression and shear tests. This tendency of decrease in stiffness and strength was also confirmed by Jungbluth [2] in 1986. More recent work, for example Mertens 2008 [3], further confirms the findings obtained. In addition to tests on small scale specimen, Mertens also determined the ultimate load on complete panels. As expected, the ultimate load of the panels decreased with increased temperature due to the lower stiffness and strength values. The failure pattern of the warm panels, however, did not change in relation to the reference components at room temperature. The decisive factor was a failure due to the achievement of the ultimate wrinkling stress.

The system of rigid polyurethane foam is constantly being further developed, which is why the statements made in [1], [2] and [3] need to be re-examined. Due to the further development of the foam system, it acquires better properties in terms of environmental compatibility, thermal insulation, dead weight and fire behaviour. The sandwich panels currently used have a core of rigid polyisocyanurate (PIR) foam. Previously, the panels were made with a pure polyurethane (PUR) rigid foam. The proportion of isocyanates in the foam formulation has increased in recent years, leading to the name PIR rigid foam. The increased proportion of isocyanates compared with rigid polyurethane foam forms stable isocyanurate rings. As a result, these foams show higher thermal stability and achieve better fire protection properties [4]. Both the PUR foams used previously and the current PIR foams are grouped together under the term PU foam.

Sandwich panels can fail in various ways and thus reach their ultimate load. In addition to failure mechanisms at the fasteners and the supports, the shear failure of the core (Figure 2) and the wrinkling of the compressive face layer (Figure 3) are of particular importance. In general, the decisive factor is the achievement of the wrinkling stress. The critical wrinkling stress σ_{cr} is a stability failure of the surface layer, which is elastically supported by the core and is under compression. It depends on the stiffness characteristics of the core E_C and G_C as well as the Young's modulus of the surface layer E_F. In simplified form, it can be determined according to equation (1).

Figure 2 Sandwich panel with a shear failure in the core in a six-point bending test after reaching the ultimate load

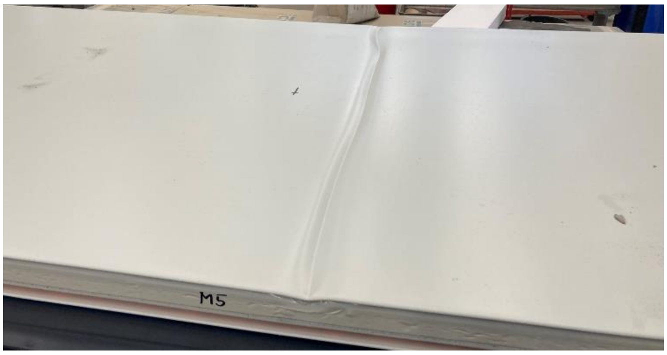

Figure 3 Failure pattern after reaching the wrinkling load with the so called wrinkling buckle by reaching the ultimate load in the six-point bending test

$$\sigma_{cr} = 0{,}82 \cdot \sqrt[3]{E_C{}^2 \cdot G_C{}^2 \cdot E_F{}^2} \qquad (1)$$

Taking into account the imperfection e_0/a_x of the compressive face plates as well as the tensile strength f_{Ct} of the core material, the wrinkling stress can be determined more accurately via (2).

$$\sigma_{cr}{}^T = \frac{0{,}82 \cdot \sqrt[3]{E_C{}^2 \cdot G_C{}^2 \cdot E_F{}^2}}{1 + 3 \cdot \frac{e_0}{a_x} \cdot \sqrt{G_C \cdot E_C} \cdot \frac{1}{f_{Ct}}} \qquad (2)$$

The approval and calculation of sandwich elements for Europe is regulated in EN 14509 [5]. The standard uses a k_1 factor to reduce the wrinkling strength at elevated temperatures, which is usually relevant for design. This factor is intended to reflect the lower ultimate load at elevated temperature. The k_1 value is composed of the ratio of the tensile stiffnesses at 80 °C and 20 °C (see formula (3)). Mertens [3] showed in his work that this reduction via the stiffness quotient value is acceptable with respect to his results.

$$k_1 = \sqrt[3]{\left(\frac{E_{Ct,+80\,°C}}{E_{Ct,+20\,°C}}\right)^2} \qquad (3)$$

Due to the already described further development of the foam formulation and the test procedure, the tensile tests at 80 °C to obtain $E_{Ct,+80\,°C}$, the wrinkling stress at elevated temperature can no longer be represented by the value described in (3). Thus, a new k_1 value was developed which also considers the ratio of the tensile strengths (4). This value leads to a reduction that is better suited to the currently produced panels.

