

ORIGINAL ARTICLE



Influence of Profiled Faces on the Overall Shear Performance of Strongly Profiled Sandwich Panel with Mineral Wool Core

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Abstract

The total shear force induced on a profiled sandwich panel by an external load is distributed between the profiled face and core. Sandwich panel with a discrete core material such as mineral wool consists of multiple transverse lamella joints across the full width of the panel, affecting the overall shear performance of the panel as these joints have negligible resistance to shear. Additionally, in some cases the core material is partially bonded only to the lower flange of the profiled face which increase the concentration of stresses in the bonded area leading to the crushing of the core on the support. This work studies the distribution of shear force in mineral wool core sandwich panels with one profiled face utilizing a shear beam test on a specimen cut from the panel including the profiled part. Based on the results and failure modes obtained, this work investigates the behavior and role of the profiled face on the shear resistance of profiled sandwich panels. The distributed shear force between the core and profiled part obtained from the shear beam tests are compared with full-scale tests suggested by the European Standard EN 14509:2013, thus, exploring the applicability of the devised shear beam test method for assessing the shear properties of profiled sandwich panel.

Keywords

Sandwich panels, Mineral wool, Shear strength, Shear modulus, Profiled face, Wrinkling, Cold formed Steel

1 Introduction

Sandwich panels when used as roofing elements are subjected to various types of external loads generating compressive stress on the panel increasing the likelihood of localized buckling or wrinkling of the faces. To avoid these issues a fully or partially profiled external face is often employed to enhance the bending stiffness, which in turn increases the ability to withstand high vertical loads [1]. The bending and shear stresses experienced by the profiled sandwich panel are assumed to be distributed across two separate load-bearing systems: the "Profiled" and the "sandwich" parts [2].

The European standard EN 14509:2013 [3], provides two methods for evaluating the shear strength of sandwich panels: a shear beam test and a full-scale test. The shear beam test is a small-scale test method that involves a sandwich beam prepared with appropriate dimensions cut from the flat part of the panel which is subjected to a two-point load until a visible shear failure is obtained. For

thicker panels, the standard EN 14509 suggests a four-point load shear beam test, but no details on conducting such a test are given. Additionally, the standard recommends a full-scale test for thicker panels and panels with lamella cores such as mineral wool (MW). In the full-scale test, the complete width of a panel is subjected to a uniform pressure load using a vacuum box or air pressure.

Currently, in the standard EN 14509:2013 [3], only the flat part of the panel is utilized in the shear beam test, which excludes the influence of profiled face on the shear force capacity. The effect of the profiled face is obviously included in the full-scale test, but the specimen is covered with a thin plastic film or rubber sheet which hinders closer inspection of the detailed behaviour of the specimen during the test. Consequently, the primary failure mode may go undetected in a full-scale shear test.

Additionally, there is a lack of literature and experimental data concerning the shear properties of strongly profiled sandwich panels using a full-scale test method. Therefore,

there is a need for research on the test methods to determine the shear properties of strongly profiled sandwich panels.

This study presents the results of an experimental campaign conducted using the small-scale shear beam test method on profiled sandwich panels with a mineral wool core. Two-point and four-point loading tests were carried out. The two-point loading test followed the specifications given in EN 14509, while the details of the 4-point loading test were specified through trial experiments such that clear shear failure was obtained. The specimens were prepared such that the profiled part of the top face of the panel was included. The primary aim is to assess the behavior of profiled sandwich panel specimens to determine the level of shear force transmission between the core and the profile. The results of the shear beam tests are compared with the results from full-scale tests for the same panels. Shear strength and shear modulus of the core are obtained from the tests along with the shear stress acting across the webs profiled face. The failure mode, which is normally not visible during the full-scale test is explored using the small-scale shear beam test, enabling the declaration of the exact failure mode during the test and supporting the applicability of devised small-scale shear beam test methods for the strongly profiled panels.

