INFLUENCES OF THE PRODUCTION PROCESS ON THE LOAD-DEFLECTION BEHAVIOUR OF THREE-LAYERED SANDWICH PANELS WITH GFRP-CONNECTORS

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A b s t r a c t

Prefabricated reinforced concrete walls with integrated insulation feature a smaller cross-sectional thickness as comparable walls constructed with in-situ concrete. A new tendency in the construction industry is to fasten the two concrete layers with discrete fastenings which run through the insulation layer. The fasteners are made of glass-fibre reinforced polymer (GFRP) bars, which are uniformly distributed over the layer area. In order to set up a concept for the design of such three-layered sandwich walls, it is important to define its load-deflection behaviour, followed by the determination of the internal forces. These are required for the verification of the ultimate and serviceability limit state of the sandwich panels. To investigate the load-deflection behaviour, wall strips with a length of 3600-4000 mm and a width of 800 mm were tested. The sandwich walls consisted of a insulation and two concrete layers. Two types of insulation material were used for the middle layer of the sandwich panels: extruded polystyrene foam (XPS) and expanded polystyrene foam (EPS). Furthermore, the influence of two different thicknesses of the middle layer was investigated, i.e. 60 mm and 140 mm. In order to investigate the load-deflection behaviour, 4-point bending tests were carried out. Due to the higher shear modulus of the extruded polystyrene foam (XPS), it was expected that the behaviour of the specimens with XPS-insulation was stiffer. This paper is aimed to present the results of the test series and to explain the reasons for the different load-deflection behaviours.

S t r e s z c z e n i e

Prefabrykowane betonowe ściany ze zintegrowaną izolacją mają mniejszy przekrój a ich właściwości są porównywalne ze ścianami monolitycznymi. Nową tendencją w konstruowaniu takich ścian jest połączenie dwóch warstw betonu za pomocą dyskretnych, ruchomych łączników. Łączniki wykonane są ze wzmocnionych włóknem szklanym polimerowych prętów (GFRP). Opracowanie koncepcji projektowania takich trójwarstwowych ścian wymaga między innymi określenia stanów granicznych użytkowania i nośności. W artykule przedstawiono wyniki badań doświadczalnych takich ścian a w szczególności relacji obciążenie-ugięcie. Badano listwy ścienne o długości 3600-4000 mm i szerokości 800 mm, składające się z dwóch warstw betonu i izolacji. Zastosowano dwa rodzaje materiału izolacyjnego: polistyren (XPS) i styropian (EPS). Ponadto, badano wpływ dwóch różnych grubości warstwy izolacyjnej: 60 mm i 140 mm. W celu określenia relacji obciążenie-ugięcie przeprowadzono badania zginania elementów.

K e y w o r d s : **Sandwich panels; GFRP-connectors.**

1. INTRODUCTION

In housing and industrial construction, the rising requirements in terms of the energy efficiency require innovative ideas in all parts of the building technology. Additionally, there are high demands for an easy and competitive construction of the buildings. This research project deals with the design of prefabricated sandwich-panels. Prefabricated reinforced concrete walls with integrated insulation feature a smaller cross-sectional thickness as comparable walls constructed with in-situ concrete. In comparison to in-situ casting, prefabrication is faster and more competitive. By the use of multiple layered wall panels, the energy efficiency of buildings is improved. To reduce thermal bridges, uniformly distributed GFRP-connectors replace the steel lattice girders which are traditionally used for the connection of the two concrete layers.

