FULL-SCALE AXIAL COMPRESSION LOADING OF SANDWICH PANELS (SIPS) WITH WOOD BASED SKINS AND A PUR-FOAM CORE – FIRST RESULTS OF A 24 YEARS EXPERIMENT WITH HIGHLY ECCENTRIC LOADS

VOLL-MAßSTÄBLICHE AXIALE DRUCKBELASTUNG VON SANDWICH-PANELEN (SIPS) MIT HOLZBASIERTEN DECKSCHICHTEN UND EINEM PUR-SCHAUMKERN – ERSTE ERGEBNISSE EINES 24 JAHRE ANDAURNDEN EXPERIMENTS MIT STARK EXZENTRISCHEN LASTEN

Simon Aicher[1], Johnny van Rie[2], Kai Simon[1]

[1] *Materials Testing Institute (MPA), University of Stuttgart, Otto-Graf-Institute*

[2] *Kingspan Unidek B.V., Gemert, Netherlands*

SUMMARY

This paper reports on the mechanical long-term behaviour of full-scale axially loaded structural insulated panels (SIPs) panels, namely the TEKpanel®, representing the wall elements of an all-sided closed test cabin. The investigated stressed skin TEK panels consist of two skins of particle board and a polyurethane (PUR) core. Since SIPs panels provide an excellent opportunity to build green, i.e. with low carbon impact, good (re-) mounting capabilities and very good insulation performance, it is very important to show that these elements are also very long lasting with high long-term performance.

The aim of this ongoing study is to provide scientific and experimental background for this type of SIP panels used as load-bearing walls. The load on such wall elements is in most cases highly eccentric bound to building physics design aiming at a good insulation performance by avoidance of gaps in the insulation shell. The floor must then be fixed in-between the walls generally by joist hangers, in order not to violate the insulation core. This leads to a pronounced load eccentricity and causes the outer skin of the loadbearing panel to be significantly under tension.

The reported study deals with the long-term deflection, hence creep and creep-recovery behaviour of the elements being highly influenced by the environmental climate. The investigation period covers 24 years of loading. The experimental results presented in this paper demonstrate the long-lasting quality of this type of SIP panels, and that it retains its original mechanical performance and shows almost no evidence of degradation, although heavily loaded.

ZUSAMMENFASSUNG

Der Beitrag berichtet über das Langzeitverhalten von vollmaßstäblichen, axial beanspruchten Sandwich (SIP-)-Elementen, nämlich dem TEKpanel®, die als tragende Wände in einem allseitig geschlossenen Versuchsbau eingesetzt sind. Die untersuchten TEK-Elemente bestehen aus zwei Spanplatten als Deckschichten und einem Kern aus Polyurethan (PUR) Hartschaum. Da SIP-Elemente eine ausgezeichnete Möglichkeit bieten, umweltfreundlich zu bauen, d.h. mit geringem Kohlenstoffausstoß, einfachen (Wieder-) Montagemöglichkeiten und mit sehr guter Dämmwirkung, ist es essentiell zu zeigen, dass diese Elemente sehr langlebig sind und sodann ein sehr gutes Langzeitverhalten aufweisen.

Ziel der andauernden Untersuchungen ist es, wissenschaftliche und experimentelle Erkenntnisse für die Verwendung dieser Art von SIP-Elementen als tragende Wände bereitzustellen. Aus bauphysikalischen Gründen ist die Belastung der Wandelemente infolge der zwischen den tragenden Wänden mittels Balkenschuhen eingehängten Holzträger als Tragkonstruktion der darüberliegenden Decke meist ausgeprägt exzentrisch. Das Vermeiden einer Durchdringung der gut isolierenden Wände und die hieraus resultierende Lastexzentrizität bewirkt, dass die außenliegende Deckschicht des tragenden Elements hauptsächlich durch Zugspannungen beansprucht wird.

Die berichteten Untersuchungen befassen sich mit den Langzeitverformungen, d.h. mit dem Kriech- und Rückkriechverhalten der Elemente, das in erheblichem Maße vom Umgebungsklima beeinflusst wird. Die Untersuchungen umfassen einen Belastungszeitraum von über 24 Jahren. Die in diesem Artikel präsentierten experimentellen Ergebnisse belegen die langlebige Qualität von holzbasierten SIP-Elementen mit einer gegenüber dem Ausgangszustand ungeachtet einer hohen Belastung nur geringfügig degradierenden mechanischen Widerstandsfähigkeit.

1. INTRODUCTION

The reported investigations focus on the long-term behaviour of SIPs panels, in particular TEK panels consisting of both-sided 16 mm particle board skins and an in-between core made of Polyurethane (PUR) rigid foam. The production of the panel is done in a continuous process where the PUR liquid is sprayed evenly on one horizontally arranged particle board and expands rapidly upwards were it hits the second particle board, hanging above in contact to a press-plate. The panel is then cured as a whole. The TEK panels were originally produced in Germany and the building approval tests as well as the reported follow-up experiment were done at MPA, University of Stuttgart. The original approvals Z-9.1-315 (1995, 2001) [1] covered loadbearing walls with a limited eccentricity of 1/6th of the wall thickness. This eccentricity measure was adopted from masonry-like walls, which are very sensitive to bending - tension.

In order to extend the range of the approval, it was decided in 1999 to investigate the building system further. The investigation focussed on a larger eccentricity of the load, to be verified for a longer test period. The reason of a large load eccentricity is bound to I-joist floor beam hangers fixed on the narrow top edge of the wall. The I-joist hangers are part of the floor construction and can transfer quite high floor loads. The advantage of the floor hanging in-between the walls is that the insulation shell can be continuous hence avoiding cold bridging.

A SIPs wall without interior stingers or studs carries in-plane loads entirely through the skins so it concentrates the stresses on the outside of the element. So, as long as the axial load is in between the skins and the eccentricity of the resulting vertical force is less then the core radius (half of core plus sheathing thickness), no tension will occur. However, once a significant load share is applied just outside the skin, the opposite skin will be partly or entirely under tension instead of compression, depending on the degree of eccentricity. The eccentricity causing bending also results in shear loading of the core. So, in permanent state the inner skin is under compression, the core carries shear and a part of the outer skin is under tension and all skins experience creep.

The original experiment for approval extension with a full-scale test cabin (Fig. 1 and 2) regarding increased eccentricities started in September 1999 [2] and was regularly monitored over a period of three years. When the production of the TEK panels stopped in Germany and was transferred to the UK the regular displacement monitoring of the experiment was no longer continued. However, very fortunate, the experimental set-up was still kept under load throughout in service class 2 climate conditions. Climate recordings are available from the begin of the test. So, in a way the experiment was silently continued. The fact, the value and the scientific potential of the ongoing not monitored tests have been discussed by MPA and Kingspan and it was decided in 2020 to revive the experiment with the test cabin again. Due to the very long-lasting loading, comprising 24 years up to this paper, the research enables a rather unique possibility to learn in how wooden SIPs and in particular TEK panels and their different components are affected by time with regard to strength and stiffness. This contribution presents a first compilation of experimental results and will be complemented by deepened analysis in a separate contribution.

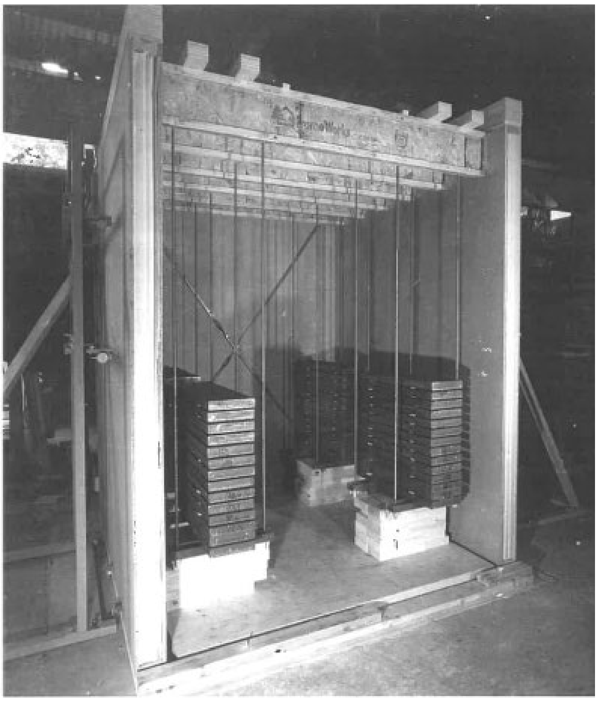

Fig. 1: Test cabin with load on the I-joist beams just before closing in September 1999 with two additional unloaded front walls including a door as shown in Fig. 2