2 Structural behavior of the profiled panel

The well-known theory of sandwich panels [1], [2], [4] is used for analysing the test results and to obtain the shear properties of the tested panels. The primary relations of the total bending moment, M , and shear force, V , acting on the cross-section of a sandwich panel with the deflection w and shear deformations γ are:

$$M = M_s + M_f = B_s(\gamma' - w'') - B_f w'' \quad (1)$$

$$V = V_s + V_f = A_c G_c \gamma - B_f w''' \quad (2)$$

where the terms with subscript S and F represent the sandwich part and steel facing, respectively, and B_s is the bending stiffness caused by the sandwich effect and B_f is the sum of the bending stiffnesses of profiled and flat faces. In the equations, the prime denotes differentiation with respect to the position coordinate x along the longitudinal axis of the panel. A_c and G_c are the cross-sectional area and the shear modulus of the core, respectively.

The governing differential equation of deflection, w , is [4]:

$$w'''' - \left(\frac{\lambda}{L}\right)^2 w'' = \frac{1}{B_t} \left(\frac{\lambda}{L}\right)^2 (M + \beta L^2 q) \quad (3)$$

$$\gamma'' - \left(\frac{\lambda}{L}\right)^2 \gamma = -\frac{1}{B_t} \beta \lambda^2 V \quad (4)$$

where L is the span length and $B_t = B_s + B_f$. The dimensionless parameters α , β and λ are calculated as:

$$\alpha = \frac{B_f}{B_s} \quad (5)$$

$$\beta = \frac{B_s d_c}{B e^2 G_c L^2} \quad (6)$$

$$\lambda = \sqrt{\frac{1 + \alpha}{\alpha \beta}} \quad (7)$$

In the above, e is the distance between the centroids of the faces and d_c is the core thickness.

Employing normalized axial coordinates $\xi = x/L$, the shear force acting on the core, V_s , and profiled face, V_{F1} , of a sandwich beam subjected to a point load F acting at location $\xi_F = \varepsilon$, can be expressed as [1; 3]:

$$V_{s1}(\varepsilon, \xi) = \frac{F}{(1 + \alpha)} \left[1 - \varepsilon - \frac{\sinh \lambda (1 - \varepsilon)}{\sinh \lambda} \cosh \lambda \xi \right] \quad (8)$$

$$V_{s2}(\varepsilon, \xi) = \frac{F}{(1 + \alpha)} \left[-\varepsilon + \frac{\sinh \lambda \varepsilon}{\sinh \lambda} \cosh \lambda (1 - \xi) \right] \quad (9)$$

$$V_{F1}(\varepsilon, \xi) = \frac{F \alpha}{(1 + \alpha)} \left[1 - \varepsilon - \frac{\sinh \lambda (1 - \varepsilon)}{\sinh \lambda} \cosh \lambda \xi \right] \quad (10)$$

$$V_{F2}(\varepsilon, \xi) = \frac{F \alpha}{(1 + \alpha)} \left[-\varepsilon - \frac{\sinh \lambda \varepsilon}{\alpha \sinh \lambda} \cosh \lambda (1 - \xi) \right] \quad (11)$$

Similarly, the bending moment acting on the core, M_s , and profiled face, M_{F1} , can be written as:

$$M_{s1}(\varepsilon, \xi) = \frac{FL}{(1 + \alpha)} \left[\xi (1 - \varepsilon) - \frac{\sinh \lambda (1 - \varepsilon)}{\lambda \sinh \lambda} \sinh \lambda \xi \right] \quad (12)$$

$$M_{s2}(\varepsilon, \xi) = \frac{FL}{(1 + \alpha)} \left[\varepsilon (1 - \xi) - \frac{\sinh \lambda \varepsilon}{\lambda \sinh \lambda} \sinh \lambda (1 - \xi) \right] \quad (13)$$

$$M_{F1}(\varepsilon, \xi) = \frac{FL \alpha}{(1 + \alpha)} \left[(1 - \varepsilon) \xi + \frac{\sinh \lambda (1 - \varepsilon)}{\alpha \lambda \sinh \lambda} \sinh \lambda \xi \right] \quad (14)$$

$$M_{F2}(\varepsilon, \xi) = \frac{FL \alpha}{(1 + \alpha)} \left[\varepsilon (1 - \xi) + \frac{\sinh \lambda \varepsilon}{\alpha \lambda \sinh \lambda} \sinh \lambda (1 - \xi) \right] \quad (15)$$

The webs of the profile resist the shear force acting on the profiled face, which is assumed to be uniformly distributed over its depth, S_w (see Figure 1). The shear stress, τ_{F1} , acting on the profiled face can be calculated as:

$$\tau_{F1} = \frac{V_{F1}}{n S_w t_{F1}} \quad (16)$$

where n is the total number of webs in the profiled face.