$$k_1 = \min\left(\sqrt[3]{\left(\frac{E_{Ct,+80\,°C}}{E_{Ct,+20\,°C}}\right)^2} ; \sqrt[3]{\left(\frac{f_{Ct,+80\,°C}}{f_{Ct,+20\,°C}}\right)^2}\right) \leq 1 \qquad (4)$$

The acceptable wrinkling stress is multiplied by the k_1 value. In this way, an increased temperature is taken into account in the design. Currently, however, there is no normative regulated reduction of the ultimate load of the other failure cases, such as shear failure, under elevated temperature. Moreover, only the results from the cube tensile tests are used to determine the value k_1. Conducting the tensile test at a temperature of 80 °C with a maximum oversize of 3 °C and undersize of 1 °C is also practically realizable only with a significantly increased effort.

2 Experimental investigations

2.1 Test setup and boundary conditions

Various tests were carried out to determine the changed material behaviour of current sandwich panels under temperature loading. Cube tensile tests are carried out to determine the tensile strength and the tensile modulus. The specimens for these tests have dimensions of 100 mm x 100 mm x component thickness. The test specimens for the compression tests have the same dimensions. The shear modulus and shear strength are determined on shear beam tests in a four-point bending test. The shear beam is 100 mm wide and approximately 800 mm to 1200 mm long, depending on the thickness of the panel. In addition to these small-part tests, six-point bending tests are also carried out to determine the ultimate load on the entire component. The length of the component depends on the thickness of the component and the spans in the structure and is usually between 4 m and 8 m. The component is tested and loaded to failure in a six-point bending test. The boundary conditions of the test setups for the tensile, compression, shear and panel tests are regulated in EN 14509.

To determine the changes in strengths, stiffnesses and load-bearing behavior with respect to an elevated temperature, the presented tensile, compression, shear and panel tests are performed with different position and test temperatures:

- Reference: The specimens are stored at room temperature and also tested at room temperature. These tests are used as initial tests or reference values. Changes from temperature, as a result of the subsequent tempered and warm conditions, are referred to these tests as a percentage.
- Tempered: The specimens are stored for 24 h in an oven at 80 °C. They then cool down again for 24 h at room temperature and are finally tested at room temperature. This boundary condition corresponds to a component that has been heated frequently by warm summer days but is in a medium temperature range at the time of the critical load.
- Warm: The specimens are stored in the oven at 80 °C for 24 h and then tested directly. During the test, the temperature is kept at 80 °C with the aid of radiant heaters or heating blankets. In practice, these tests correspond to the situation where the component has already been heated several times by solar radiation (warm summer days) and where there is a warm condition at the time of the critical load. Figures 4,5 and 6 show examples of the tensile, shear and component tests at warm conditions.

The tests with the described boundary conditions are referred to in the following as reference, tempered and warm. The results of the tempered and warm tests are related to the reference tests as a percentage.

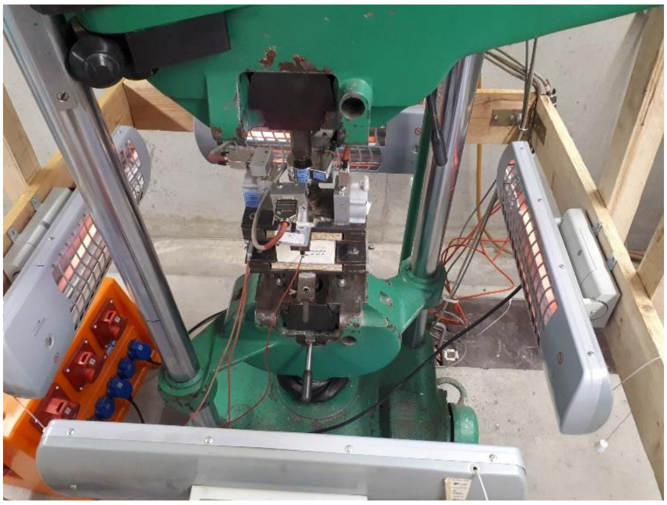

Figure 4 Test setup and performance of the warm tests. Cube tensile test with heat lamps

