Article

A More Sustainable Way for Producing RC Sandwich Panels On-Site and in Developing Countries

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Abstract: The purpose of this work is to assess if traditionally used welded connectors for joining the two skins of reinforced concrete (RC) sandwich panels, used as structural walls and horizontal structural elements, can be substituted with bent ones. In this way, the scope of the effort is to reduce drastically the energy required during manufacturing, thus having a much more sustainable building product. Wire mesh on site production, in fact, requires a large amount of energy for the welding process, as stated by several Environmental Product Declaration (EPD). In addition, the production of sandwich panels with bent connectors requires a low level of automation and no qualified labor allowing the diffusion in developing countries. The procedures used to execute the work were both experimental and numerical. Structural performances were examined by testing full-scale sandwich panels under (axial and eccentric) compression and flexural loads. Additionally, a Finite Element (FE) study was developed to investigate and to optimize the dimension of welded mesh and the number of connectors. The major findings show that it is possible to substitute welded connectors with bent ones without compromising the structural performance of the tested RC sandwich panels, thus having a more sustainable way for producing these last ones.

1. Introduction

Globally, buildings are responsible for at least 40% of energy, electricity, water and materials consumption [1]. At the same time, the building sector has the greatest potential to deliver significant cuts in emissions at little or no cost [1] if the development of environmentally compatible and more sustainable construction products occurs in accordance with energy saving international protocols.

A recent innovative building component is the reinforced concrete (RC) sandwich panel that is a composite material having structural-thermal properties composed by two RC layers separated by rigid insulation material and usually joined by steel connectors that ensure a fully- or semi-collaborating structural behavior. The interest in these panels is diffuse worldwide because of their performance (transferring load and insulating the building), aesthetic (any architectural form can be created), adaptation (panels may be attached to any type of structural frame), durability (the sandwich panel provides resistance to impacts, thefts, and vandalisms), fast mounting procedures, and costs [2].

Applications of RC sandwich panels are widespread and this technology was used to build residential buildings, schools, office buildings, warehouses, industrial buildings, justice facilities, and hospitals. Aside from their typical use for exterior walls, they have been used as internal partition walls, particularly around temperature-controlled rooms (e.g., in subzero freezer applications) [2].

There are two main methods to produce RC sandwich panels depending on the cast of concrete, cast-in-situ concrete and precast concrete. Actually, connectors are welded to steel wire, and it is

not possible to produce sandwich panels in situ totally, butonly the concrete layers can be produced in situ. This limits their diffusion i.e., in developing countries because the welding of connectors requires a high level of automation. In addition, a high amount of energy is required as stated by the Environmental Product Declaration (EPD) [3,4]. In detail, 530 MJ are needed to produce 1 ton of RC sandwich panels, and 511 MJ are composed of non-renewable (fossil) energy. Eighteen percent (about 95 MJ) of this energy is required for the assembly stage [3,4]. Another limiting factor is the need of specialized labor for welded connectors, while i.e., developing countries can count on much not-specialized labor.

In the case of industrialized countries, the welding of connectors is not a problem, but this process can be carried out and certified only inside factories. Then, panels must be transported to construction sites causing difficult handling operations, additional energy consumption (175 MJ), potential smog creation (2.9 kg O_3 eq.), and high costs consequently [3,4].

As the manufacturing stage is a substantial consumer of energy and responsible for a significant rate of the impacts, any process or energy conservation improvements could lead to significantly lowering the environmental profile of RC sandwich panels. Thus, the modification of the production methods (especially the connection type of connectors) could lead to a simplification of the system allowing its diffusion in developing countries, and allowing the assembly of RC sandwich panels in situ.

This manufacturing modification could lead to the production of more sustainable RC sandwich panels only if the mechanical performance is the same or remains under acceptable limits.

Several papers on RC sandwich panels can be found in literature, and some reviews have been written through the years [2,5–7]. These studies focus on the compression load (axial and eccentric) [5,6,8–11], flexural load [12–19], and dynamic load [20,21] of these components, and they provide evidence of the key role of connectors in both structural and thermal performances [22].