According to EN 1993-1-3, Clause 6.1.5 [5], the design shear resistance of the profiled face with unstiffened web can be determined as:

$$V_{FR} = \frac{h_w \sin \phi f_{Fv1} t_1}{\gamma_{M0}} = S_w f_{Fv1} t_1 \quad (17)$$

where f_{Fv1} is the design shear strength of the web of the profiled panel considering the shear buckling, which is calculated using the measured tensile yield strength, f_{y1} , of the profiled steel face. The value of the partial factor $\gamma_{M0} = 1.0$ [5]. The determination of f_{Fv1} depends on the conditional equations expressed as:

$$i) \quad f_{Fv1} = 0,58 f_{y1} \quad \text{if } \bar{\lambda}_w \leq 0,83 \quad (18)$$

$$\text{ii) } f_{Fv1} = \frac{0,48f_{y1}}{\bar{\lambda}_w} \quad \text{if } 0,83 \leq \bar{\lambda}_w \leq 1,40$$

$$\text{iii) } f_{Fv1} = \frac{0,67f_{y1}}{\bar{\lambda}_w^2} \quad \text{if } 1,40 \leq \bar{\lambda}_w$$

Where the $\bar{\lambda}_w$ is the slenderness of the web of the profile which can be calculated as:

$$\bar{\lambda}_w = 0,346 \frac{S_w}{t_{F1}} \sqrt{\frac{f_{y1}}{E_{f1}}} \quad (19)$$

3 Experimental investigations

3.1 Geometry and material properties

Panels with a core thickness of 100 mm and 150 mm were used for the experiments. For both thicknesses, three shear tests were conducted for 2-point and 4-point loading setups. To ensure consistency among the tests, each specimen was cut from different panels consisting of one profiled face with an incompletely bonded face-core interface as shown in Figure 1 and left to acclimate in room conditions for 24 hours before testing. Dimensional measurements were subsequently conducted following EN 12085 [6]. Each test specimen possessed a symmetrical profiled face with a steel grade of S280GD on one side, with the opposite side being (nearly) flat. Material tests on three specimens for each profiled and flat steel face were conducted using a tensile testing machine following the standard EN ISO 6892-1:2019 [7]. To determine the thickness of the steel face, existing layers of paints and coatings were removed and then measured.

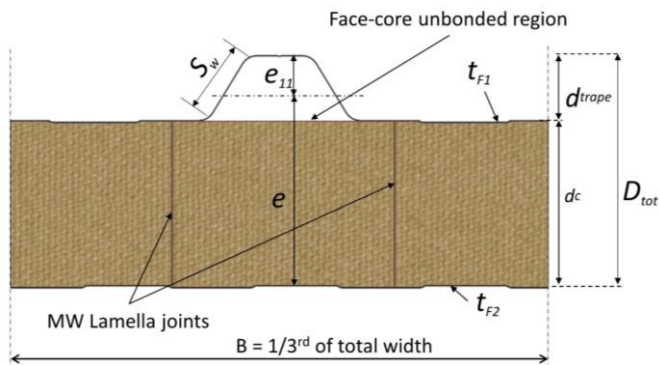


Figure 1 Cross-sectional view of beam sample with profiled part

3.2 Test methods

Two shear beam test methods were employed to investigate the behavior of the profiled face and the MW core with lamella joints. The first method followed the procedure given in EN 14509:2013 [3], where two loads were applied at a distance equal to one-third of the total length. The loading/support plates with a width of 150-200 mm were used. The second method introduced four load points, aiming to reduce the bending moment at the mid-point, thus mitigating the risk of wrinkling failure or local buckling of profiled face, and enhancing the concentration of shear force in the core material. The distance between the loading plates was determined based on experimental results after observing the failure modes. In both test

methods, the free distance between the inner edge of the support plate and the outer edge of the loading plate was set to $1,2 \times d_c$ [3]. The final span length was then determined based on the width of the loading and support plates used. The loading conditions for the beam tests and the full-scale test are depicted in Figure 2. The full-scale test was conducted using a vacuum box following the instruction given in the standard EN 14509 [3].