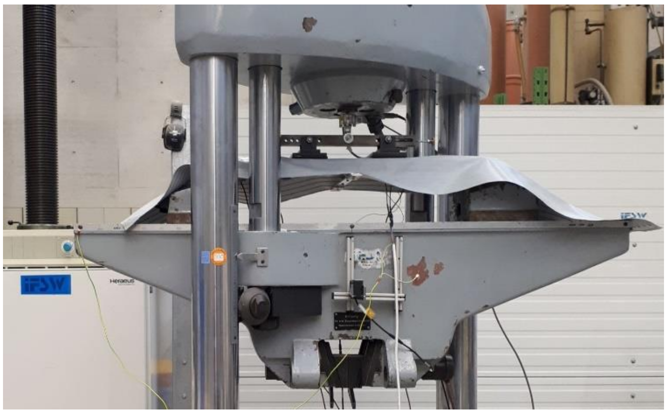

Figure 5 Test setup and performance of the warm tests. Shear beam test with heating blankets

Figure 6 Test setup and performance of the warm tests. Six-point bending test of a panel with heating blankets

2.2 Test results of the small part tests

The results show strong changes in stiffness and strength values in both the tempered and the warm tests. But also the load-bearing behavior, meaning the failure mode, changes after temperature treatment. The amount of change depends on many influencing factors, but the tendencies, such as decrease or increase, are usually similar. The results are influenced by the following factors:

- Manufacturer of the panels, as well as manufacturer of the foam system
- Age of the specimens
- Geometry and type of elements (core thickness, geometry of cover sheets, wall or roof panels)
- Position of the specimen in component width
- Test direction (isotropic material behavior of the core)

Due to the many influencing factors, in the following results only data from one production run and from the same period are directly compared and related to each other in terms of percentages.

In the tensile tests, the tempered tests show an increase in stiffness (tensile modulus) and a decrease in tensile strength. The warm specimens, on the other hand, show a decrease in stiffness and strength. The decrease in strength due to testing at 80 °C is greater than the decrease in strength due to tempering. Figures 7 and 8 show the mean values of the stiffnesses and strengths from the tensile tests of series from various manufacturers plotted as a percentage of the reference tests.

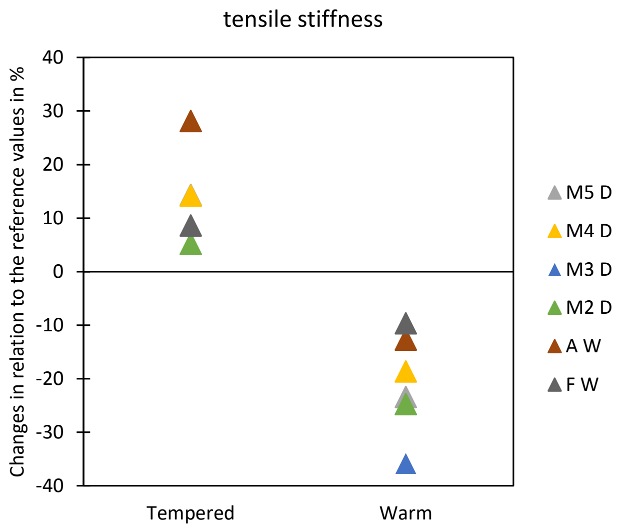

Figure 7 Mean values of the tensile stiffness of cube tensile test series of different manufacturers in percent related to the reference tests

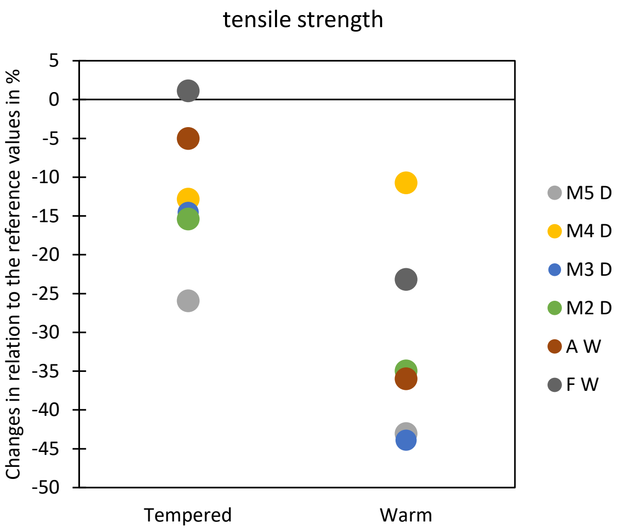

Figure 8 Mean values of the tensile strength of cube tensile test series of different manufacturers in percent related to the reference tests

Compared to the tensile tests, the results of the compression tests do not show such large changes due to a temperature load. The changes are in a range that is usually below 10 %. However, in some cases the material parameters behave in the opposite direction to the tensile test results. Here, the material parameters compressive modulus and compressive strength increase for the tempered boundary condition. Stiffness and strength decrease for the warm specimens.