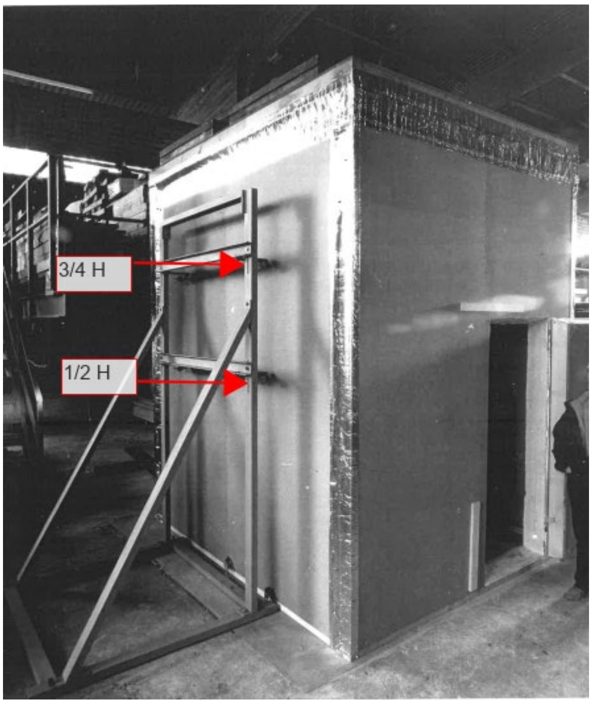

Fig. 2: Front view of finished test cabin with all structural and non-load bearing walls with diffusion-tight sealed edges and steel frames for mounting of displacement transducers

2. EXPERIMENT: THE CABIN

2.1 Build-up

The test cabin consists of four walls numbered 1-4, see Fig. 4. Each wall is made of two sandwich panels, i.1 and i.2 connected to each other by tongue and groove connection, and one flat roof made of two panels. Fig. 1 shows the test cabin without wall 3 and without the roof and Fig. 2 shows the finished test house.

In total the cabin is made of ten TEK panels, two on top and two on each side. Each TEK panel consists of two particle boards with a thickness of 16 mm and a core manufactured with an in-situ foamed urethane PUR insulation foam with a thickness of 110 mm. The dimension of each individual panel is 1250 mm in width and 3000 mm in height resulting in dimensions of the cabin of 2.50 m in width, 2.82 m in depth and 3.15 m in height.

The ceiling construction consists of six TJI 350 beams (according to German Technical Approval Z-9.1-277 [3]) supported by Simpson Strong tie ITT 3511.88 hangers (acc. to the German Technical Approval Z-9.1-302 [4]), mounted to walls 1 and 2. The loading of the ceiling is explained below. Above the I-joists of the ceiling a horizontal roof plate exists, also made of two sandwich panels. The roof plate is exclusively supported by the loaded walls 1 and 2.

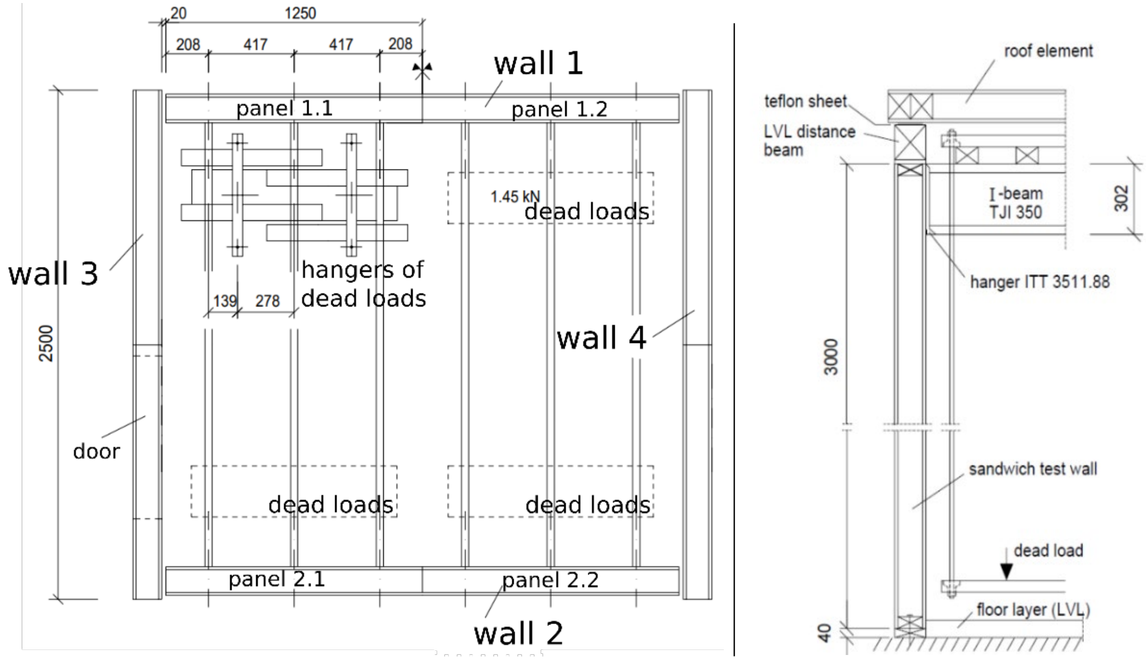

Fig. 3: top view of the cabin (left) and half cross section (right)

The build-up of the test cabin and details of the load application to the I-beams are shown in Fig. 3. Walls 3 and 4 are not considered to be load bearing and represent non-load bearing interior walls. Walls 3 and 4 are separated from the load bearing walls 1 and 2 and also from the roof panel by elastic foam layers and teflon. All edges of the cabin are sealed using diffusion tight bituminous-aluminium-foil, to ensure a controlled climate inside the cabin. For further details see [2].

2.2 Loads and stresses

The loads consist of four packs each with 14 stacked steel plates [2]. Per pack this makes 1500 kg, so the total load on the six I-joists amounts to 6 tons and hence results in 1.5 tons per load bearing panel 1.1, 1.2, 2.1 and 2.2. Additionally, the roof is loaded with four packs each consisting of 120 kg steel plates and additional steel disks (4 x 20 kg) positioned centrically above the load-bearing walls. So, per panel (1.1 to 2.2) 250 kg centric load is added. Together with the self-weight of the roof and the ring beams on top of the panels weighing about 62 kg, the centric load $q_{E,centric} = q_1$ results in 3.12 kN/1.25 m = 2.5 kN/m while the eccentric load comes to $q_{E,\,eccentric} = q_2$ = 1500 kg/ 1.25 m =12 kN/m at an eccentricity $e_2 = T/2$ +7.5 mm =33 mm where T = 51 mm is the bearing length of the hanger shoe (see [2]). The notations of centric (q_1) and eccentric (q_2) loads and eccentricities e and e_2 are given in Fig. 5. The eccentricity moment then is

$$M_e = q \cdot e = \; q_2 \cdot (e_2 + D/2) \tag{1}$$

resulting in

e = 86 mm and M = 1.247 kNm/m.

Assuming roughly sandwich membrane theory, the centroid stresses of the inner and outer skins are

$$\sigma_{s,in} = \frac{q}{2t_s} + \frac{M_e}{t_s(D-t_s)} = \; -(0{,}453 + 0{,}618) = -1{,}07\; N/mm^2 \tag{2}$$

and

$$\sigma_{s,out} = (0{,}618 - 0{,}453) = 0{,}165\; N/mm^2.$$

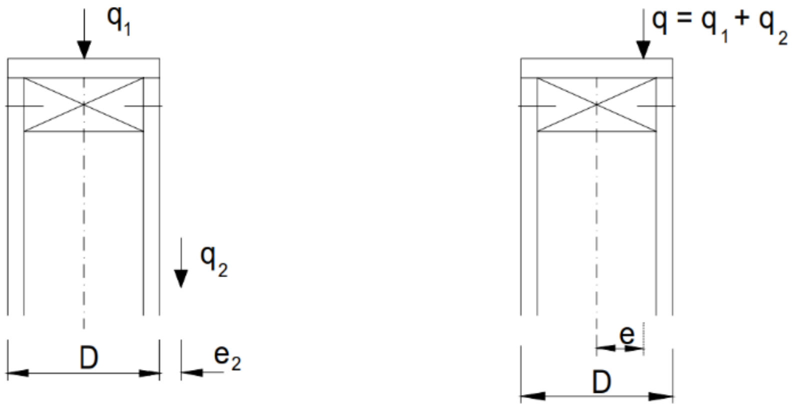

Fig. 4: Definitions of loads q_1, q_2, q and eccentricity dimensions e and e_2

Apparently, the inner skin carries the total vertical compression load whilst the outer skin is slightly under tension. Note: An exact analysis would result in slightly (about 7%) higher stresses at the outer fiber of the inner and outer skin.