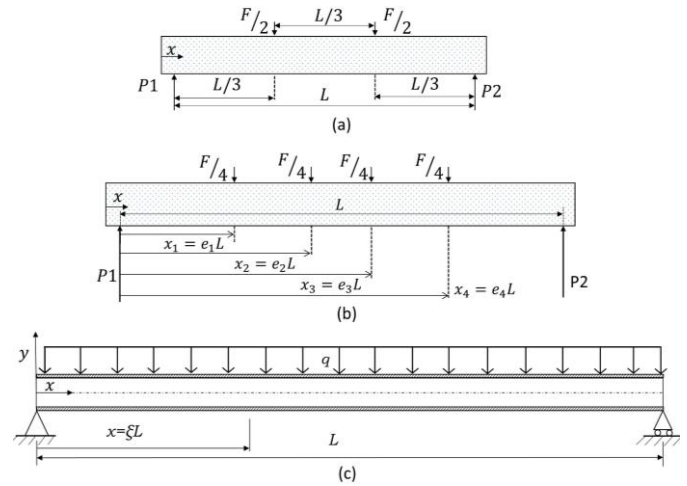


Figure 2 Test configuration; a) 2-point load test, b) 4-point load test, c) Full-scale test

During the tests, the deflection of the beam is measured using a displacement transducer at the mid-span along with the load applied, which is then used to plot a force-displacement graph. It should be noted that the displacement in the shear beam test must be recorded from the lower face of the sandwich beam, instead of the displacement of the cross-head of a hydraulic cylinder.

3.3 Solution to Full-scale test

The calculation of results for the full-scale test is carried out following the instructions given in EN 14509:2013 [3]. For the panel subjected to uniform load, q , as shown in Figure 2c, the total deflection, w , is the sum of the deflection caused by the bending component of deflection, w_b , and a shear component of deflection, w_s . The bending deflection can be calculated as :

$$\Delta w_B = \frac{\Delta FL^3}{B_t} \left[\frac{5}{384} - \frac{\cosh\left(\frac{\lambda}{2}\right) - 1}{\alpha \lambda^4 \cosh\left(\frac{\lambda}{2}\right)} \right] \quad (20)$$

The shear deflection Δw_s can then be evaluated as:

$$\Delta w_s = \Delta w - \Delta w_B \quad (21)$$

where Δw is the total deflection recorded at mid-span during the test.

The shear modulus can then be calculated as:

$$G_c = \frac{\Delta FB_s L d_c}{8 \Delta w_s B e^2 B_t (1 + \alpha)} \quad (22)$$

Since G_c is initially unknown and Δw_s depends on the parameter λ , which again depends on G_c (see equation (7)),

an iterative calculation must be performed to obtain the value of G_c . An initial estimate of the shear modulus is made, and the shear deflection is calculated by equation (21). The shear modulus is then updated by equation (22). The value of shear modulus is increased with an increment of 0,05 MPa until convergence is achieved.

The shear strength of a strongly profiled sandwich panel subjected to uniform load can be calculated as [3]:

$$f_{cv} = \frac{F_u}{2(1 + \alpha)A_c} \left[1 - \frac{\sinh\left(\frac{\lambda}{3}\right) + \sinh\left(\frac{2\lambda}{3}\right)}{\sinh(\lambda)} \right] \quad (23)$$

3.4 Solutions to 4-point loading test

The standard EN 14509:2013 does not offer an analytical solution to the 4-point loading shear beam tests for panels with profiled parts included. In order to determine the overall shear force acting on each component of the profiled sandwich panel, an analytical approach is employed. The force-displacement data obtained from the test is used to evaluate the shear force and bending moment acting on each part of the panel using Equations (8)-(15) based on the loading conditions as shown in Figure 2. The shear modulus, G_c , of the profiled panel obtained from the full-scale test is used to calculate the parameter β (see equation (6)).

