EXPERIMENTAL INVESTIGATION OF COMPOSITE ACTION OF THIN LAYERED FIBER REINFORCED SANDWICH PANEL WITH SHEAR CONNECTORS

***Dana Puzanova, Ulvis Skadins**
Latvia University of Life Sciences and Technologies, Latvia
*Corresponding author's email: dana.puzanova@lbtu.lv

Abstract
The construction industry faces growing pressure to create sustainable, cost-effective building solutions while ensuring structural performance. Traditional precast concrete sandwich panels often use excessive materials due to conservative design approaches and typical reinforcement methods. This research investigates the structural behaviour of innovative thin-layered sandwich walls (SW) manufactured using steel fibre reinforced concrete (SFRC) with integrated shear connectors. The experimental program examines 6 almost full-scale SW specimens measuring 1900×1000×270 mm, consisting of two SFRC bearing layers and an insulation core. The panels incorporate PD210 shear connectors and steel fibre reinforcement at a dosage of 30 and 50 kg m^{-3}. Concrete with strength class C40/50 was used for the bearing layers, with an intermediate layer of TENAPORS EPS 150 insulation. The study evaluates the composite action between layers and the effectiveness of shear connection systems under load. It involves full-scale specimen testing to assess bending behaviour and composite action efficiency, focusing on deformation characteristics and shear connector performance. The goal is to provide insight into the structural effectiveness of thin-layer SFRC sandwich panels for potential use as load-bearing components in building envelopes. The experimental tests showed a weak composite action of the SW specimens, which was determined based on the load–deflection behaviour and strains measured on each surface of the wythes. A parallel study investigates the performance of these walls under eccentric compression. The study evaluates the necessity of composite action, suggesting that thin layer wall structures can support significant axial loads even without it.
Keywords: fibre reinforced concrete, experimental study, four-point bending, level of layer composite action.

Introduction

In today's world, where the construction industry is focused on reducing carbon emissions generated during the construction process, we are compelled to seek more efficient solutions that minimize the consumption of building materials.

Three-layer panels are frequently used in building construction. Traditionally, concrete is reinforced with steel bars. In low-rise buildings, the thickness of these panels often exceed load-bearing capacity requirements. Conventional reinforcement must be provided with minimal thicknesses of concrete cover following current building codes EN 1992 (CEN, 2024). The thickness of the panels could be reduced by replacing conventional reinforcement bars with an alternative that does not require such a large thickness of concrete cover.

Many authors have demonstrated in their studies how concrete reinforced with fibres can be used in load-bearing structures, reducing the inefficient use of cross-section. (Naaman, 2003; Katzer & Domski, 2012). Steel fibre reinforced concrete (SFRC) can be used to produce rather thin concrete wythes ensuring sufficient ductility and load bearing capacity for single-storey buildings (Barros et al., 2007; Lameiras et al., 2021).

Skadins et al. (2023) in their numerical analysis of three-layer thin-walled fibre reinforced concrete panel showed that the load-bearing capacity of panels with 60 mm thick wythes exceeded the design loads of a single-storey family house for around 100 times. This demonstrates the significant potential for optimizing these structural elements.

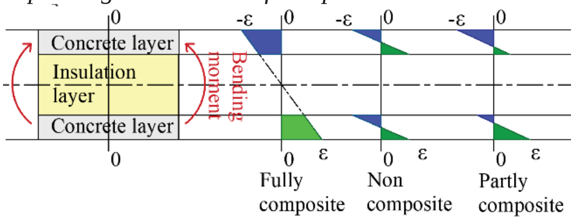
In this research endeavour, we build upon our previous analytical study by incorporating experimental methodologies to investigate the findings further. This continuation aims to validate our initial hypotheses through hands-on experimentation, providing a more comprehensive understanding of the subject. Recent studies have shown changing views on precast concrete sandwich panel behaviour. Anand and Singhal (2023) highlighted the important role of shear connection systems while noting that new research questions whether full composite behaviour is always needed or cost-effective. This viewpoint is confirmed by the previous study Skadins et al. (2023), which shows that thin-layer wall structures can withstand significant loads even without full composite action.