Previous research on sandwich panels suggest that the nonlinear behavior of connectors is the main complexity of this system, being caused by the interaction between concrete layers and connectors [6,23,24]. Experimental campaigns show that the formation of cracks in the concrete layers is the most critical aspect in terms of structural resistance because it causes instability of the panels and increases stress in connectors [8]. The arrangement of connectors plays a key role in the structural behavior of panels; for example, connectors perpendicular to external layers do not contribute to shear load, while truss-shaped steel connectors are the most effective connection in transferring the shear force [6]. Anyhow, stress in connectors (when concrete faces were broken) is very low if compared to yield stress of steel [9].

The uncertain role of the shear connectors and the interaction between its various components have led researchers to rely on experimental investigations backed by simple analytical studies, and different Finite Element (FE) models can be found in the literature [7,10,14,25–27]. Other mathematical models can be found in the literature about the relationships between displacements and interface stresses of elements composed of two identical isotropic outer layers and a more compliant inner interlayer [28,29].

The aim of this research is to assess if traditionally used welded connectors for joining the two RC skins can be substituted with bent ones (Figure 1) so as to allow their hand-made assembly, to save costs and energy consumption during manufacturing and thus have a much more sustainable building product even on-site. In addition, the production of RC sandwich panels with bent connectors requiring a low level of automation and no qualified labor could allow their diffusion in developing countries.
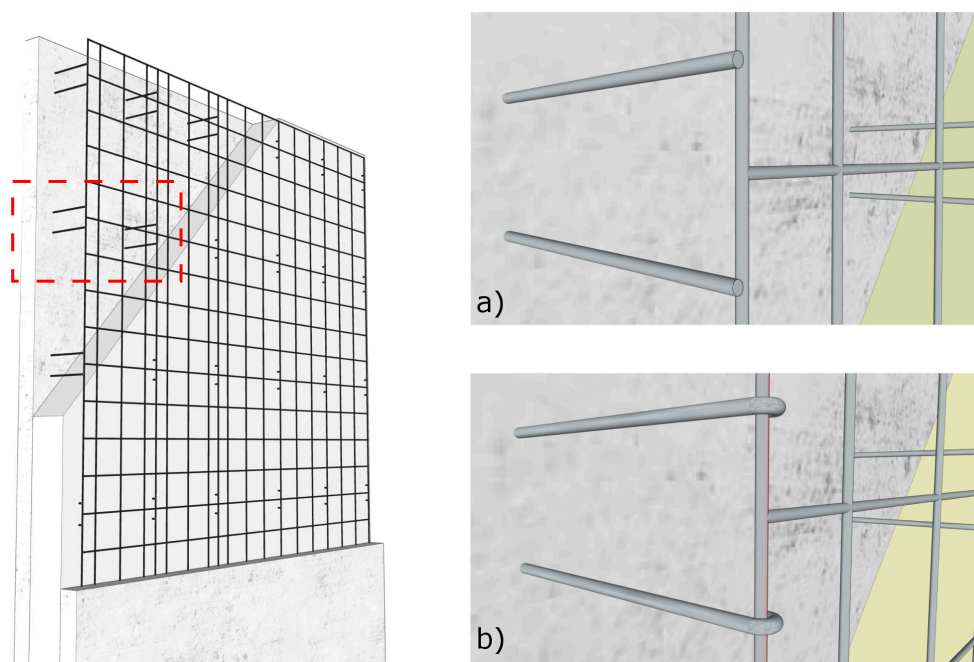
Figure 1. Illustration of traditional welded connectors (**a**) and bent ones (**b**).

This modification can be implemented if structural performances of RC sandwich panels remain unvaried (or vary within an acceptable limit) if compared to traditional ones. Thus, this paper focuses on structural behavior of RC sandwich panels with both welded and bent connectors tested under (axial and eccentric) compression and flexural loads. The differences in load-displacement diagrams and failure mode between the two solutions have been analyzed. In addition, an FE model was carried out to study different configurations of the welded mesh and the number of connectors to further simplify production process and reduce costs.

2. Materials and Methods

2.1. Materials

This study examines full-scale sandwich panels made by two RC layers separated by a rigid insulation material and assembled by means of steel connectors (Figure 2).