Figure 2(b) illustrates the 4-point loading configuration of the sandwich beam, where e_1 - e_4 represents the load location relative to the left side of support point P_1 . The total load acting on the left-hand side of the beam can be evaluated as:

$$P_1 = \frac{F}{4L} \left(4L - \sum_{i=1}^4 x_i \right) \quad (24)$$

Where x_i is the distance from the support point to the loading points.

The total shear force, which attains its maximum close to the support, acting individually on the core and profiled face can be calculated by setting $\xi=0$ and $\varepsilon=e_i$ in equations (8)-(11). The total shear force in the core and the profiled face can be then calculated as:

$$V_s = V_{s2}(e_1, 0) + V_{s2}(e_2, 0) + V_{s1}(e_3, 0) + V_{s1}(e_4, 0) \quad (25)$$

$$V_f = V_{f2}(e_1, 0) + V_{f2}(e_2, 0) + V_{f1}(e_3, 0) + V_{f1}(e_4, 0) \quad (26)$$

The shear stress acting on the core of the panel can then be calculated as:

$$\tau_c = \frac{V_s}{A_c} \quad (27)$$

Similarly, the maximum bending moment at the mid-point can be calculated by setting $\xi=0,5$ and $\varepsilon=e_i$ in the equations (12)-(15) which gives the total bending moment as:

$$M_s = M_{s2}(e_1, 0,5) + M_{s2}(e_2, 0,5) + M_{s1}(e_3, 0,5) + M_{s1}(e_4, \xi_{0,5}) \quad (28)$$

$$M_f = M_{f2}(e_1, 0,5) + M_{f2}(e_2, 0,5) + M_{f1}(e_3, 0,5) + M_{f1}(e_4, 0,5) \quad (29)$$

The calculated bending moment at mid-span can be used to determine the bending stress, σ_w , in accordance with EN 14509:2013 [3] by:

$$\sigma_w = \frac{M_s}{eA_{F1}} + \frac{M_f E_{F1} e_{11}}{B_f} \quad (30)$$

4 Test results and analysis

For each shear beam test method, three tests were conducted on each panel type, whereas five tests were performed using the full-scale test method. The measured mechanical properties and the thickness of the steel facing of the tested sandwich panels are given in Table 3. The naming of the panel is based on the thickness of the panel, for example in the panel type R-MW 140/100, the letter 'R' represents the roof panel with a total thickness of 140 mm and a core thickness of 100 mm.

Table 1 Measured values of the density, yield strength of profiled face (f_{y1}), yield strength of flat face (f_{y2}), steel-facing thickness and their corresponding standard deviations (StD)

Panel types	Density [kg/m3]	f_{y1} [MPa]		f_{y2} [MPa]		Steel Facing thickness, mm	
		Mean	StD	Mean	StD	Profiled	Flat
R-MW 140/100	122	460	7,5	375	9,1	0,52	0,44
R-MW 190/150	114	443	7,5	482	5,7	0,53	0,43

The observed failure modes in both shear beam test methods as depicted in Figure 3 and Figure 4.