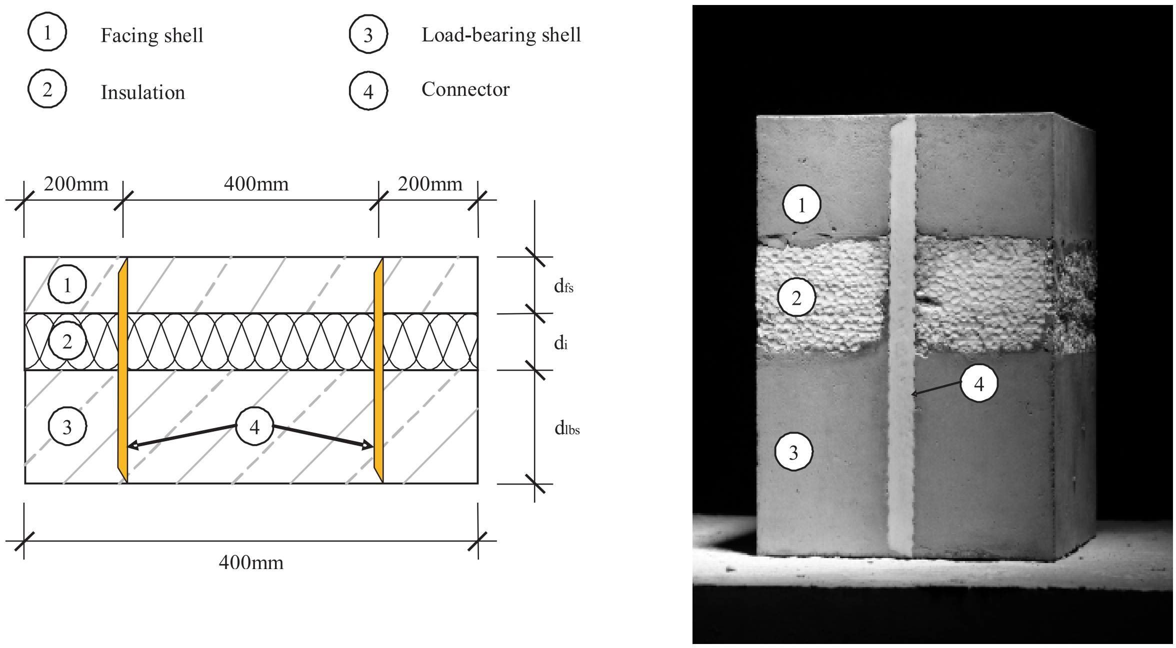


Figure 1.
Cross-section of the specimens

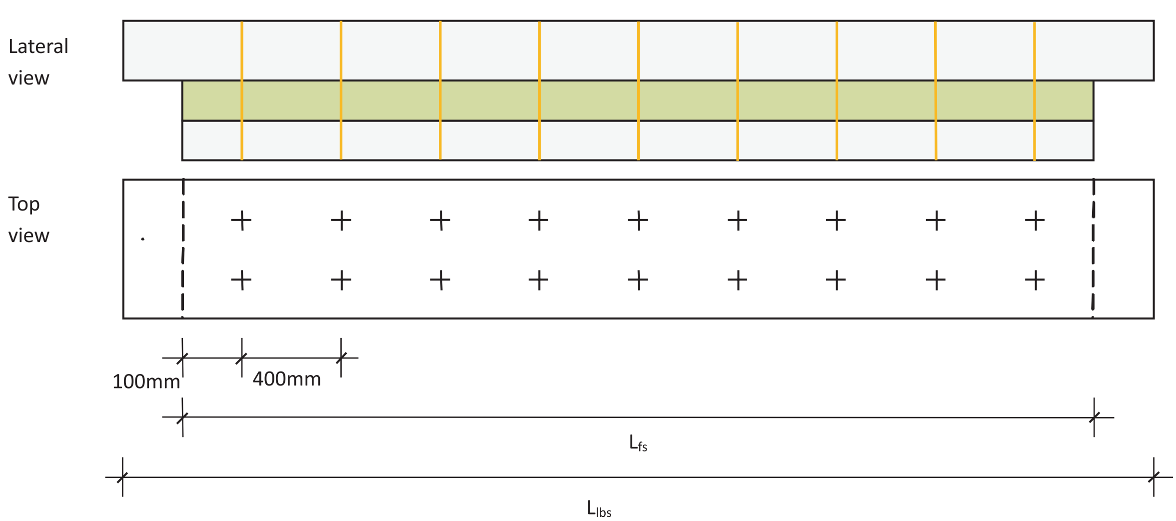


Figure 2.
Lateral and top view of the specimens

2. TEST SERIES, SPECIMENS AND MANUFACTURING PROCESS

For the verification of the ultimate and serviceability limit state of the sandwich panels, the internal forces of the sandwich panels need to be determined. Therefore, it is important to analyse the load-deflection behaviour of the three layered sandwich panels. To investigate the load-deflection behaviour detailed tests were worked out. The specimens consisted of two concrete layers: i.e. an internal wall panel (load-bearing shell) and an external wall panel (facing shell). The enclosed core-layer consisted of insulation material. Discrete connectors which ran through the insulation layer were used to connect the two concrete layers. The length of the connectors was the same as the thickness of the sandwich-panel cross-section (Figure 1 and Figure 2).