2.3 Test phases I - IV

In total four test phases of the experiment have to be considered. The first phase comprises the initial ramp loading and the subsequent long-term measurement from December 1999 until April 2002. In this phase the inside temperature and humidity was very well controlled and recorded and the outside was shielded alike as in all subsequent test phases, from direct rain and other precipitation, so actually was in climate service class 2. Note, although the displacement measurements stopped in 2002, the load was never removed and the cabin door was throughout tightly closed, certainly leading also in the follow-up test phases to a rather significant differential climate between cabin in- and outside.

In the second phase of the experiment (July 2021 – April 2022) more displacement measuring points together with a datalogger was added (see chapt. 3) and it was decided to unload the cabin after 22 years of constant dead weight exposure to obtain data about the creep recovery. The unloading of the cabin was performed step-wise exactly as done in the initial loading in 1999, however, in reversed order. For each opposite pair of panels the load, which was acting onto the I-joist beams, was taken away rather slow and simultaneously in four steps, respectively. The unloaded situation was kept for 10 months and the creep recovery was monitored over this time period.

In the third phase (April 2022- July 2023) the cabin was reloaded in the same way as the original experiment had started. In order to obtain more detailed deformation data an extended deflection monitoring was now installed at the cabin.

In the fourth, still ongoing phase (July 2023-) investigations with cut-outs started. The aim of the research is to find the residual strength of the panels, and its load-bearing capacity with considerably sized non-reinforced openings. For this purpose, the I-joists were unloaded. It was decided to remove the unloaded walls 3 and 4 (including the door, compare Fig. 3) to exclude an influence of load-transfer for the case the bending deformation of the loaded walls is getting too large. Then wall 1 and 2 each consisting of two panels of width of 1.25 m and connected along total panel height by tongue and groove connection (tongue being a particle board strip of 100 mm width) were cut along the connection to separate the panels, following termed wall 1.1 and 1.2 and wall 2.1 and 2.2 (compare Fig. 3). Now each panel is able to deflect individually.

The openings placed in the oppositely located walls 1.1 and 2.1 are investigated with two significant different sizes. Firstly, a medium sized hole H1 with edge lengths of 625 mm x 625 mm was cut at mid-width and -height into the panel (H2: 800 mm x 800 mm). The both-sided remaining studs at holes H1 have widths of 312 mm, respectively. The respectively adjacent walls 1.2 and 2.2 without holes now serve as reference walls for judgment of the hole influence. The tests with holes H1 are ongoing. A mechanically highly interesting question is at what hole size the load bearing capacity is changing from a plate behaviour to a structural resistance which is dominated by eccentrically loaded clamped columns which may be designed according to e.g. [5].

Additionally, mechanical properties of the compound components (particle board and core foam) such as compression, shear and tension strengths and stiffnesses, densities and moisture contents were investigated from samples cut from the four disassembled panels from walls 3 and 4 and the cut-out pieces from the holes H1. Several of these tests are still ongoing.

3. MEASUREMENTS

Measurement during test phase I (Sep. 1999 – Apr. 2002)

During test phase I, measurements of horizontal displacements were performed at mid-span and one quarter the height from the top end at the outer four panel surfaces of the loaded walls 1 and 2, see also [6]. The eight displacement measurements were performed with traditional dial indicators. They were fixed to a rigid steel frame installed next to the cabin and fixed at the floor of the testing hall (see Fig. 2). The results were read out manually hourly and daily immediately after the load application and was changed to a sequence of about twice a week for the total period until 2002. In addition, the climate conditions being air temperature and relative humidity was monitored in the inside and on the outside of the cabin. Further, the evolution of the moisture content of the particle boards and of the foam was directly measured by weighing and later oven-drying of control board and foam samples stored in immediate vicinity outside and inside of the cabin.

Measurement during test phases II and III (July 2021 – Apr. 2022)

Since the original steel frames for fixation of the transducers had been removed and used otherwise, Kingspan provided a new steel frame and 24 LVDT's were mounted on it. The displacement monitoring contained the same eight measurement points as in test phase I. Additionally to the horizontal measurements at ½ and ¾ of the wall's height LVDT's were mounted at ¼ and full height of the walls to gather information about the bending line of the outer panel surfaces of the loaded walls, not discussed here in detail. Four vertical LVDT's were installed at the upper edge of the outer panel surfaces, too, to get information about the vertical compressive deformation of the walls in load direction.

Now a datalogger enabled a more precise measurement interval of 30 s during and immediately after the load application and an hourly reading for the long-term measurement. Fig. 5 depicts the newly installed steel frame and the positions of the mounted LVDT's at the loaded wall 1.

For the test phase III it was decided to only observe the deformations of wall 1 (panels 1.1 and 1.2) but with additional displacement positions at the panel surfaces inside the cabin. The reason for doing so is / was bound to the assumption that due to the load eccentricity the deformations at the inner skins, being highly stressed in compression, should be different from the outer ones. The LVDT's inside the cabin were also mounted at the outer steel rig via rigidly connected aluminium cantilevers reaching in the inside through two rather small holes (d = 80 mm) drilled into the panels.

A monitoring of the climate conditions is also available for test phases II and III, providing information on the air temperature and relative humidity outside of the cabin.

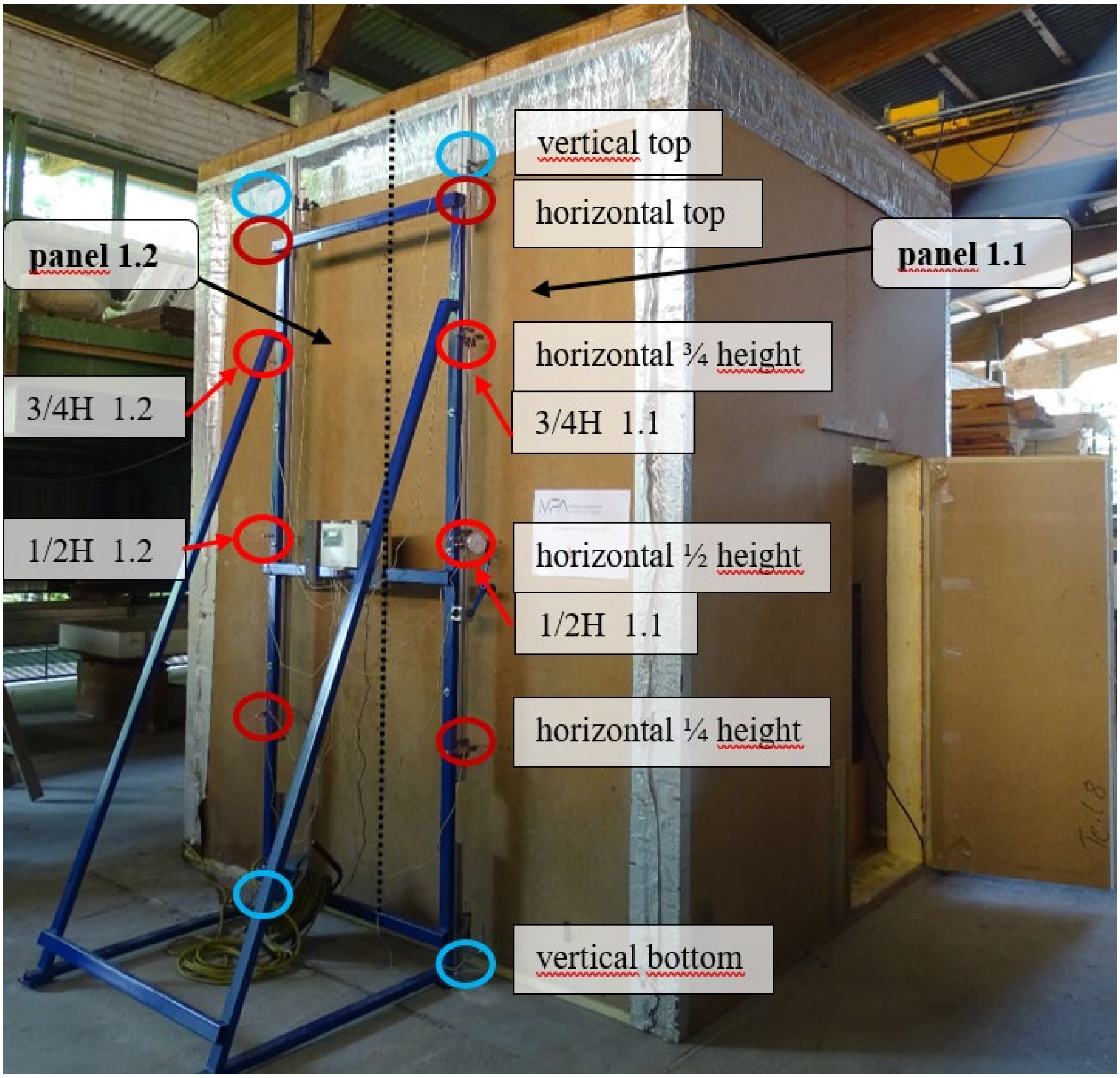

Fig. 5: View of the cabin with steel frame for mounting of the displacement transducers and positions of vertical and horizontal LVDT's and notation of the relevant LVDTs (1/2H_1.1, 3/4H_1.1 and 1/2H_1.2, 3/4H_1.2) for evaluation

Measurement during test phase IV

In test phase IV focussing on the effect of different sized holes in two opposite panels, strain gauges were mounted on the panel surfaces, too. This step was / is bound to the intention to monitor apart from global deflection representing the effect of the holes in smeared manner the long-term strain and hence stress (re-) distribution in the hole vicinity and in the studs at both hole sides. The LVDT's of test phase III are still active at rather the same positions, however, some of them had to be shifted because of the holes. The climate monitoring is continued as in test phases II and III. Note: The results of test phase IV are not discussed in this contribution as the measurements of the smaller hole sizes H1 are still ongoing and a discussion of the assumed hole size-effect is presently not possible.