If slender elements are subjected to compressive load, they can buckle before reaching the resistance of the cross-section. The thinner walls are, the smaller load is needed for them to buckle. A solution to this problem is the use of composite cross-section or so-called sandwich type walls (SW). The outer layers or wythes of such walls are made of concrete, while the inner layer is for thermal insulation purposes. If the composite action of such a wall's layers is obtained, the moment of inertia as well as the radius of gyration is increased significantly and thus the critical buckling load.

Shear connectors can provide composite or non-composite, but usually semi-composite, action between the outer layers of a panel (Benayoune et al., 2008). Typical strain profiles for the different composite and non-composite cases were described in many articles (Pessiki & Mlynarczyk, 2003; Flansbjer et al., 2018; Anand & Singhal, 2023; O'Hegarty et al., 2019) and are displayed in Figure 1. In the composite behaviour of the panel, both outer layers of the panel jointly resist bending, which is observed in the strain diagram as a continuous line connecting the compressive strain on the upper panel surface with the tensile strain on the lower panel surface through a zero point at the panel centre of gravity. This can be achieved by ensuring full shear force transfer from the upper layer to the lower one.

In the case of non-composite behaviour, each layer resisted bending independently. This is observed as 2 separate strain diagrams with neutral axes passing through the centre of gravity of each layer.

Figure 1
Illustration of strain profiles in a fraction of a sandwich wall (SW) subjected to pure bending depending on the level of composite action



However, according to the previous numerical study (Skadins et al., 2023), the composite action is not always favourable. Indeed, the SW with non-composite section reached the same load bearing capacity as the ones with the composite section. Due to the composite behaviour, the temperatures caused by solar radiation can result in unfavourable lateral deformations and cracking. Thus, to prevent thin wythes from buckling, it is more important to connect them with an adjacent and unloaded wythe than to try to introduce very expensive shear connectors.

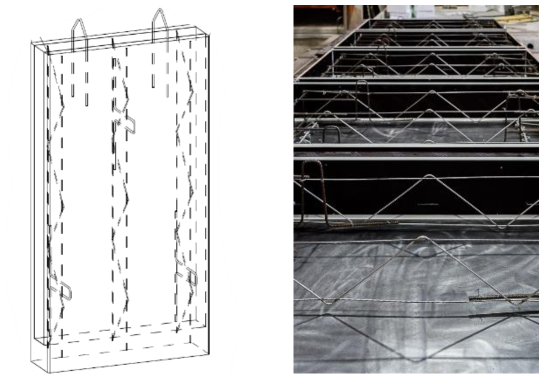
To verify the validity of the conclusions based on the numerical analysis, an experimental study of large size thin-layer SW is conducted. The study consists of two parts dealing with the evaluation of the composite action and with the load bearing capacity under compression. The aim of this study is to present the evaluation of the level of composite action of such walls obtained by experimental loading if steel lattice girders are used as the shear connectors. The results presented in this paper are going to be used in further evaluation of necessity of complex shear connectors to ensure sufficient load bearing capacity of thin layer SW.

Materials and Methods

Two series (SW1 and SW2) of full scale thin-layer sandwich wall specimens were tested in the four-point bending test setup. All specimens were fabricated at the production plant of MB BETONS group in Liepaja, Latvia. Each series consisted of three identical specimens having two different contents of fibre. The specimens represent a wall of a single-storey building, consisting of two self-compacting steel fibre reinforced concrete (SFRSCC) outer layers or wythes that are connected at the bottom of the wall and an insulation layer in between. The SW specimens were 1.0 m wide, 1.9 m tall with overall thickness of 270 mm. A 3D representation of the panels is given in Figure 2(a). Each panel was reinforced with three Peikko PD 210 single-lattice girders equipped with loops at each end to prevent cracking during lifting and transportation, several lifting loops (see Figure 2(b)), and steel fibres randomly distributed in the concrete. Two different fibre dosages were used in this study – of 30 kg m^{-3} for SW1 series panels and 50 kg m^{-3} for SW2. The PD 210 single-lattice girders were used as shear connectors between the wythes of the panels.

Figure 2
SW test specimen: (a) 3D visualization, (b) reinforcement of the specimen before casting

(a) (b)



Composite action of the specimens was evaluated by measuring mid-span deflection of the panels and strains on both sides of each layer.