The concrete layers were constructed with concrete of normal strength (C35/45) and were reinforced with steel bars and meshes. Because of the small thickness of the facing shell, the locations of the points of load application as well as the locations of the supports were transferred to the load-bearing shell. Due to the reason that the horizontal, relative displacement between the concrete layers was not restrained, the facing shell was 30 cm shorter than the load-bearing shell.

The middle layers of the three-layered sandwich panels were different in type and thickness of the insulation material. The two types of insulation material were used in order to examine the influence of the shear modulus of the insulation material on the load-deflection behaviour. Therefore, extruded polystyrene foam (XPS) and expanded polystyrene foam (EPS) with two different thicknesses were used.

Both insulation types had a smooth surface. As connectors, bars made of glass-fibre reinforced polymer (GFRP), which were uniformly distributed over the layer area, were used. The biggest advantages of GFRP are its chemical resistance and very low heat conductivity. Due to these advantages the thermal bridges can be reduced. Table 1 shows the test series.

The specimens were produced in a precast factory to simulate real conditions. As a first step, the facing shell was reinforced with a minimum reinforcement. Afterwards, the facing shell was cast, and compacted with the use of a vibrating formwork-table. Then, the insulation panels were laid on the concrete and the connectors were stuck through the insulation layer into the fresh concrete, followed by further compaction with the formwork table. Finally, the load-bearing shell was reinforced, cast and compacted. The manufacturing process of the specimens differed in one point. The specimens S1, S2, S5 and S6 were cast by means of the wet-on-wet method within two hours. In comparison, the specimens S3 and S4 were manufactured in two days. In this way, the concrete of the facing shell hardened without any additional pressure on the insulation layer, due to the reasons that the load-bearing shell was casted on the second manufacturing day. Table 2 shows in diagram form the differences in the manufacturing process of the six specimens.

As a result of the shear stress, the core layer might fail in two different ways. On the one hand, the load in the core layer might reach the value of the maximum shear stress resistance of the insulation. On the other hand the bonding between insulation and concrete might fail due to the shearing force. Two additional test series were carried out to determine precisely the characteristics of the core layer. Figure 3 shows the testing setup to determine the shear strength resistance [1]. The test results show that the shear strength of the extruded polystyrene foam (XPS) is about 1.75 times higher than the strength of the expanded polystyrene foam (EPS).

Table 1.
Summary of the tested parameters

Specimen	Insulation	Thickness of facing shell d_{fs}	Thickness of Insulation d_i	Thickness of load-bearing shell d_{lbs}	Length of facing shell L_{fs}	Length of load-bearing shell L_{lb}	Bearing distance
		[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
S1	XPS	60	60	100	3000	3600	3400
S2	EPS	60	60	100	3000	3600	3400
S3	XPS	60	140	100	3000	3600	3400
S4	EPS	60	140	100	3000	3600	3400
S5	XPS	60	140	140	3400	4000	3800
S6	EPS	60	140	140	3400	4000	3800

Table 2.
Production steps in precast factory

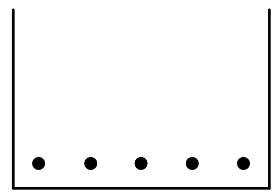
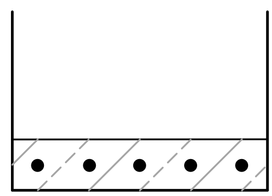
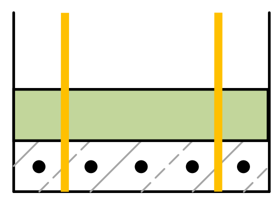
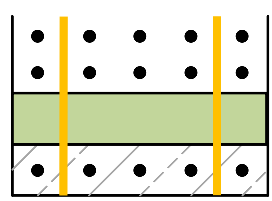
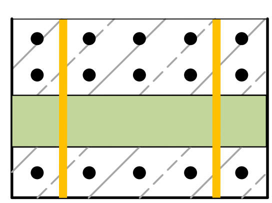
Production step		Specimen S1, S2, S5 and S6	Specimen S3 and S4
Reinforcing of the facing shell			
Casting of the facing shell			1st day
Installation of the insulation panels and connectors		1st day	
Reinforcing of the load-bearing shell			2nd day
Casting of the load-bearing shell			