The results of the shear tests show a quite analogous picture to the cube tensile tests. Here, too, the stiffness increases with tempering and decreases with warm testing. The shear strength decreases under both boundary conditions. The reduction is higher for warm tests. Figures 9 and 10 show the shear stiffnesses and shear strengths of the tempered and warm tests in relation to the reference tests. The decreases in the tensile tests are somewhat more pronounced compared to the shear tests.

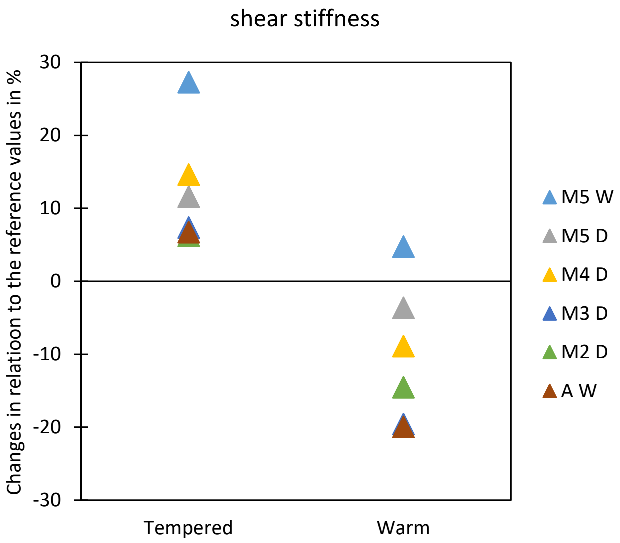

Figure 9 Mean values of the shear stiffness of shear beam test series of different manufacturers in percent related to the reference tests

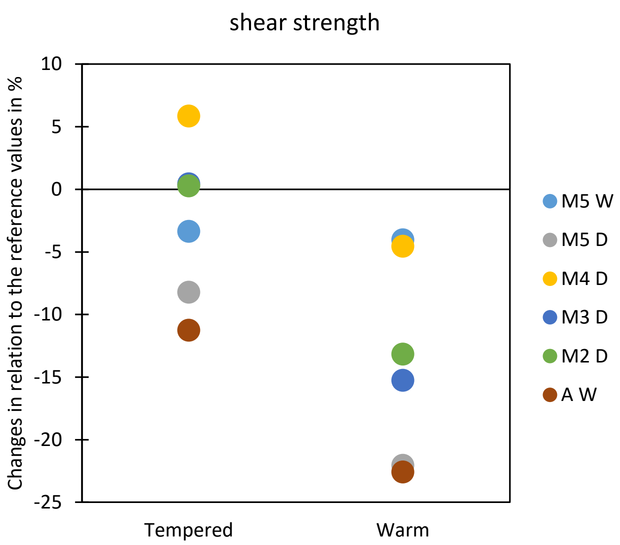

Figure 10 Mean values of the shear stiffness of shear beam test series of different manufacturers in percent related to the reference tests

The progress of the tests is shown qualitatively in Figure 11. The strengths and stiffnesses are clearly visible in the form of the slope in the linear range. It is also clear that the changes in the compression tests are smaller and that an increase in strength can occur here with the tempered specimens.

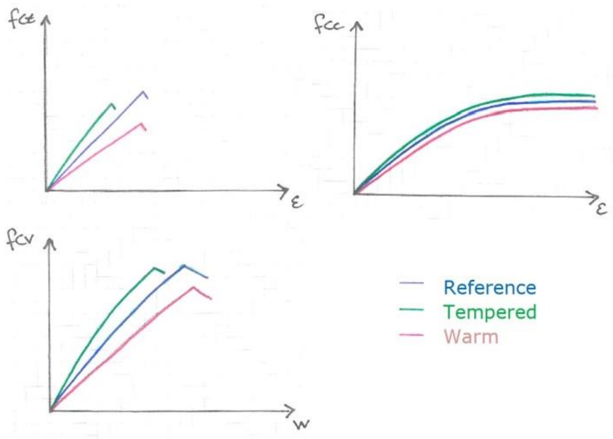

Figure 11 Qualitative trend of the test results. Top left: qualitative trend of the cube tensile tests. Top right: qualitative trend of the cube compression tests. Bottom: qualitative trend of the shear beam tests