4. RESULTS

4.1 Climate evolution in test phase I

The climate at the outside of the test cabin, affecting the moisture content of the outer skin, is shown in Fig. 6. The correlation between temperature and relative humidity with the moisture contents of particle boards has been investigated by several authors [11-13]. Quantitative relationships for particle boards manufactured with different hot setting adhesives (PF, MUF, MDI) are given by Drewes [13] depending on board thickness with the general format:

$$u(\varphi, \vartheta) = e^{(a_0 + a_1\varphi + a_2\varphi^2 + a_3\varphi^3 + a_4\vartheta)} \tag{3}$$

with

φ = relative humidity in %,

ϑ = air temperature in °C.

For MDI (methylene diphenyl diisocyanate) bonded particle board of 16 mm thickness as used for the investigated SIPs, parameters

$a_0 = 1.8953$, $a_1 = 0.02124$, $a_2 = -0.3783 \cdot 10^{-3}$, $a_3 = 3.266 \cdot 10^{-6}$, $a_4 = -0.00291$

are specified.

Based on Eq. (3) and the respective MDI parameter values the moisture content of the outer skin has been evaluated by means of the recorded climate data and is further amplified by the seasonal temperature changes. The particle board moisture varies throughout any of the three recorded years very roughly from 23% in winter to about 13% in summer. The calculated moisture contents are fully applicable to the outer face of the outer skin and decrease to the inside. In the cabin inside the climate was characterized by a constant temperature of 20°C and a relative humidity variation in the range of 35 – 55% (graph not shown here for the reason of paper length). These inside climate conditions result in surface moisture contents of about 7.5% to 8.5%. The calculated moisture content derived from the climate data conform in case of the inside skins very well with the measured moisture contents obtained from the particle board samples stored inside. In case of the outside skins the measurements forwarded moisture contents in the range of 10.5% in summer to 15% in winter. These moistures are lower as compared to the calculated ones especially regarding the winter months. This discrepancy is to some extent due to the fact the measured moistures, based on weighing represent the total bard thickness and hence include retardation effects and do not represent the equilibrium state.

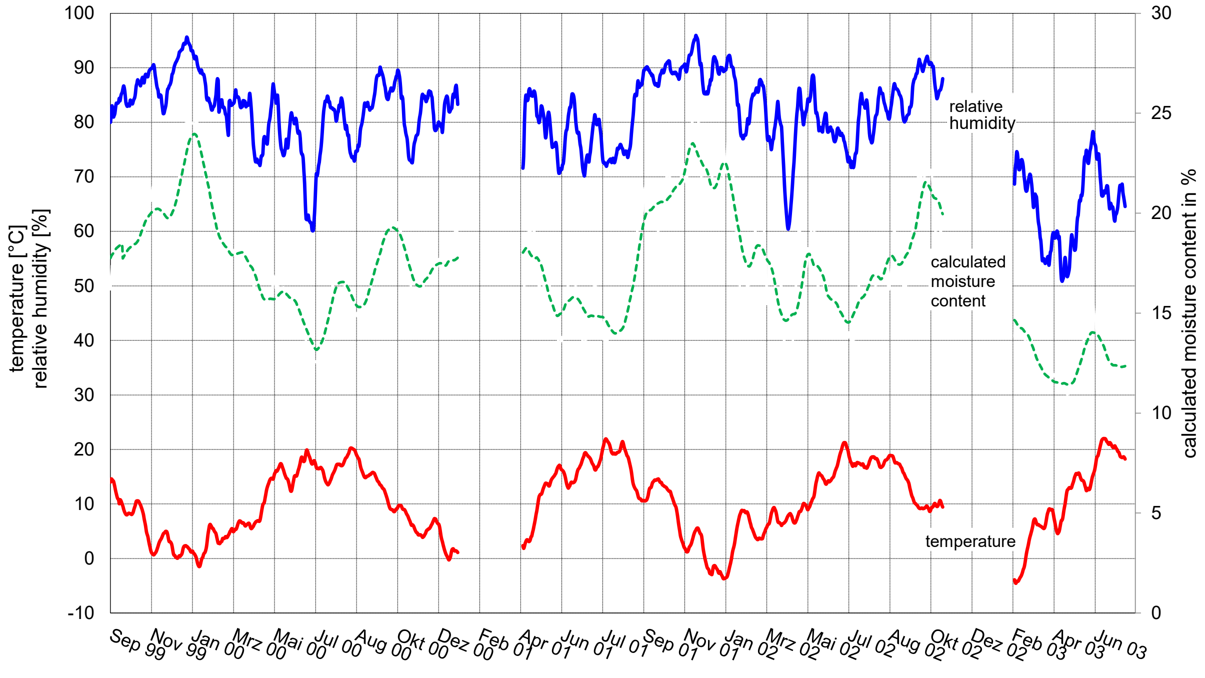

Fig. 6: Evolution of the outside climate and calculated equilibrium moisture content of the outer skins of the SIPs acc. to Eq. (3) [13]

4.2 Horizontal displacements during phase I (primary loading)

The deflection development within the first 48 hours, 1000 hours and 3 years of test phase I (September 1999 to August 2002) of the panels 1.1 and 1.2 (wall 1) are shown in Fig. 7a – c. For LVDT notations compare Fig. 5. The initial mean horizontal mid-span deflection in outward direction was 0.72 mm, increasing degressively in linear visco-elastic manner to 1.76 mm after 48 hours (Fig. 7a). The deflections in the quarter points were rather affine to those at mid-span although the direction of the initial elastic quarter point deformation seems rather strange. However, immediately after ramp loading the displacements changed in the first creep phase into the same direction as the mid-span deflection.

Fig. 7b depicts the displacement evolution between 0-1000 hours. In a rough approximation the deformations increase linear due to moisture uptake of the outer particle board skins and mirror desorption inside. Within the first 1000 hours from 28th September to mid-November 1999 the relative humidity of the outside climate changed (mean values) from about 80% to 87% while the temperature decreased from 14°C to 7°C. Contrary at the inside of the cabin the relative humidity decreased slightly from 55% to about 50% while the controlled temperature remained constant at 20°C as throughout the hole test phase I.

The resulting roughly linear relative humidity and temperature differences between the inside and outside panels during the first 1000 hours can be seen in Fig. 7c. The quantitative correlation of the deflection increase with the moisture difference of inside and outside panel is discussed in a separate paper.

The displacements and climate changes evolution over the first three years are given in Fig. 7c. A very similar displacement behaviour can be seen in any year following the seasonal climate changes acting predominantly at the outside panel. The relative humidity inside the cabin follows the outside variation in damped manner with an amplitude of about ΔRH = 15% (RH = 40% - 55%). It can be seen, that the mid-span deflection varies throughout the year by roughly 8 mm with large outward displacements in January / February and small deflections in summer (July / August). This seasonal displacement variation is caused by almost affine differential moisture and temperature variations as shown in the lower part of Fig. 7c.