Figure 3.
Expanded polystyrene foam (EPS) during shear test

The second test series was carried out to investigate the characteristics of the bond between the concrete and the insulation material. The general aim of these tests was to determine the maximum adhesive shear stress of the concrete-insulation bond. The specimens consisted of 300 mm wide, 300 mm long and 150 mm high concrete cubes. The cubes were cast on a 500 mm wide, 1000 mm long and 60 mm thick insulation slab. The insulation slab was glued onto a 20 mm thick timber panel. The load application was parallel and close to the contact surface between concrete and insulation. The load was applied by a hydraulic cylinder. The applied load was measured by a load cell. Behind the concrete cube, the lateral displace-

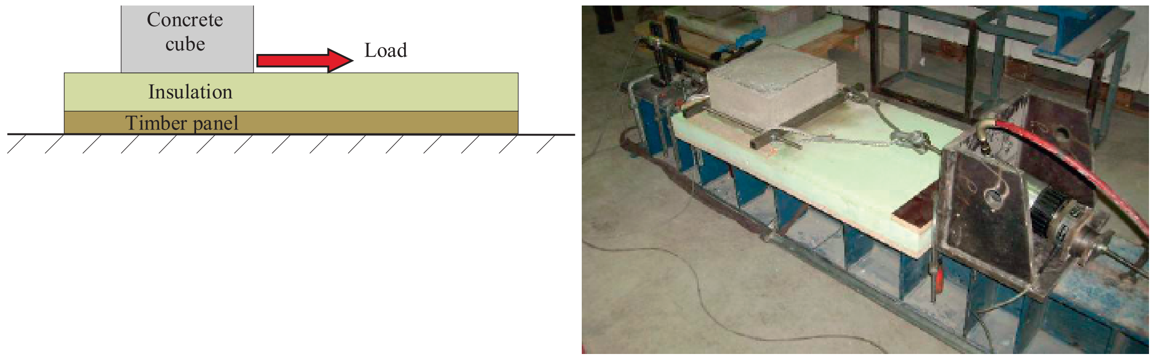


Figure 4.
Test setup of adhesive shear stress tests

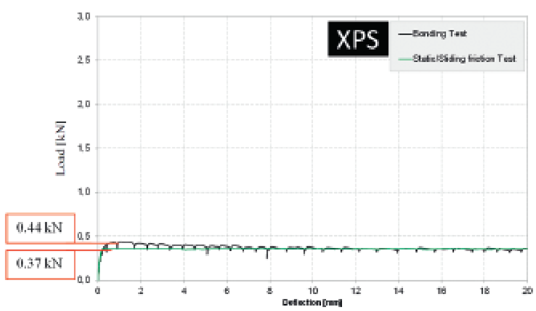


Figure 5.
Load-deflection curves of a selected specimen (XPS – V2) with XPS-insulation

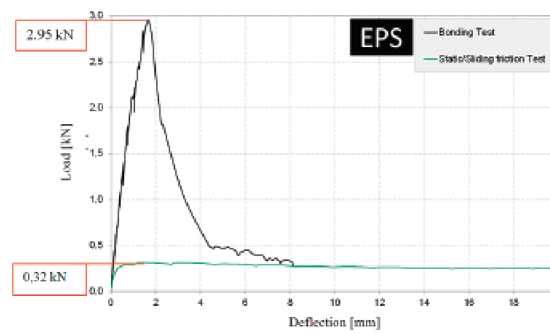


Figure 6.
Load-deflection curves of a selected specimen (EPS – V2) with EPS-insulation

Table 3.
Summary of the test results of adhesive shear stress tests

Specimen	Maximum loads (Bonding tests)	Maximum loads (Static/sliding friction test)	Average of the maximum adhesive shear stress (Bonding tests)	Average of the maximum static friction stress (Bonding tests)
	[kN]	[kN]	[kN/m²]	[kN/m²]
EPS – V1	2.42	0.32	27.20	3.63
EPS – V2	2.95	0.32		
EPS – V3	2.04	0.34		
XPS – V1	0.33	0.31	4.36	3.74
XPS – V2	0.44	0.37		
XPS – V3	0.41	0.33		

ment was measured with the help of transducers. Figure 4 shows the test setup of this test series. To determine the maximum adhesive shear stress, the load was increased until the bonding failed. Afterwards, a sliding friction test was carried out. With both insulation types (EPS, XPS), three specimens were cast and tested, respectively.