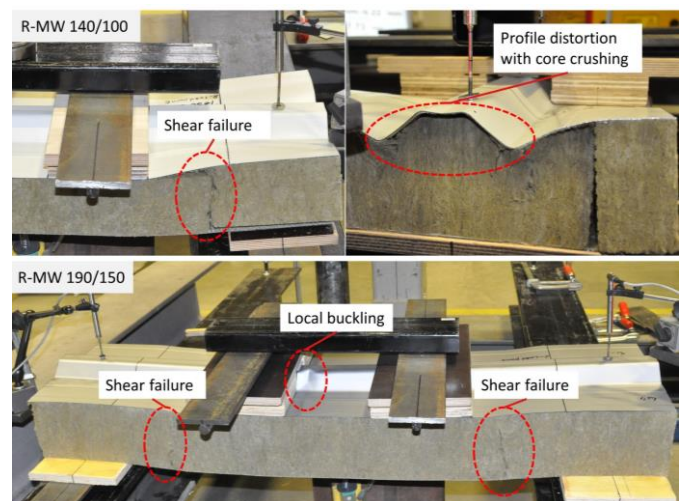


Figure 3 Common failure modes observed in 2-point loading tests

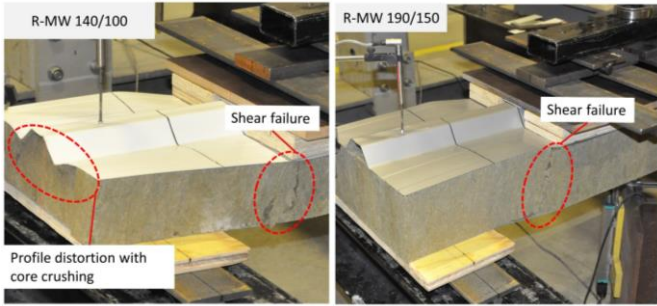


Figure 4 Common failure modes observed in 4-point loading tests

In both the test methods, it indicates a clear tendency towards shear failure, except for the R-MW 140/100 panel which experienced crushing failure with distortion of a profiled face on the support plate. Additionally, local buckling of the profiled face was noted close to mid-span in a few tested specimens as a post-failure. The lamella joints started to disconnect only when the failure occurred on the support plate by the crushing of the core. This suggests that the MW lamella joints were bonded enough to resist the shear.

Figure 5 displays a typical force-displacement curve. It can be seen that there was an elastic deformation of the beam until it reached the ultimate load and failed in shear. Generally, in the case of a profiled panel, any occurrence of the local buckling on the profiled face during the test should hinder the linearity of the graph as there will be a sudden drop in the force, which in both cases is not visible. This concludes that there was no buckling as a primary failure mode during the test. The primary failure modes were either the crushing of the core or the core shear.

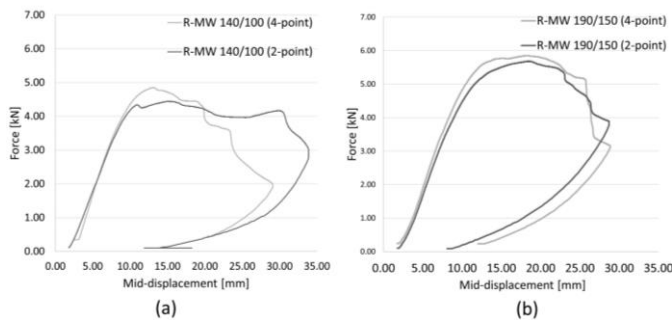


Figure 5 Comparison of force-displacement graph between test methods

The ultimate load of each sandwich beam specimen acquired after the test is utilized to compute the proportion of shear force distributed between the core and profiled faces which is calculated using equations (25) and (26). The shear force distributions between the core and profiled face in the different test setups and for the two panel types are depicted in Figure 6. In the full-scale tests, the whole width of the panel is included, while for the shear beam tests only, one-third of the total width (see Figure 1) is used. This resulted in a large difference in the level of force between the shear beam test and the full-scale test. Therefore, the percentage of force distributed between the core and profiled face is considered for the comparison. The graph illustrates that, during all the shear beam test methods, the core of the panel primarily resists the shear

force, with a portion of it being resisted by the webs of the profiles.

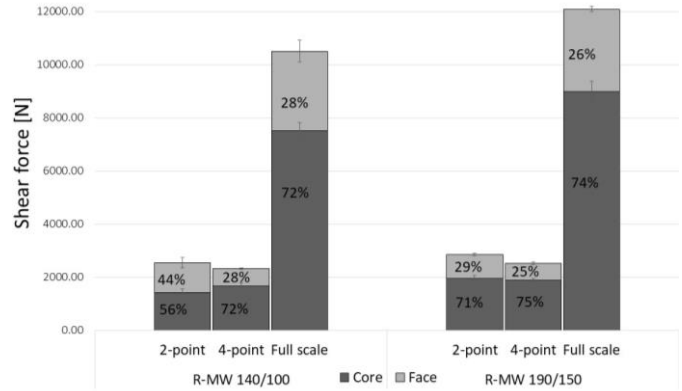


Figure 6 Distribution of shear force between the core and profiled face

For the thinner panel (R-MW 140/100), the core resisted higher force when tested with the 4-point and full-scale test over the 2-point loading test method. Even though the specimens failed ultimately in shear, in some cases local crushing of the core at the support was observed too. This is the reason for the reduced shear force acting on the core of the thinner panel. Contrary to the thinner panel, crushing of the core at the support was not observed in the thicker panel (R-MW 190/150), which mostly failed by core shear as the primary failure mode. The core of the thicker panel experienced an equal level of force when tested with two-point and full-scale tests, while the shear force acting on the core using the four-point test method was the highest.