Self-compacting concrete of grade C40/50 was used. Hooked end steel fibres with diameter 0.5 mm, length 35 mm and nominal tensile strength of 960–1350 MPa were used. The shear connectors were made of 5 mm steel (500 and 600 MPa) and stainless steel (520–720 MPa) wires. The loops were made of ribbed steel reinforcement bars (grade B500) embedded for lifting and transportation purposes.

Material properties of SFRSCC used in the specimens were obtained by testing standard 150 mm cubes under compression according to standard EN 12390-3 (CEN, 2019) and prisms in the three-point bending according to standard EN 14651 (CEN, 2022). There were three cube specimens tested per each series. The mean compressive strength f_{cm} was 83.26 and 73.85 MPa with the coefficient of variation (CoV) 1.5% and 4.2% for SW1 and SW2, respectively. There were ten prisms with dimensions of 150×150×600 mm used in each series to measure the post-cracking flexural tensile strength at crack mouth opening distance (CMOD) 0.5 and 2.5 mm, respectively. The mean flexural tensile strength f_{R1} (at 0.5 mm) was 3.13 and 6.44 MPa (CoV = 10.4 and 12.2%), and fR3 (at 2.5 mm) was 2.60 and 5.93MPa (CoV = 15.2 and 14.2%) for series SW30 and SW50, respectively. The mean modulus of elasticity calculated from the mean cylindrical compressive strength according to EN 1992-1-1 (CEN, 2024) was 38510 and 37000MPa for series SW1 and SW2, respectively. Material properties were obtained for specimens at concrete age of 75 to 80 days and is shown in Table 1. SW panels were tested at concrete age of 260 to 380 days.

Table 1
Material properties of the test series

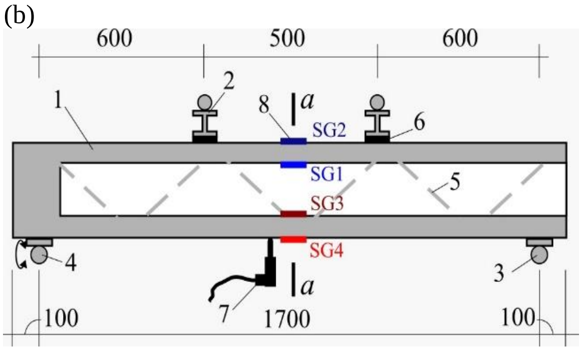
Series name	Number of SW specimens	Concrete strength, MPa	Fibre content, kg m^{-3}	f_{R1}, MPa	f_{R3}, MPa
SW1	3	83.26	30	3.13	2.60
SW2	3	73.85	50	6.44	5.93

The experimental program includes loading of full-scale SW specimens to assess bending behaviour and the level of composite action. Key parameters monitored include load–deflection behaviour and strains on all the surfaces of the wythes. Composite action of the specimens was evaluated based on the measuring mid-span deflection and the strains.
To measure strains in both top and bottom concrete layers, four HBM linear strain gauges with base length 20 mm and gauge factor 2.19 were used. They were placed as shown in Figure 3(b) in the direction of the length of the panel and in Figure 3(c) in a cross section through the middle of the panel.

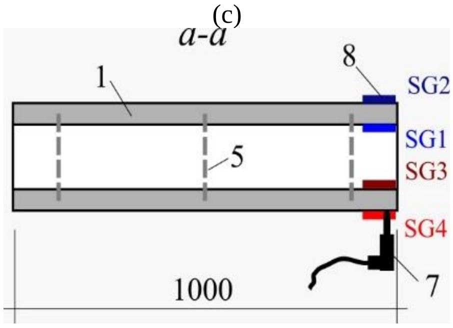
Figure 3
Sandwich panel test setup:
(a) image of SW in the loading frame,
(b), (c) schematic representation (1 – sandwich wall specimen, 2 – steel beam for load distribution with roller, 3 – roller support, 4 – double acting roller support, 5 – shear connector, 6 – rubber, 7 – displacement transducer, 8 – strain gauges with labels SG1–SG4)

(a)

(b)



(c)