The results in Table 3 show, that the maximum adhesive shear stress of the concrete and the XPS-insulation is only 16 per cent of the maximum adhesive shear stress of the concrete and the EPS-insulation. The selected curves of the tests with the XPS insulation (Figure 5) show, that there is now significant difference between the bonding and the static friction resistance. This is clearly visible by comparing the curves "Bonding test" and "Static/sliding friction test" of the XPS specimen. In contrast, the bonding resistance between the concrete and the EPS insulation in the selected test is over nine times higher than the static friction resistance (Figure 6).

3. COMPONENT TEST

The specimens were tested with a 4-point bending test. The loading was split into two phases. Before the test was started, the specimens were stiffened with a steel beam to prevent any deflection caused by self-weight (Figure 7). Afterwards, the specimens were supported with the help of hydraulic presses. Next, the measurement was started and the presses under the specimens were lowered (first loading phase). Finally, the load was applied by the hydraulic cylinder until the system collapsed (second loading phase).

Figure 7.
Specimen before the test

Figure 8.
Specimen during the test

4. TEST RESULTS

By comparing the load-deflection curves of the specimens S1-S2 and S5-S6, it is obvious, concerning each pair of specimens, that the tests with EPS-insulation were stiffer than the tests with XPS-insulation (Figure 10). Between the test of the specimens S3 and S4 there were no significant differences. After the tests for the determination of the shear strength of the used insulation material [1], it was expected that the layer which consisted of XPS-insulation and GFRP-connectors would be stiffer than the layer with EPS-insulation and GFRP-connectors. Due to the fact, that for example the specimens S1 and S2 merely differ in the type of the insulation, it was expected that the specimen S1 shows a stiffer load-deflection behaviour than S2. The results of the elastic modulus tests of the concrete [2] are presented in Table 4.

Table 4.
Summary of the elastic modulus of the concrete

Specimen	Elastic modulus Facing shell [N/mm²]	Elastic modulus Load-bearing shell [N/mm²]
S1	27 479	25 831
S2	26 622	26 762
S3	23 743	24 693
S4	23 899	24 378
S5	23 867	24 692
S6	23 607	24 450