The shear force acting on the core and the profiled face is utilized to determine the shear stress acting on each component. The results given in Table 2 show that the design shear resistance, V_{FR} , of the webs of a profile is clearly higher than the shear force, V_F , suggesting that the webs of the profile were not close to achieving the shear capacity, which is in line with the test results. Table 2 also provides the bending stresses of the profiled face.

Table 2 Shear force acting on the profiled face, V_F , the design shear resistance of the profiled face, V_{FR} , and bending stress, σ_w , with their corresponding standard deviations, SD.

	R-MW 140/100		R-MW 190/150		R-MW 140/100		R-MW 190/150	
	2-point	4-point	2-point	4-point	2-point	4-point	2-point	4-point
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
V_F [N]	1131,6	197,1	659,07	34,7	895,94	42,7	640,3	37,9
V_{FR} [MPa]	3319,7	13,6	3315,2	12,4	3507,5	3,5	3675,4	15,1
σ_w [MPa]	27,6	6,1	33,7	1,7	31,6	0,6	32,4	1,4

Table 3 Results showing the tested panels with their span length, L , shear strength, f_{cv} , of the panel obtained from 2-point and 4-point loading tests and the Shear modulus, G_c , obtained from full-scale test

Panel type	Test method	L [mm]	f_{cv} [MPa]		G_c [MPa]	
			Mean	StD	Mean	StD
R-MW 140/100	2-point	810	0,043	0,004		
	4-point	1160	0,050	0,002		
	Full-scale	1900	0,068	0,003	3,88	0,4
R-MW 190/150	2-point	1140	0,039	0,001		
	4-point	1280	0,038	0,001		
	Full-scale	2000	0,056	0,002	2,39	0,02

The results of the shear beam tests are given in Table 3. It can be seen that, in the case of R-MW 140/100 panels, the 4-point loading test resulted in higher shear strength of the panel along with the higher bending stress acting at the mid-span. For thick R-MW 190/150 panels, both test methods resulted in a similar level of shear strength of the core and bending stress at the mid-span (see Table 2). Comparing the 2-point and 4-point test methods, it is observed that the 4-point test method is suitable for both thicker and thinner panels for the determination of shear properties. On the other hand, the shear strength obtained from the full-scale test is higher than the strength obtained from the shear beam test methods.

5 Conclusions

The 4-point shear beam test method resulted consistently in clear shear failure of the specimen. Moreover, the crushing of the core was reduced substantially compared to the 2-point shear beam test. Nevertheless, both shear beam test methods yielded approximately the same ultimate load.

The analysis of the portion of shear force distributed between the core and the faces (see Figure 6) shows that a consistent share of shear force was acting on the profiled face of both thin and thick panels when tested with a full-scale and 4-point shear beam methods, whereas there is some discrepancy in the results of 2-point shear beam tests. Additionally, the obtained shear strength is notably higher in the full-scale test contrary to the shear beam tests, even though the portion of shear force acting on the core in all the test methods were at a comparable level.

This suggests that further detailed comparison of the shear properties obtained from the small-scale shear beam test and the full-scale test is required.

The failure mode observed during the 2-point and 4-point loading tests on the support plates such as the crushing of the core and distortional buckling can be studied in detail by performing the compression tests on the core material and comparing the compressive stress level acting on the core. Additionally, this study solely focuses on sandwich panels with MW core material, and it is important to investigate also sandwich panels with homogeneous foam as core material. The panels used in this research had a profiled face that was not fully bonded to the core (see Figure 1). Therefore, it is necessary to understand the behavior of panels with fully bonded profiled face and core and account for the reduction factor caused by the bonds. The formula to determine the bending deflection of profiled panel subjected to point load requires thorough investigation and a solution is required based on experimental analysis. Finally, numerical analysis is required to comprehend the behavior of lamella joints during the tests.

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