Methods to evaluate the level of composite action
The level of composite action of the panels was evaluated by two approaches. First, the obtained strain pattern was compared to the theoretical strain distributions in case of fully composite and non-composite sections. Second approach was to find a moment of inertia from the load–deflection behaviour and compare to the moments of inertia of fully composite and non-composite cross-sections.
In the first approach, plain strain hypothesis is assumed and the depth of the neutral axis x_i is calculated from the strains on both sides of a layer according to equations (1).

$$x_i = \frac{h_i}{|\varepsilon_{it}| + |\varepsilon_{ib}|} \cdot |\varepsilon_{it}| \tag{1}$$

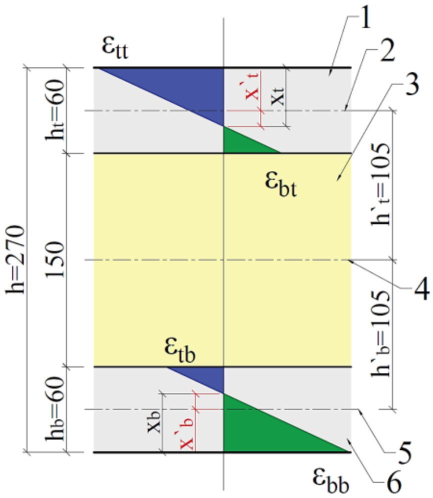
where h_i is the thickness of the top or bottom layer, ε_{it} and ε_{ib} are strains measured on the top and bottom surface of the considered layer. Graphical representation of the designations used in equations (1) to (3) is given in Figure 4. The index i should be replaced by t or b depending on the layer under consideration.

The reference to the fully-composite and non-composite sections is made by relating the experimentally measured neutral axis to the axes of fully composite and non-composite sections with a distance $x`_i$ according to the equation (2).

$$x`_i = \frac{x_i - h_i}{2} \tag{2}$$

Figure 4

Graphic arrangement of symbols used in equations (1) to (3) (1-top concrete layer, 2- fully non composite panel top layer neutral axis, 3-insulation layer, 4- fully composite panel neutral axis, 5- fully non composite panel bottom layer neutral axis, 6- bottom concrete layer)



The level of composite action can be determined using the equation (3), giving value between 0 and 100%, where 0 stand for non-composite and 100% – for fully composite.

$$k_\varepsilon = \frac{x`_i}{h`_i} \cdot 100\% \tag{3}$$

where $h`_i$ is the distance between neutral axes in case of fully composite and non-composite sections.

In the second approach, deflection δ of the SW panels with the span and cross-section identical to the test specimens with fully composite and non-composite sections are calculated by equation (4). This calculation includes the applied load P, the distance a from the support to the load application point, the panel span L , and the modulus of elasticity E determined from compressive strength.

$$\delta = \frac{\frac{P}{2} \cdot a \cdot (3L^2 - 4a^2)}{24EI} \tag{4}$$

The experimental moment of inertia can be derived from equation (4) by substituting the deflection δ with the deflection obtained experimentally. Then, the level of composite action is evaluated by comparing the experimental moment of inertia with the ones of fully composite and non-composite sections.

The moment of inertia for a fully composite panel I_c is calculated by equation (5) and for non-composite action I_{nc} by equation (6).

$$I_c = \frac{b \cdot {h_t}^3}{12} + A_t \cdot h`^2_t + \frac{b \cdot {h_b}^3}{12} + A_b \cdot {h`_b}^2 \tag{5}$$

$$I_{nc} = \frac{b \cdot {h_t}^3}{12} + \frac{b \cdot {h_b}^3}{12} \tag{6}$$

In this paper, the composite action percentage, $k(\%)$, is calculated based on the measured deflection δ during bending tests by equation (7), following the method outlined by (Pessiki & Mlynarczyk, 2003).