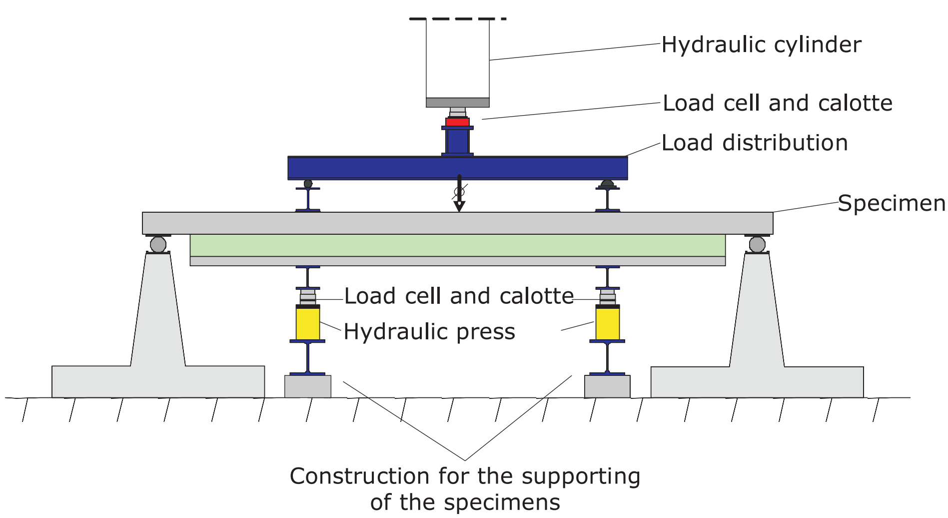


Figure 9.
Schematic test setup of a 4-point bending test

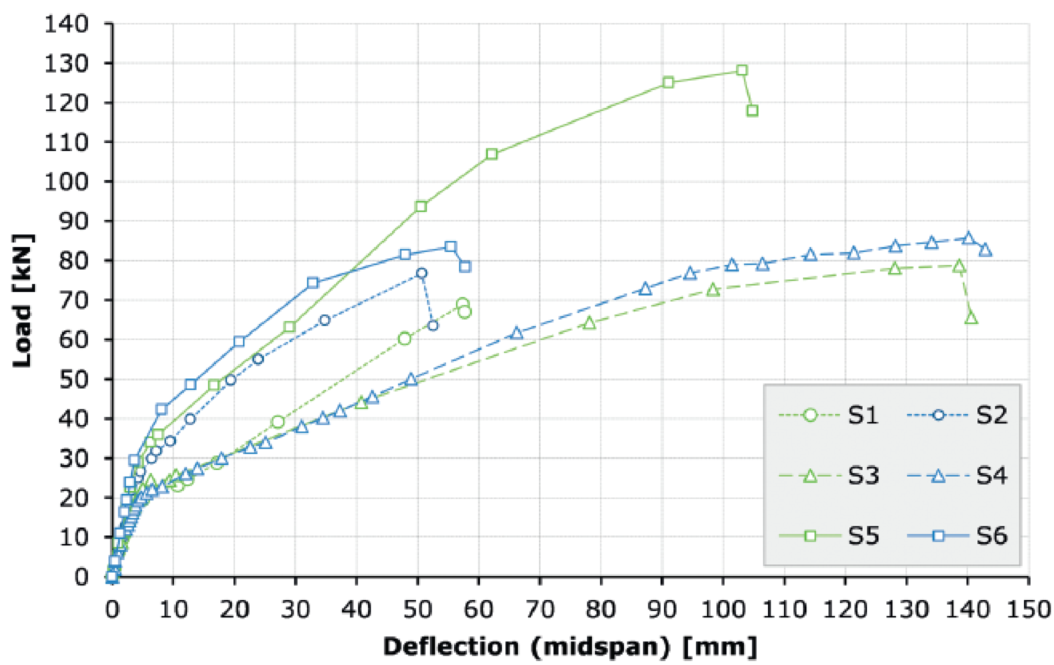


Figure 10.
Load-deflection curves

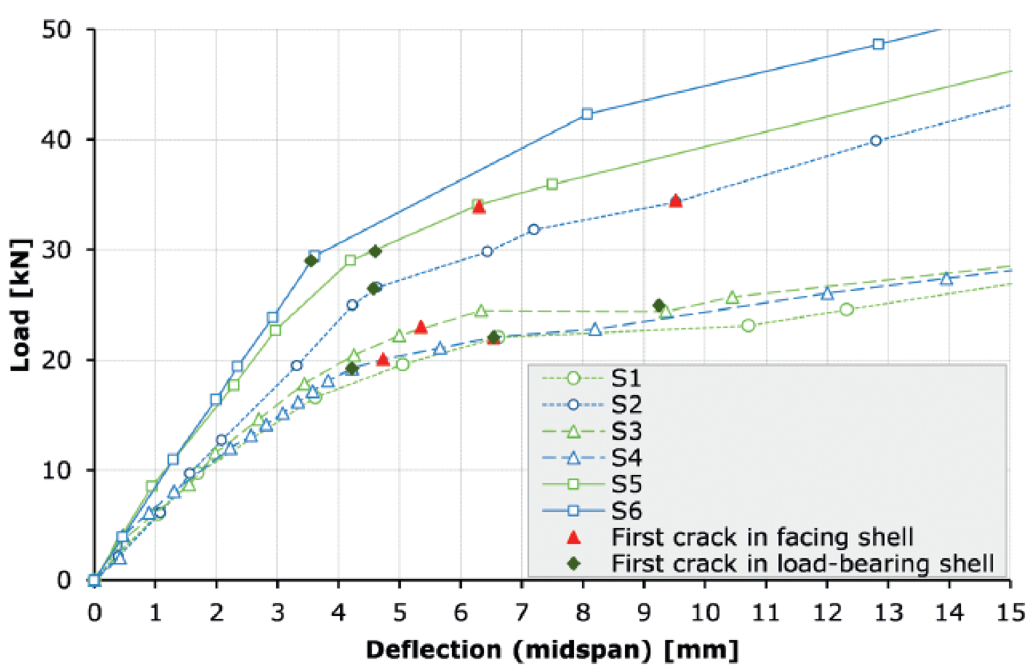


Figure 11.
Load-deflection curves before the first cracks developed

By comparing the testing curves just before the first crack appears (Figure 11), it can be seen that the load-deflection curves