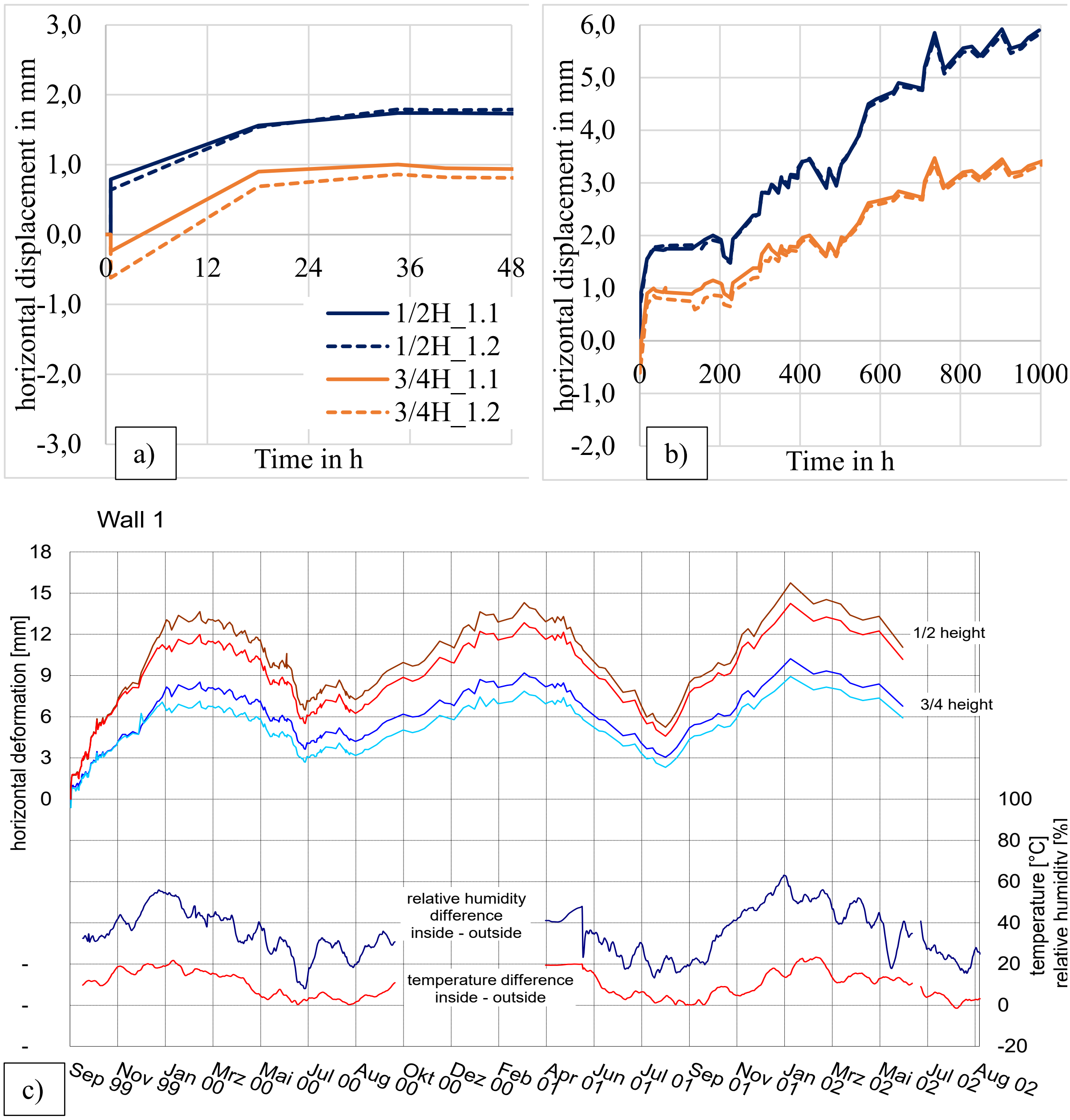

Fig. 7: Evolution of the horizontal outwards deflection during test phase I of panels 1.1 and 1.2 for different time periods after load application. a) 48 hours, b) 1000 hours and c) 3 years (further shown is the variation of the temperature and relative humidity difference ΔT and ΔRH between inside and outside of the cabin)

4.3 Displacements during test phase II (unloading) (July 2021 - April 2022)

After installing the new monitoring equipment all measurement values were tared immediately before taking away the loading. Analogous to test phase I, Figs. 8 a-c show the horizontal deflection for the time periods 48 hours, 1000 hours and ten months after unloading of the walls. The initial horizontal inward deflection at mid-height of the outer panels 1.1 and 1.2 is at the mean level roughly 1.0 mm (see Fig. 8a). This value is slightly higher than the outward deflection at the same points at the initial load application in test phase I, obtained 22 years earlier.

As the measuring interval in the first phase after unloading was very short, one can see immediately after unloading the day / night correlated deflections representing noise caused by temperature changes acting on the steel frame and transducers still to be smoothed out. Fig. 8b depicts the deflection evolution over the first 1000 hours after the unloading process. The graph reveals two superimposed deflection variations. Firstly, there are the daily changes as shown in Fig. 8a, now representing the zig-zag deflection pattern. Secondly, here is a superimposed deflection variation with a cycle length of about 500 hours. It is a bit surprising that unloading not only leads to negative displacements, i.e. reduction of the outward deflection, but also to positive outward displacement just by seasonal effects. This wall behaviour in unloaded state clearly reveals that the main driver, even over several months, is the climate and secondary the mechanical loading.

Fig. 8c depicts the deflections within 10 months after unloading. It can be seen that the climate, i.e. the relative humidity and hence moisture increase at the outer panel starting at mid-September 2021 up to end of January 2022 is closely mirrored by an increase of the outward displacement by almost 5 mm.

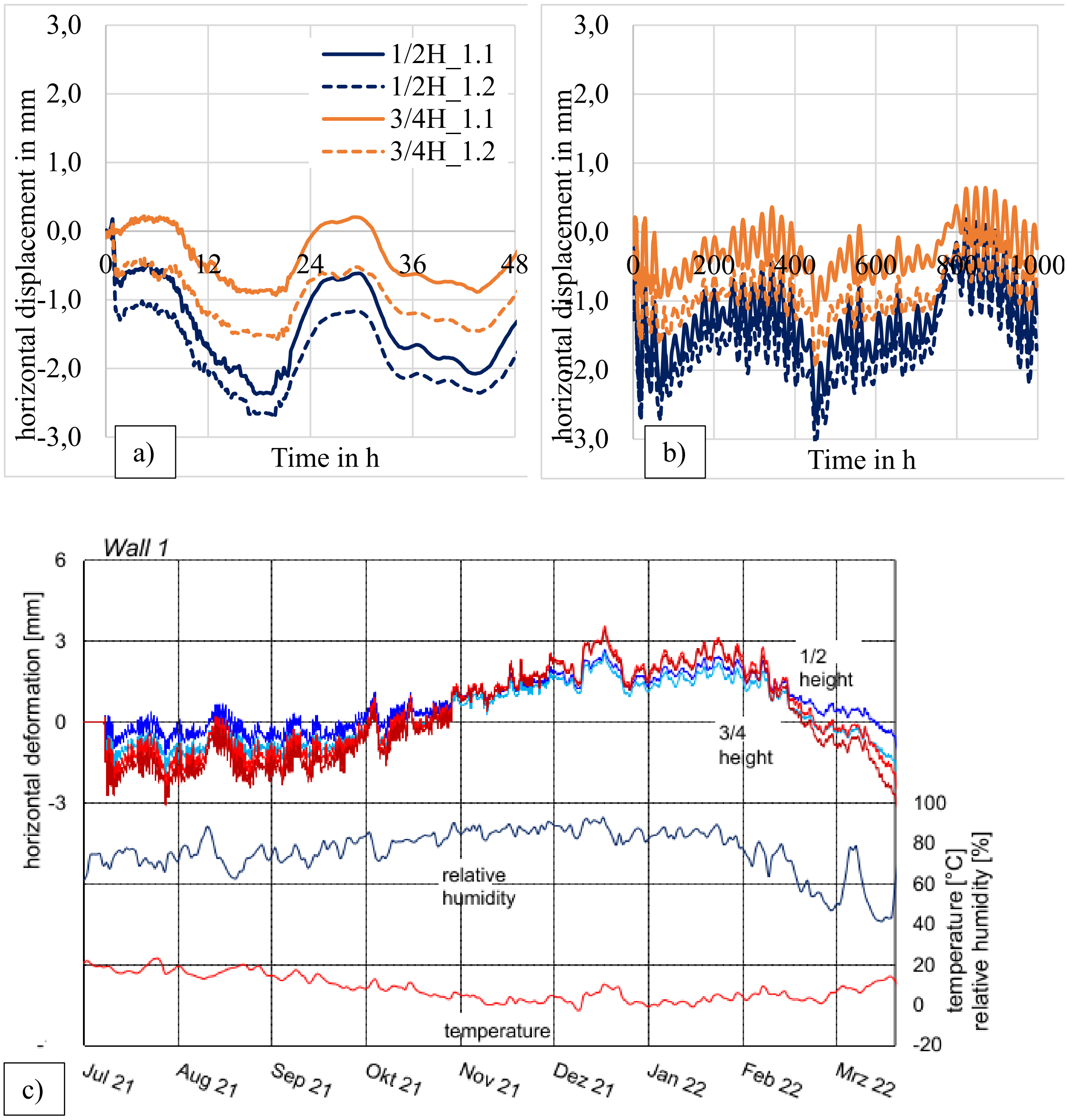

Fig. 8: Evolution of the horizontal predominantly inwards deflection during test phase II (unloading and without load) of panels 1.1 and 1.2 for different time periods after unloading. a) 48 hours, b) 1000 hours and c) 10 months (also shown are the outer air temperature and relative humidity)

4.4 Displacements during test phase III (Apr. 2022-July 2023)

As mentioned above, in this part, the reloading is done the same way as in the initial test phase I in 1999, now however, with LVDT's installed exclusively at the outside and inside of wall 1.