$$k(\%) = \frac{I_{exp} - I_{nc}}{I_c - I_{nc}} \tag{7}$$

Results and Discussion

Strain analysis

Strains on four surfaces of the tested specimens registered during loading are given in Figure 5. All the specimens were subjected to cyclic loading except for SW1.1 that was used to determine load levels for the cycles. In all cases with cyclic loading, the first cycle shows some nonlinearities, after which all other cycles seem to follow a consistent path. Magnitudes of the strains vary from -300 microns on the top surface up to 150 microns on the bottom surface. The variation of the strains among different surfaces differs from specimen to specimen. For some specimens (SW1.2, SW2.1, SW2.2) a sudden drop of strains of the lower wythe during the firs cycle can be observed. That can be explained with appearance of a crack, after which large part of the deformations are accumulated in the crack and lower levels of strains remain in the bottom wythe. In the case of specimens SW1.3 and SW2.3 no such drop of strains is visible; consequently, the levels of strains in both wythes remain mutually similar. The strain diagrams along a section going through the strain gauges (at midspan) are compared among the specimens in Figure 6. The comparison is made before the first cycle at the moment indicated with a black dashed line in Figure 5 to avoid the influence of a crack.

Based on the measured strains, the neutral axis location and the level of composite action were calculated for each specimen, as shown in Table 2. In all the cases, there are both compression and tension side on both wythes, having a neutral axis within the thickness of the wythe. In the top wythe, the compressive strains are larger than the tensile strains, while in the bottom wythe the tensile strains are governing.

Experimental composite action (k_ε) for sample, SW1 varies from 8.7% to 17.6% and from 8.2% to 14.7% for SW2. These values indicate that the tested SW walls show a weak composite action even at the very beginning of the loading before cracking starts.

Load-deflection behaviour

The load–deflection behaviour is compared among the specimens together with the theoretical lines in the case of fully composite and non-composite section in Figures 7 and 8.