of the specimens S1 and S5 flatten before the concrete cracked first. This behaviour can be explained in a way that the stiffness of the cross section decreases. Due to the load, the concrete layers move relatively, horizontally to each other. This behaviour results in shear stresses

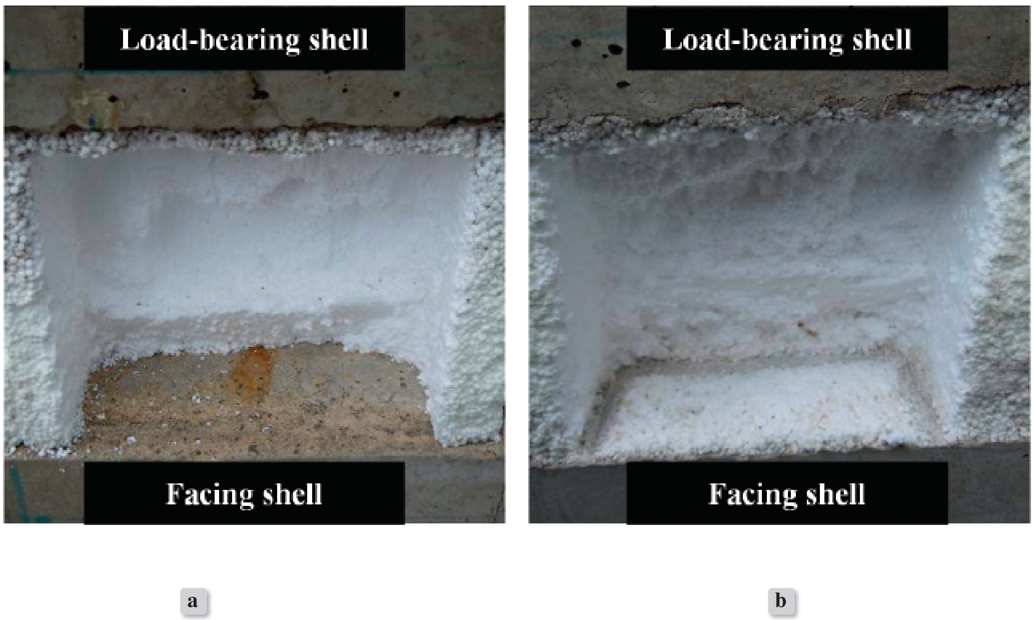


Figure 12.
Additional inspection of the bond between the insulation and the facing shell