Fig. 9a depicts the horizontal displacements within the first 48h after loading. The mean initial outward deflection at mid-height of both panels 1.1 and 1.2 is

1.2 mm, i.e. roughly 1.5 times higher as compared to the initial ramp loading in 1999 and very close (5%) to the instantaneous unloading deflection in 2021. The increased initial deflection as compared to the first loading in 1999 should partly be owed to a higher moisture content of the panels, as the load application was now in April whereas initial loading was at end of September. The presumably temperature caused displacement evolutions shown in Figs. 9a, b, with pending curve smoothing, are not discussed. Fig. 9c presents the deflection evolution from March 2022 to July 2023. Disregarding the temperature induced noise, a continuous reduction (approx. 2 mm) of the initial outward displacement can be seen in the time period from mid-March to end of August which is related to a decreasing relative humidity and an increasing temperature. From end of July onward a pronounced humidity driven increase of the deflection in outward direction by about 5 mm occurs.

4.5 Vertical displacements during test phases II and III

Since there were no results for vertical deformations for test phase I vertical deformation measuring at the top of the outer edges of panels 1.1 and 1.2 was started at test phase II. The results are shown in Fig. 10a. Immediately after unloading the vertical deflection in the upper direction of the outer particle board is of minor magnitude (0.1 to 0.5 mm) and superimposed by daily climate / temperature variations, too.

Considering the main axial load bearing inner skin one would expect (assuming $E_{c,mean}$ = 2500 N/mm² and $\sigma_{s,in}$ = 1,07 N/mm² and height of the measuring point h = 2950 mm) an upward deformation of about 1.26 mm would be expected. This value is about four times higher than the measured vertical deformation of the outer skin. For a better understanding of the obtained mismatch between measured and roughly approximated elastic vertical deformation, additional vertical LVDT’s were mounted at the inner skin for the second loading of the cabin (test phase III), see also chapter 3. The results of the vertical deformations of both, the outer and inner skins, are shown in Fig. 10b. As expected, a very pronounced difference of the vertical compressive deformation between the inner and outer skins can be seen. The mean vertical deformation of the inner skin is now about 1.35 mm, which conforms very well to the calculated value.

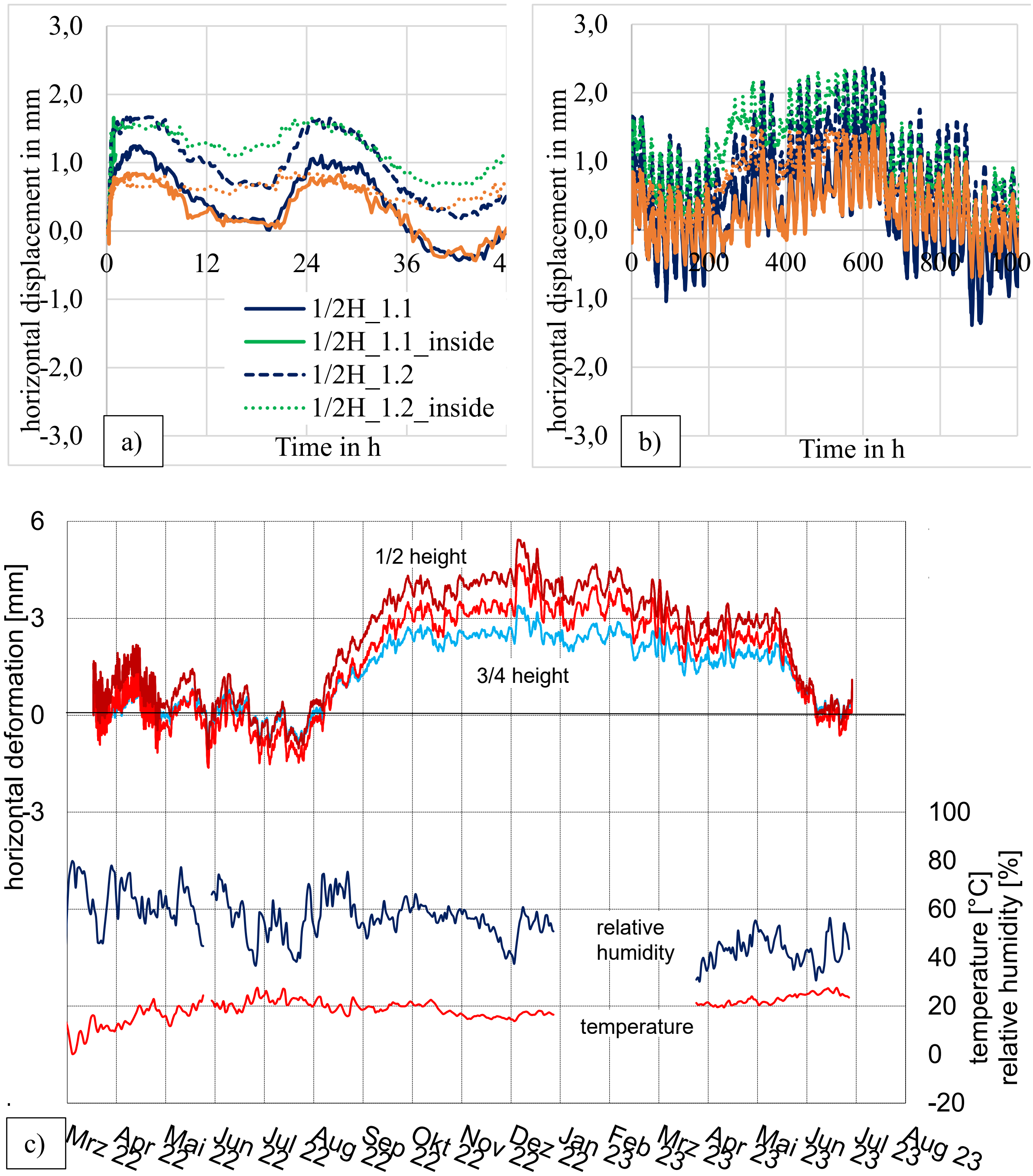

Fig. 9: Evolution of the horizontal outwards deflection during test phase III of panels 1.1 and 1.2 for different time periods after load application. a) 48 hours, b) 1000 hours and c) 9 months (also shown are the outer air temperature and relative humidity)

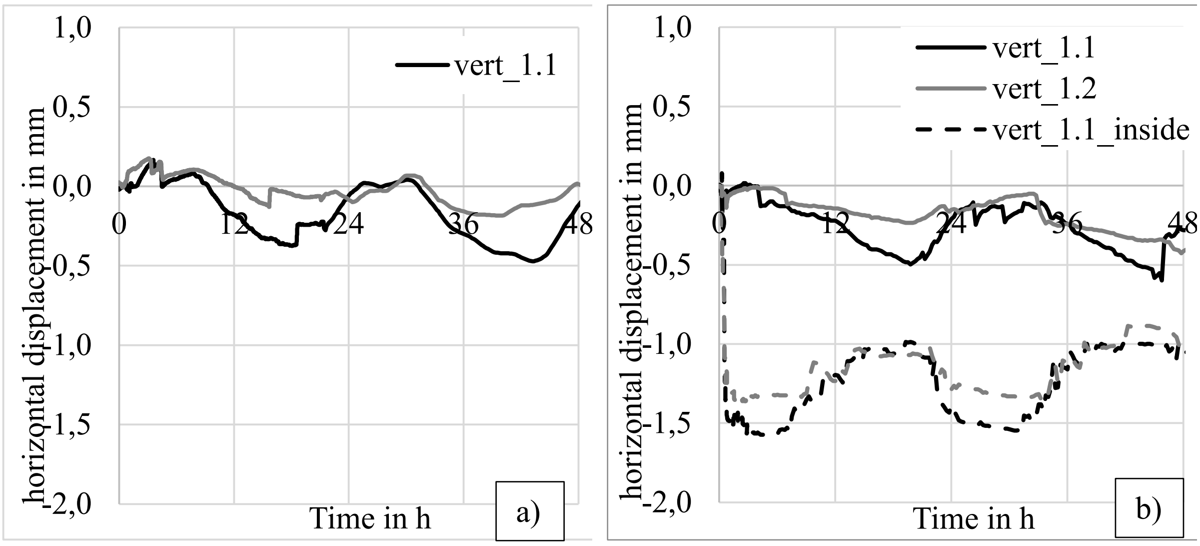

Fig. 10: Evolution of the vertical compressive deformation during test phases II and III of the outer and inner skins of panels 1.1 and 1.2 for a time period of 48 hours after unloading (a) and reloading (b)
a) test phase II (unloading; measurement of vertical deformation exclusively at outer skin, b) test phase III (reloading), measurement of vertical deformations at outer and inner skins

5. PROPERTIES OF THE PANEL COMPOUND

In order to enable a realistic computation of the deformations and finally of the load capacity behaviour of the elements the relevant material properties of the skins made from particle board and of the PUR foam core have to be known. The exclusive use of strength and stiffness data taken from literature and standards is considered being too imprecise.