Figure 5
Strains measured on the test specimens during the cyclic loading

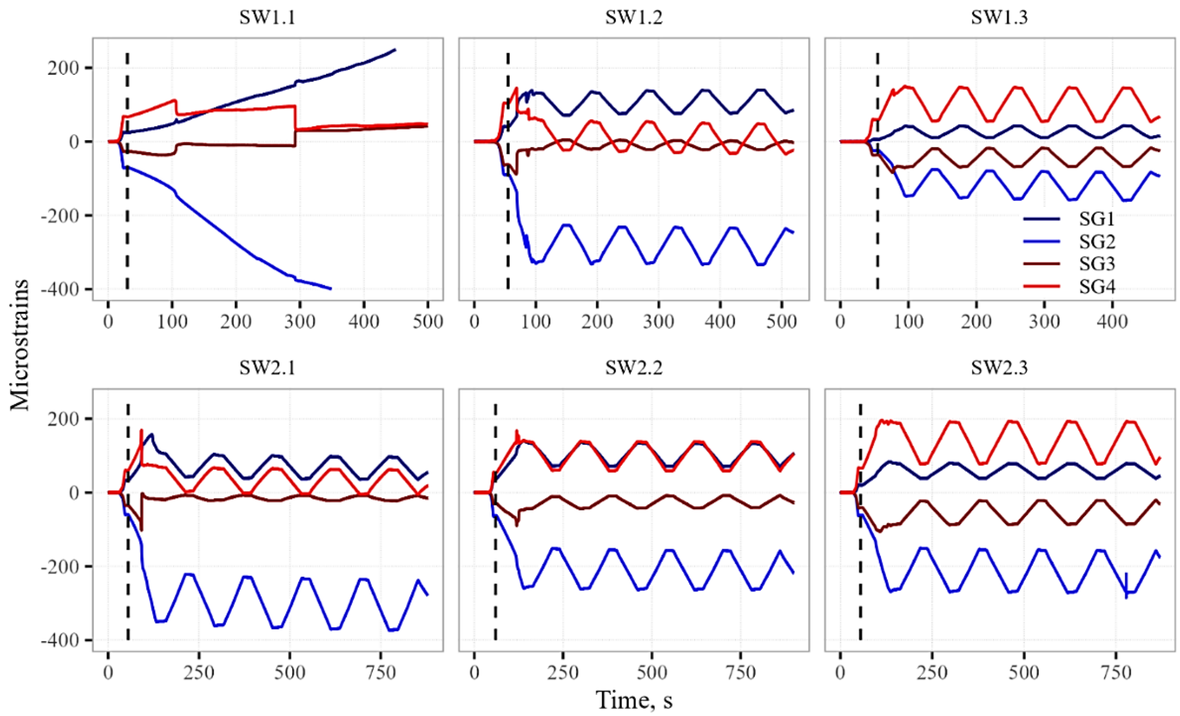


Figure 6
Strain diagrams at the middle section of the specimens before cracking

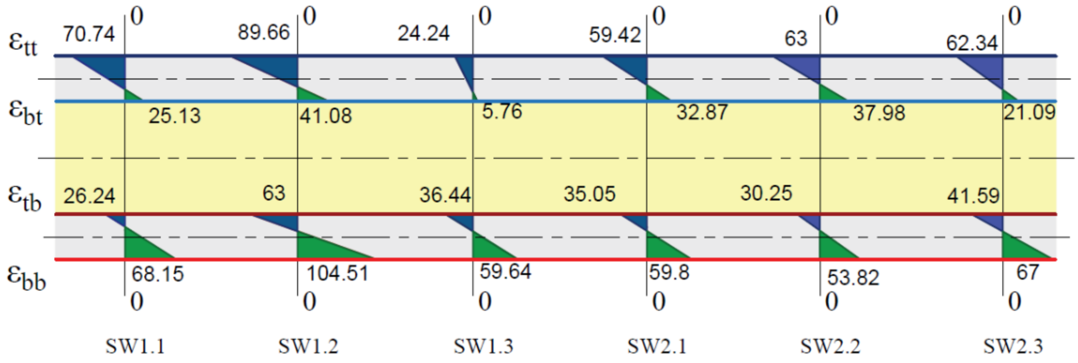
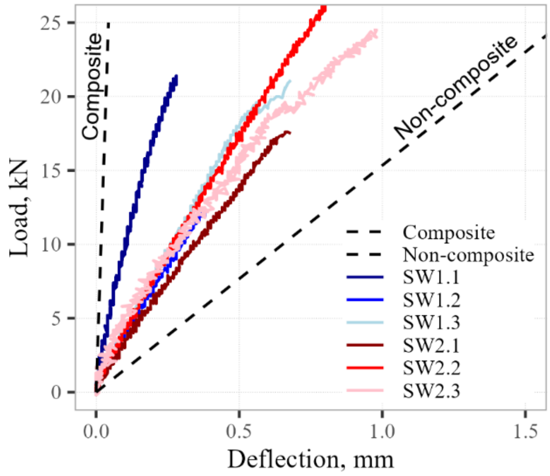


Table 2
Neutral axis location and composite action percentage for tested specimens

Specimen		ε_{tt}	ε_{bt}	ε_{tb}	ε_{bb}	x_t *(mm)*	x_b *(mm)*	$x`_t$ *(mm)*	$x`_b$ *(mm)*	$k_{\varepsilon t}(\%)$	$k_{\varepsilon b}(\%)$
Fibre content 30 kg m^{-3}	SW1.1	70.74	25.13	26.24	68.15	44.27	43.32	14.27	-9.18	13.6	8.7
	SW1.2	89.66	41.08	63.00	104.51	41.15	37.43	11.15	-15.07	10.6	14.3
	SW1.3	24.24	5.76	36.44	59.64	48.48	37.24	18.48	-15.26	17.6	14.5
Fibre content 50 kg m^{-3}	SW2.1	59.42	32.87	35.05	59.64	38.63	37.79	8.63	-14.71	8.2	14
	SW2.2	63.00	37.98	20.25	53.82	37.43	38.41	7.43	-14.09	7.1	13.4
	SW2.3	62.34	21.09	41.59	67.00	44.83	37.02	14.83	-15.48	14.1	14.7

Figure 7

Experimentally obtained load–deflection diagrams up to the first cracks compared to theoretical limits of fully composite and non-composite cross-sections

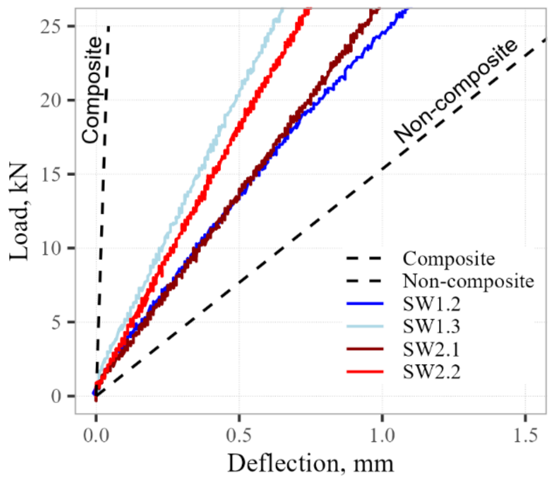


In Figure 7, the range up to the appearance of the first crack is plotted, representing the initial stiffness of the specimens.