In summary, the following conclusions can be drawn from the small part tests for the two selected temperature boundary conditions and applied to the components:

- Warm: The stiffnesses and strengths decrease in all tests carried out (tension, compression and shear). For the load-bearing behavior, this means a reduced ultimate load. In particular, the resistance to wrinkling is reduced by the lower material parameters (see also formula (1) and (2)). The panels will experience a wrinkling failure with reduced ultimate load.
- Tempered: The stiffnesses (tension, compression and shear) increase with a simultaneous decrease in strength (tension and shear). The decrease in the reduction in strength is not as significant as in the warm tests. Due to this uneven change in the material parameters (increase in stiffness with decrease in strength), the previously existing relationship of the material parameters to each other changes. This not only changes the absolute ultimate load, but also the failure pattern.

2.3 Test results of the panels

The panels are tested in a six-point bending test. For the warm tests heating blankets are used to keep the panel uniformly at a temperature of around 80 °C (Figure 6). As already expected from the small part tests, there is a drop in the ultimate load with the warm specimens. The failure pattern continues to correspond to a wrinkling failure by attainment of the wrinkling load-bearing stress (see also Figure 3). This can be attributed to the quite uniform decrease in the material properties, stiffness and strength.

In general, the tempered panels also have a reduced load-bearing capacity. However, the reduction is usually not as great as for panels tested in the warm state. However, the failure pattern is altered. Instead of a wrinkling failure, as occurs with the reference elements and the warm elements, a shear failure in the core is now evident (Figure 2).

Table 1 shows the percentage changes in the ultimate load with respect to the reference tests at room temperature and presents the failure modes.

Table 1 Percentage change in the ultimate load of the components in relation to the reference tests as well as the failure pattern

Test series	**Percentage changes in relation to the reference tests and failure pattern**	
	Tempered	**Warm**
A W1	- 33,7 % (shear fracture)	-61,4 % (wrinkling)
A W2	- 29,2 % (shear fracture)	- 10,5 % (wrinkling)
M5 W	- 5,7 % (shear fracture)	- 25,9 % (wrinkling)

3 Discussion

These test results listed here, especially with reference to the results of the further specific tests carried out by the author ([6], [7]), show a change in the material parameters under the influence of temperature. By dividing the tests into reference, tempered and warm, conclusions can be drawn about an increased storage temperature and an increased test temperature. Both selected temperature boundary conditions are relevant in practice. Due to the increasingly hot summers, it is important to note that façade elements must also be examined in particular regarding their temperature load. The special characteristic of the sandwich elements is the polyurethane rigid foam core. This core is being continuously developed and adapted to steadily increasing physical and economic requirements. For these reasons, the investigation of sandwich panels must be continued on an ongoing basis, and attention must be paid not only to the physical construction aspects but also to changes in the mechanical properties. In addition, it can lead to previous research and designs based on it being no longer valid.

The results on the current foam systems show that the tensile and shear strengths decrease after and during increased temperature influence. The stiffnesses, on the other hand, increase after the influence of elevated temperature. Nevertheless, the stiffnesses also decrease when the test temperature is increased. This effect is least evident in the compression characteristics of the foam system. Here, a slight increase in strength is even observed after a storage at warm temperature.

The panel tests clearly show that the reduction of the material properties in the warm tests also leads to a reduction of the ultimate load in the entire panel with the same failure pattern (wrinkling). The reduction coefficient listed in equation (3) is based on the tensile stiffnesses at room temperature and at 80 °C. The tests are carried out under these conditions. However, carrying out the test at this elevated temperature is time-consuming and there is a high risk of obtaining an increased stiffness due to the influence of storage and simultaneous cooling of the specimen. Thus, extending the reduction factor with strength (equation (4)) is an important step to capture the influence at elevated temperature on stiffness and strength. In addition, the influence of inaccurate test performance is minimized.

This reduced ultimate load, which is present in the warm specimens, is also found in the tests that were only heated during the storage period. Here, however, the failure mode is shear failure instead of the otherwise usually decisive wrinkling failure. These tests thus show that not only a reduction of the wrinkling failure mode under elevated temperature is necessary. The shear failure can also become decisive for the design due to the changed constellation of material parameters. There are currently no specifications for shear failure that take increased temperature into account.