5.1 Properties of the particle board

In case of the particle boards used for the skins essentially the in-plane compression and tensile properties (strength and MOEs) as well as the plate bending values are of prime relevancy. Below it is reported on the finished compression tests.

The tests were performed with specimens acc. to EN 789 [7], Annex A, which specifies to bond three stripes of the boards on the wide side to overcome the buckling problem which would occur while compressing only one single stripe. The specimen dimensions (3 x panel thickness x widths x lengths) were 3 x 16 mm x 50 mm x 270 mm. In total 2 x 8 specimens were manufactured and tested. In order to enable an integral assessment of the particle board properties of all four non-load bearing walls, four specimens were made from each wall. Hereby throughout two specimens were manufactured from the outer sandwich panel skin and two from the inside skin. So, in total there were eight compression specimens from the outer and inner skins representing each wall with the same number of specimens.

Before testing all specimens were stored in climate 20°C / 65%RH resulting in an equal moisture content of 10.7% in average. In [7] a gauge length of 75 to 150 mm for dial gauges or LVDTs is specified for measurement of modulus of elasticity (MOE). Unfortunately, a readily available strain gauge-based device of MPA had a restricted gauge length of 50 mm. The impact of the reduced measurement length is, however, considered rather marginal as the bonding of three plate stripes leads to a significant homogenization. The MOE evaluation was performed according to [7] by a linear fitting of the stress-strain curve between 10% and 40% of ultimate load / compressive strength. Fig. 11a shows the realized test set-up with the mounted strain measuring device and Fig. 11b depicts a typical stress-strain curve of the conducted compression tests including the linear curve approximation. Fig. 12 depicts a typical fracture appearance of a specimen.

Table 1a contains a statistical evaluation of the test results, separately for the specimens of the climate exposed outer skin boards and for the interior panels. Table 1b gives the results for the combined specimen samples from the outer and inner skins. Density ρ_{12} of the specimens from inside and outside skins is almost identic and denoted by an average mean value of 789 kg/m³ altogether with a very low coefficient of variation of only 2%. It can be seen that the means of MOE and compressive strength of the outer and inner skins are almost equal. Slightly lower values were obtained for the outer skin boards altogether with slightly higher coefficients of variation. Consequently, the inner and the outer skin results differ somewhat more expressed at the 5% quantile level. The minorly higher stiffnesses and strengths of the particle boards at inside of the cabin were observed for all four disassembled panels. Hence it might be supposed that the impact of climate changes over many years affects the stiffness and strength properties of the particle boards in minor manner.

The obtained MOE and compression strength level is very high in absolute terms, i.e. when compared to characteristic values specified, e.g. in EN 12369-1 [8] for high strength particle boards for use in humid conditions. The obtained characteristic compressive strength and the mean MOE values exceed the standard values, specified for structural design of particle boards (13 – 20 mm thickness) of type

P7, by 12% and 14%, respectively. The obtained high strength and stiffness properties have to be seen in the context of the very high density of the investigated particle boards which exceed the characteristic value given in [8] by 27%.

Table 1a: Statistical evaluation of the results of compression tests and density measurement of the particle board material of the SIPs elements. Given are compressive stiffness E_c, compressive strength f_c and density ρ_{12} separately for the inner and outer skin

distribution parameter	$E_{c,inside}$	$E_{c,outside}$	$f_{c,inside}$	$f_{c,outside}$	$\rho_{12,inside}$	$\rho_{12,outside}$
	N/mm²	N/mm²	N/mm²	N/mm²	kg/m³	kg/m³
mean	3260	3166	18.5	17.7	796.0	781.5
std	264	319	1.02	1.47	12.7	20.5
COV	8.1%	10.1%	5.5%	8.3%	1.6%	2.6%
5%-quantile	2926	2752	17.1	15.8	777.5	750.6

Table 1b: Statistical evaluation of the results of compression tests and density measurement of the particle board material of the SIPs elements. Given are compressive stiffness E_c, compressive strength f_c and density ρ_{12} combined for the inner and outer skins

distribuation parameter	E_c	f_c	ρ_{12}
	N/mm²	N/mm²	kg/m³
mean	3214	18.1	788.7
std	287	1.30	18.1
COV	8.9%	7.2%	2.3%
5%-quantile	2786	16.1	760.7

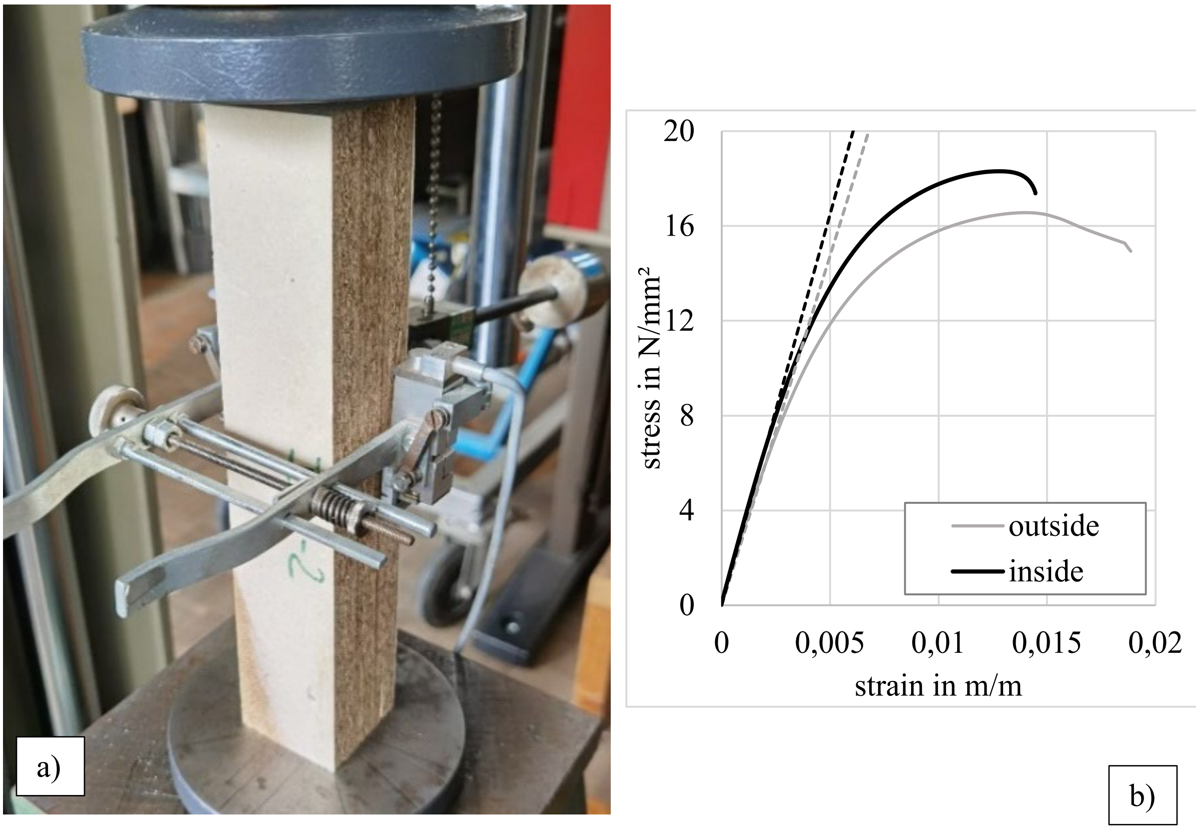

Fig. 11: Axial compression tests with particle board material of the unloaded cabin walls 3 and 4
a) photograph of the realized test set up
b) exemplary stress-strain curves of an inner and outer particle board

Fig. 12: Particle board compression strength specimen with typical failure

5.2 Properties of the foam and particle board interface

Tension and compression tests perpendicular to the skin face of compounds with a foam core in order to obtain strength and stiffness values for the bulk foam material are standardized (ISO 22542 [10]). Hence no further details on test set-ups are given. Very different from the mentioned tests is the non-standardized interface shear test performed by Kingspan for stressed skin element compounds. The principle of the company's specific test set-up is shown in isometric view in Fig. 13a. Fig. 13b depicts the realized test set-up with a mounted specimen. As can be seen, the width of the shear area is confined by two saw cuts parallel to compression shear length.