In Figure 8, the loading data during the last cycle are shown setting their starting point to zero. The theoretical limits are calculated according to equation (4). The figures show that all experimental deflection curves lie between the boundary lines of non-composite and composite action, indicating semi-composite behaviour action.

Figure 8

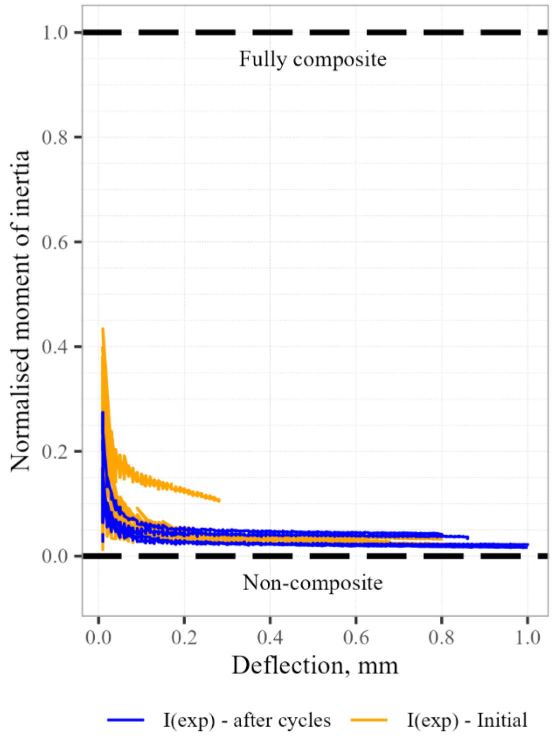
Experimentally obtained load–deflection diagrams in the range of the last loading cycle compared to theoretical limits of fully composite and non-composite cross-sections



The derived values of the moment of inertia from the equation (4) for both the initial loading stage and during the last loading cycle in normalised form according to equation (7) are given in Figure 9. At the deflections up to 0.2 mm, the normalised moment of inertia representing the level of composite action drops from 40% to 5% (upper bound) during the initial loading and from 28% to 5% (upper bound) during the last cycle. Over this point, the composite action of the test specimens both at the initial loading and during the last cycle were in the range of 2% to 5%.

Figure 9

Level of composite action based on the moment of inertia



The study agrees with O'Hegarty et al. (2019, 2020) in demonstrating that shear connectors offer only limited interlayer interaction, and achieving full composite performance in sandwich panels continues to be a challenge. This finding aligns with reviews by Amran et al. (2022), who observed that connection quality is crucial for panel performance. Our findings confirm that linking the layers effectively remains challenging. This study also supports the theory proposed by Pessiki & Mlynarczyk (2003) that the degree of composite action exhibited by a panel may vary throughout the panel's loading history.

Conclusions

This paper represents an experimental study of thin-layer steel fibre reinforced concrete (SFRC) sandwich walls (SW) subjected to flexural loading with the aim to evaluate its composite action. The main conclusions are the following:

1. Truss-type shear connectors made of 5 mm steel wires ensure a weak composite action between sandwich panel wythes.
2. SW panels with different dosages of steel fibres showed similar level of composite action, suggesting that the amount of fibres does not affect it significantly.
3. The level of composite action at the initial loading

stage was in the range of 7% to 18% based on the analysis of strains on all the surfaces of the wythes.

4. The level of composite action is in the range of 2% to 5% based on the analysis of deflection and moment of inertia of the cross-section.