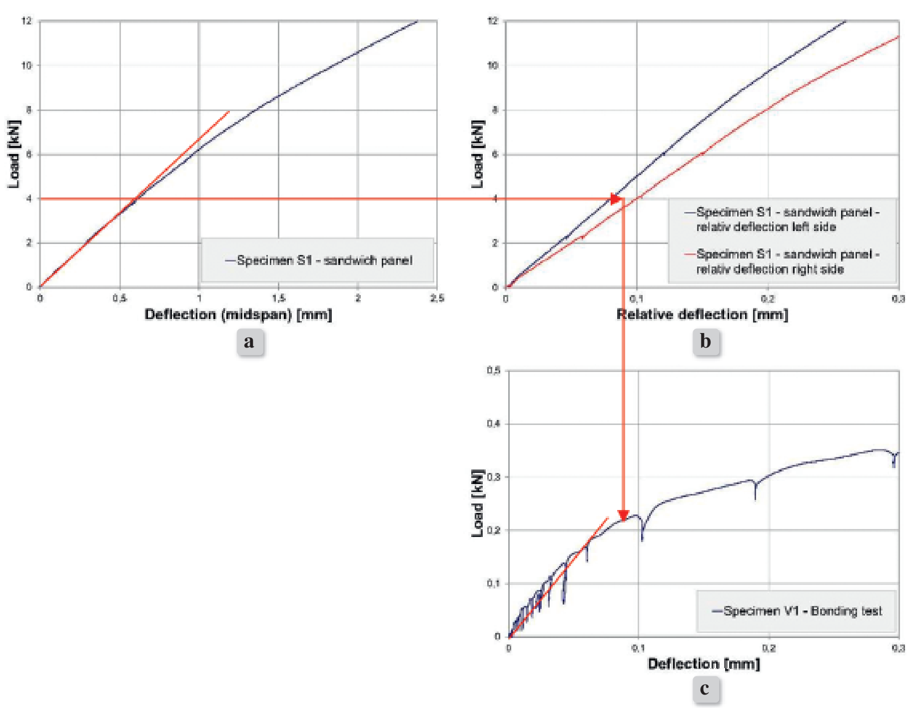


Figure 13.
Comparison of specimen S1 and the selected specimen of the adhesive shear stress tests

in the core layer. A closer look at the load-deflection curves shows, that the EPS-test specimen S2 and S6 exhibited a linear load-deflection behaviour until the first crack began to form. It can be concluded, that the middle layer – consisting of insulation and GFRP-Connector – is not damaged. Specimens S1 and S5 have a non-linear behaviour before the stiffness decreases, due to the cracks in the facing shell or load-bearing shell. As already mentioned above, this behaviour can be explained by a reduction of the stiffness of the cross section. The decrease of local stiffness can be ascribed to the change of the characteristic of the core layer, more precisely the release of the shear resistance of this layer. This is the main result of the test for the determination of the characteristics of the bond between concrete and insulation. Due to the increase of the shear stress, which is caused by the relative deflection between the two concrete layers, the bonding between the XPS-insulation and the concrete fails at a low load category. A comparison of specimen S1 and the selected specimen of the adhesive shear stress tests (XPS – V1) should verify this statement. In both tests the same insulation type and thickness was used. It can be assumed, that the test V1 represents both ends of the facing shell, where the biggest relative deflection between both concrete layers appear. The measured values are compared in Figure 13. It can be shown, that at the point where the load-deflection curve of specimen S1 got non-linear (Figure 13a), the bonding between the concrete and XPS-insulation of specimen XPS – V2 started to fail.

The non-linear behaviour of specimen S4, before the first crack began to form, although the core layer consist of EPS-insulation, is attributed to the fact that the production of the specimens S3 and S4 was different to the production of the other specimen. The specimens S3 and S4 were produced within two days (Table 2). Due to the missing pressure of the fresh concrete on top of the insulation, the bond between the concrete and both insulation-types are virtually non-existent. This result was confirmed by the inspection of the core layer at midspan of the specimens, where no relative deflection appeared. The insulation could be removed very easily, without any residual material on the concrete; whereas in case of the EPS insulation of specimen S6, the failure plane lay in the insulation layer (Figure 12).

5. SUMMARY

In order to set up a concept for designing a three-layered sandwich wall, it is important to define its load-deflection behaviour, followed by the determination of the internal forces. In order to investigate the load-deflection behaviour, 4-point bending tests were carried out. The two concrete layers were fastened with GFRP-bars. Two different types of insulation materials (extruded polystyrene foam (XPS) and expanded polystyrene foam (EPS)) of two different thicknesses were used for the core layer.

Due to the higher shear strength of the XPS-insulation, it was expected, that the layer which consisted of XPS-insulation and GFRP-connectors would be stiffer than the layer with EPS-insulation and GFRP-connectors. The load-deflection behaviour highly depends on the characteristics of the core layer. The tests show, that the less stiff behaviour of the specimens with XPS-insulation is the result of the weak bonding between the insulation material and the concrete.

On the one hand, the characteristic of the core-layer depends on the used insulation type. On the other hand, the manufacturing process influences the characteristic of the core-layer. When designing a sandwich wall, it must be kept in mind that the way in which the panel is manufactured can lead to a very weak bonding between the insulation material and the concrete. It can be concluded, that the characteristics of the core-layer, which can consist of different insulation types, influences the internal forces for the verification of the ultimate and serviceability limit state. In further research work, the tests should be analysed with finite-element calculations. In a further research project, lightweight concrete will be used for the sandwich panels. These results will be presented in an additional paper.

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