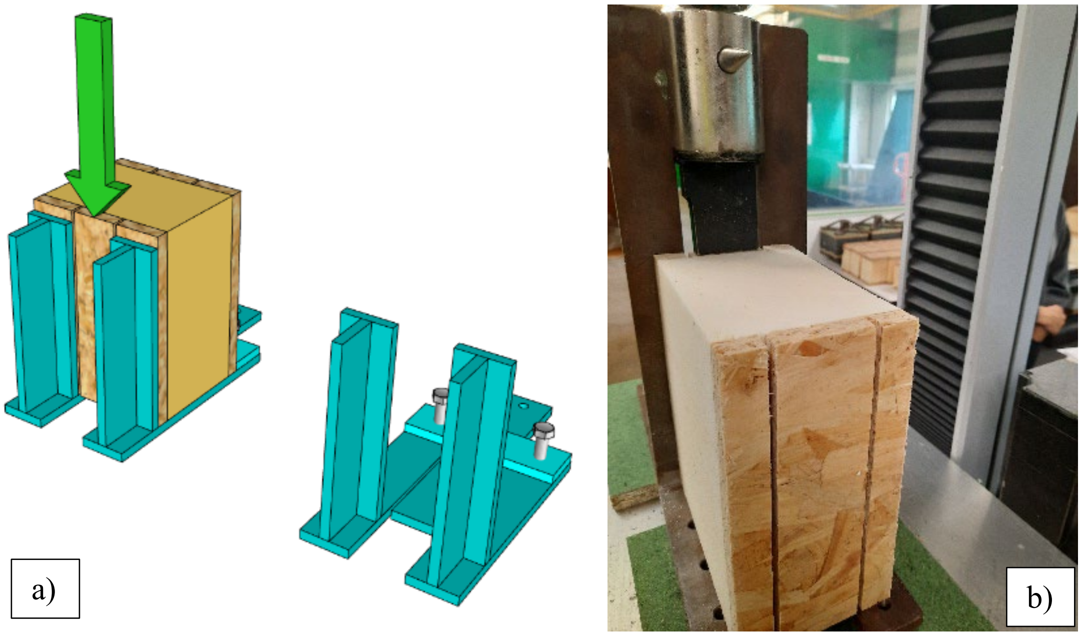

Fig. 13: Principle (a) and realization (b) of the test set-up for an interface shear test between board and foam of sandwich panels

The results of the tension and compression tests on the foam core perpendicular to the skin faces foam core, and of the skin-core interface shear tests are given in Table 2 altogether with respective requirements stated in the approvals [1] and [3]. It can be seen that the test results obtained for each strength property with a limited number of specimens (six or seven) conform with regard to mean and 5% quantile values in almost all cases well with the approval requirements stated in [1] and [3]. Compression strength at 10% strain actually exceeds the required threshold level significantly. In case of the interface shear strength a significant difference was obtained for the particle board – foam core interface of skins exposed to the inside and outside of the cabin, respectively. The interface shear strength of the inside skin shows a very small scatter (COV = 6%) and exceeds the required strength level by a factor of two. Contrary hereto, the outside oriented interface shows a much higher scatter (COV = 18%) and much lower strength values which are about 40% of the mean and characteristic strength level of the inside interface.

It might at first view be argued that this strength difference stems from a more pronounced aging of the outside interface exposed to a significantly higher climate impact. However, an alike probable explanation is that the difference is production bound and stems from the sequence of the foam - particle board bond formation where the liquid foam is firstly sprayed on the "bottom" skin and then after expanding adheres to the "top" panel with a qualitatively lower bond behavior. Bottom and top panel here might be the interfaces "1" and "2". This open question is followed up in detail in subsequent investigations.

Table 2: Statistical evaluation of compression and tension tests on the foam core and for shear tests on the core-particle boar interface. Also given are the required ETA [3] values

distribution parameter	**compressive strength[1)] perp. to skin plane**	**tensile strength perp. to skin plane**	**interface shear strength**	
			interface 1 (inside)	**interface 2 (outside)**
	N/mm²	N/mm²	N/mm²	N/mm²
mean	0.200	0.086	0.135	0.287
std.	0.022	0.017	0.024	0.016
COV	11.2%	19.9%	17.8%	5.7%
minimum	0.153	0.063	0.107	0.265
5% quantile value	0.167	0.067	0.110	0.267
required value acc. to ETA [1]	0.08	0.07	0.12	0.12

[1)] at 10% strain

6. CONCLUSIONS

The experimental results on axially loaded wood-based sandwich panels (SIPs) with outer skins made from particle board and an interior core from PUR hard foam proved a so far not validated excellent mechanical long-term behaviour. The on-going full-scale experiments with TEK-SIPs, now lasting for 24 years, are performed in differential climate, whereby the outside skins are exposed to sheltered outdoor climate and the inside skins within the cabin experience constant or damped climate variations. The experiments are further distinguished by the highly eccentric vertical load application, resulting in a tension loading of the outer skin.

No pronounced visco-elastic deflection increases of the elements due to creep of the wooden skins and the shear loaded foam core was found. The measured variations of the horizontal and vertical deformations of the eccentrically loaded wall elements resulted mainly from the climate impact and hereby mostly from the difference of relative humidity and moisture content of the outside skins. The residual strength and stiffness properties of both compound materials and of their bonded interface showed in majority no indications of excessive creep or even damage, i.e. of duration of load.

The presented results prove apart from the highly resilient mechanical long-term behaviour of the wood-based SIPs that the very high creep related k_{def} values specified for particle boards in Eurocode 5-1-1 [9] are much too severe for in-plane compression loading of this type of reconstituted materials.

REFERENCES

[1] Z-9.1-315: *German technical Aproval: Sandwich Elements as Structural and Planking Wall and Roof components* (in German) Manufacturer: Kingspan TEK GmbH, Klosterfelde, Germany, Deutsches Institut für Bautechnik (DIBT), Berlin (1995, 2001, 2006)

[2] AICHER, S., HÖFFLIN, L.: *Long-term performance Test of eccentrically loaded sandwich wall elements with woodbased skins*, in Otto-Graf-Journal. Vol 10 (1999), pp. 128-143

[3] ETA-11/0466: *European Technical Assessment; Kingspan Tek ® - Prefabricated Woodbased Loadbearing Stressed Skin Panels*, Manufacturer: Kingspan Insulation Ltd. United Kingdom (2012, 2018)

[4] FINDLEY, W.N., LAI, J.S., ONARAN, K.: *Creep and relaxation of nonlinear visco-elastic materials.* North-Holland Series in Applied Mathematics and Mechanics, North-Holland Publ. Company, Amsterdam, Netherlands, 1976

[5] AICHER, S.: *Computation and design of axially loaded sandwich wall elements with wood-based sheathings* (in German). Bautechnik 66 (5): 159-168, Ernst u. Sohn, Verlag f. Architektur u. technische Wissenschaften; Berlin, 1989

[6] SIMON, K., AICHER, S.: *Long-Term Experiments with a full-scale Sandwich Timber-Urethane-Panel (TEK) Test House*. Status Report December 2022. Materials Testing Institute (MPA), University of Stuttgart

[7] EN 789:2004: *Timber Structures – Test Methods: Determination of mechanical properties of wood based panels*, European Committee for Standardization CEN, Brussels, Belgium

[8] EN 12369-1:2001: *Wood-based panels - Characteristic values for structural design - Part 1: OSB, particleboards and fibreboards*, European Committee for Standardization CEN, Brussels, Belgium

[9] EN 1995-1-1:2010: *Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings*, European Committee for Standardization CEN, Brussels, Belgium

[10] ISO 22452:2011: *Timber structures – Structural insulated panel walls – Test methods*, International Organization for Standardization ISO, Geneva, Switzerland

[11] ROFFAEL, E., SCHNEIDER, A: *Zum Sorptionsverhalten von Holzspanplatten, Teil 1: Einfluß des Bindemitteltyps und des Bindemittelaufwands auf die Gleichgewichtsfeuchtigkeit,* Holz Roh-Werkstoff 36:393-396; 1979, *Teil 2: Einfluß der Holzart auf die Gleichgewichtsfeuchtigkeit.* Holz Roh-Werkstoff 37: 259-264; 1980, *Teil 3: Untersuchungen an mit Phenolformaldehydeharzen gebundenen Spanplatten.* Holz Roh-Werkstoff 38:151-155; 1981, *Teil 4: Einfluß von Zusatzstoffen auf die Gleichgewichtfeuchtigkeit*. Holz Roh-Werkstoff 39:17-23, Springer Verlag, 1978

[12] GRESSEL, P.: *Influence of sorption behavior on particleboard properties*. Holz Roh-Werkstoff 42: 393-398, Springer Verlag (1984)

[13] DREWES, H.: *Equilibrium moisture contents for wood based construction materials.* In: Holz Roh-Werkstoff 43: 97-103, Springer Verlag, 1985