5. This study is part of a research project where a thin layer SFRC SW is investigated experimentally under different loading conditions. The findings presented in this paper are going to be discussed with the results of load bearing capacity under eccentric compression suggesting that thin layer wall structures are capable to withstand significant axial loads even without composite action.

Acknowledgements

The tests specimens were sponsored by ʽMB Betons' (https://www.mbbetons.lv/en).

References

Amran, Y. H. M., El-Zeadani, M., Lee, Y. H., Lee, Y. Y., Murali, G., & Feduik, R. (2020). Design innovation, efficiency and applications of structural insulated panels: A review. *Structures*, 27, 1358-1379. https://doi.org/10.1016/j.istruc.2020.07.044

Anand, A. & Singhal, V. (2023). Structural Behaviour of Precast Concrete Sandwich Panel: A Review. In: Shrikhande, M., Agarwal, P., Kumar, P. C. A. (Eds.). Proceedings of 17th Symposium on Earthquake Engineering, 1. SEE 2022. *Lecture Notes in Civil Engineering*, 329. Springer, Singapore. https://doi.org/10.1007/978-981-99-1608-5_2

Barros, J., Pereira, E., & Santos, S. (2007). Lightweight Panels of Steel Fiber-Reinforced Self-Compacting Concrete. *J. Mater. Civ. Eng.*, 19, 295–304. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:4(295)

Benayoune, A., Abdul Samad, A. A., Trikha, D. N., Abang Ali, A .A., & Ellinna, S. H. M. (2008). Flexural behaviour of pre-cast concrete sandwich composite panel - Experimental and theoretical investigations. *Construction and Building Materials, 22*(4), 580-592. https://doi.org/10.1016/j.conbuildmat.2006.11.023

CEN. (2019). *Testing hardened concrete - Part 3: Compressive strength of test specimens (EN 12390-3:2019).* European Committee for Standardization.

CEN. (2022). *Test method for metallic fiber concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual) (EN 14651:2022).* European Committee for Standardization.

CEN. (2024). *Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings (EN 1992-1-1:2024).* European Committee for Standardization.

Flansbjer, M., Williams Portal, N., Vennetti, D., & Mueller, U. (2018). Composite Behaviour of Textile Reinforced Reactive Powder Concrete Sandwich Faćade Elements. *International Journal of Concrete Structures and Materials*, 12, 71. https://doi.org/10.1186/s40069-018-0301-4

Katzer, J. & Domski, J. (2012). Quality and mechanical properties of engineered steel fibres used as reinforcement for concrete. *Construction and Building Materials,* 34, 243-248. https://doi.org/10.1016/j.conbuildmat.2012.02.058

Lameiras, R., Barros, J. A., Valente, I. B., Poletti, E., Azevedo, M., & Azenha, M. (2021). Seismic behaviour of precast sandwich wall panels of steel fibre reinforced concrete layers and fibre reinforced polymer connectors. *Eng. Struct.* 237, Article 112149. https://doi.org/10.1016/j.engstruct.2021.112149

Naaman, A. E. (2003). Engineered steel fibers with optimal properties for reinforcement of cement composites. *Journal of Advanced Concrete Technology, 1*(3), 241-252. https://doi.org/10.3151/jact.1.241

O'Hegarty, R., West, R., Reilly, A., & Kinnane, O. (2019). Composite behaviour of fibre-reinforced concrete sandwich panels with FRP shear connectors. *Engineering Structures*, 198, Article 109475. https://doi.org/10.1016/j.engstruct.2019.109475

O'Hegarty, R., Kinane, O., & West, R. P. (2020). Review of precast concrete sandwich panels and their innovations. *Construction and Building Materials*, 233, Article 117145. https://doi.org/10.1016/j.conbuildmat.2019.117145

Pessiki, S. & Mlynarczyk, A. (2003). Experimental evaluation of the composite behavior of precast concrete sandwich wall panels. *PCI Journal, 48*(2), 54-71. https://doi.org/10.15554/pcij.03012003.54.71

Skadiņš, U., Kuļevskis, K., Vulāns, A., & Brencis, R. (2023). Thin-Layer Fibre-Reinforced Concrete Sandwich Walls: Numerical Evaluation. *Fibers 2023*, 11, 19. https://www.mdpi.com/2079-6439/11/2/19