According to the general sandwich theory, the cover plates receive the normal stresses and the core absorbs the shear stresses [8]. According to this, the failure criteria shear failure and wrinkling can be established according to the following analytical relationships.

Wrinkling failure occurs, when

$$\sigma_{Ed} = \frac{M}{A_F \cdot a} \geq \frac{0{,}82 \cdot \sqrt[3]{{E_C}^2 \cdot {G_C}^2 \cdot {E_F}^2}}{1+3 \cdot \frac{e_0}{a_x} \cdot \sqrt{G_C \cdot E_C} \cdot \frac{1}{f_{Ct}}} = {\sigma_{cr}}^T \tag{5}$$

or at elevated temperature with k_1 from formula (4):

$$\sigma_{Ed} \geq k_1 \cdot {\sigma_{cr}}^T \tag{6}$$

Shear failure, on the other hand, appears when

$$\tau_{Ed} = \frac{V}{a \cdot l_y} \geq f_{Cv} = \tau_{Rd} \tag{7}$$

Where M and V are the internal forces, bending moment and shear force, of the global system. A_F, a and l_y are geometrical parameters of the sandwich panels.

The test results show a shear failure of the panels, which occurs at significantly lower stresses than the limit shear stress f_{Cv} from the shear beam tests. Initial numerical investigations show that, contrary to the analytical approaches used in the design of sandwich panels, the shear stress distribution in the core in the area of load introduction is no longer homogeneous across the core thickness and a superposition of stresses occurs here.

It tends to be possible to maintain the reduction of the ultimate load via the wrinkling stress, since this is usually lower than the ultimate load of the shear failure. Nevertheless, the shear failure leads to other failure patterns in the facades and roofs. In practice, cases of damage occur from time to time. Here, failure occurs in the core material as well as delamination between the cover sheet and the core. The damage occurs particularly in spring, when the differences between the cold and warm cycles are very large, or in summer, when particularly high cover sheet temperatures are reached.

4 Summary

Sandwich panels are directly exposed to climatic conditions due to their use as roof and facade elements. The increased temperature changes the mechanical properties of the PU core material. These include, above all, changes in the tensile and shear strengths and their related stiffnesses. Changes result on the one hand from an increased temperature before the actual loading (tempered), and on the other hand from increased temperatures at the time of loading (warm). Both cases are relevant for the design but show different results in the material parameters and the failure modes. Currently, only the wrinkling stress is reduced in the design at elevated temperature. However, it also makes sense to consider the shear failure mode, since this can also represent a decisive failure mode after shifting the material parameters. Experimental results show that shear failure does not usually occur in roof components, due to the strong profiling. However, the failure mode can occur in weakly profiled wall components, as the results show. In the future, however, roof components will also be subjected to higher shear loads due to the expansion of solar and photovoltaic systems, which trigger shear forces close to the supports, and will thus be at risk of shear failure. Due in particular to the recent development of the core material from PUR to PIR, these investigations show results that are not directly comparable with previous research or lead to different results compared to these.

References

[1] Berner, K. (1978) *Stahl/Polyurethan – Sandwichtragwerke unter Temperaturbeanspruchung.* [Dissertation]. Technischen Hochschule Darmstadt

[2] Jungbluth, O. (1986) *Verbund- und Sandwichtragwerke.* Berlin Heidelberg New York Tokyo: Springer-Verlag

[3] Mertens, R. (1994) *Untersuchungen von Zwangsschnittgrößen bei ebenen Polyurethan-Sandwichelementen unter Temperaturbelastung*. [Dissertation]. Technischen Universität Darmstadt

[4] Davies, J.M. (2001) *Lightweight Sandwich Construction*. Oxford: Blackwall Science Ltd

[5] EN 14509 (2013) *Self-supporting double skin metal faced insulating panels – Factory made products – Specifications.* Beuth, Berlin

[6] Steineck, S.; Lange, J. (2022) *Einfluss von Temperatur auf Sandwichelemente mit PU-Hartschaum*. DASt-Forschungskolloquium, Technische Universität Dortmund, pp. 25-28.

[7] Steineck, S.; Lange, J. (2022) *Influence of temperature on sandwich panels with PU rigid foam*. SEMC 2022, Cape Town, Zigoni, A., CRC Press, pp. 489-493.

[8] Plantema, F. J. (1966) *Sandwich Construction The Bending of Sandwich Beams, Plates and Shells*. John Wiley &Sons, inc., New York, London, Sydney