The thickness of each concrete layer was 40 mm and insulation material (Expanded polystyrene—EPS) between the concrete had an average thickness equal to 80 mm and a density of about 15 kg/m^3. Two types of connectors were tested: welded connectors and bent connectors. Two RC beams were built at the base and at the top of each panel in order to avoid concentration of the load and to facilitate handling operations (Figure 2).
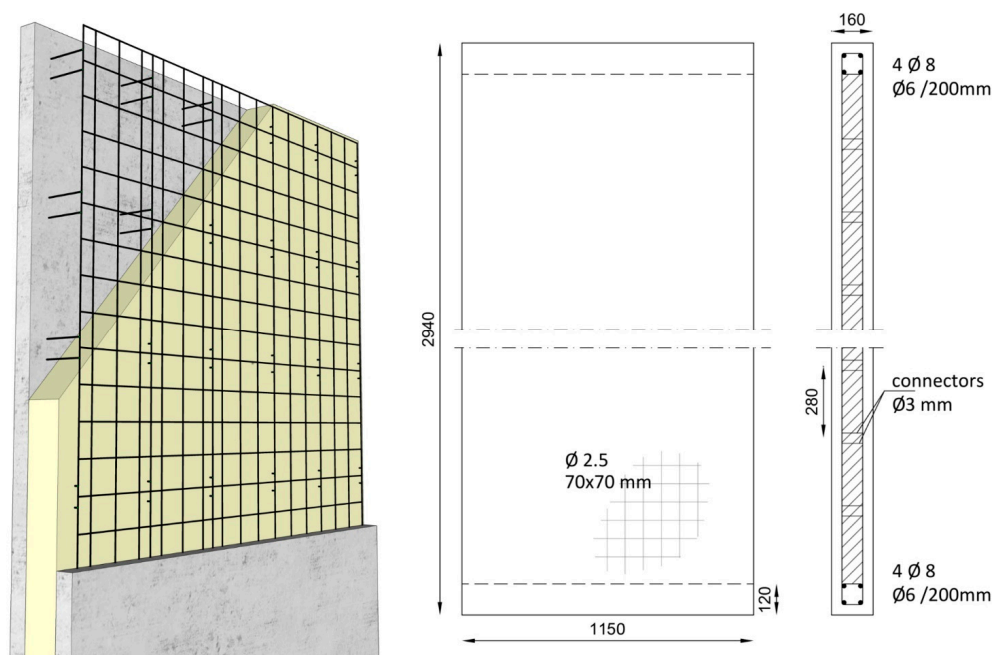
Figure 2. Axonometric view and technical drawings of the tested reinforced concrete sandwich panels.

2.2. Compression Test

Eight full-scale panels were tested varying the load application (axial and eccentric) and the type of connectors (welded and bent). Sample identification and specification are present in Table 1.

The configuration of the test apparatus designed for the compression test is reported in Figure 3: panels were positioned vertically on a semi-cylindrical support (made of steel with a length of 1200 mm) and confined at the top by an industrial belt. Load was applied by means of four hydraulic jacks (maximum load 500 kN each) fixed to a rigid steel frame, and its value was measured by transducers connected to a hydraulic control unit (Figure 4).

Lateral deflection (Δh) was measured by means of two transducers (S_1 and S_2 in Figure 3) placed at half of the height of the panel. Two other transducers (S_5 and S_6 in Figure 3) were placed vertically on each side to measure vertical displacement (Δv). In addition, two 45° inclined transducers (S_3 and S_4 in Figure 3) were placed across the thickness of each panel at half of its height to measure the longitudinal (slip Δs) and transversal (separation Δc) components of the relative displacement between the two concrete layers. All transducers from S_1 to S_6 had a sensibility of $\pm 1 \times 10^{-3}$ mm, and they worked in a range of ± 50 mm. Values of Δs were calculated by averaging the longitudinal component of displacement measured by transducers $S_3 - S_4$ and the difference between data collected by S_5 and S_6 (Equation (1)):

$$\Delta s = \frac{S_3 \text{Sin} 45° + S_4 \text{Sin} 45° + (\, |S_5 - S_6| \,)}{3} \tag{1}$$

Values of Δc were calculated by averaging the transversal component of displacement measured by transducers $S_3 - S_4$ and the difference between data collected by S_1 and S_2.

Transducers registered positive values in the case of shortening and negative values in the case of elongation, and their reference system is reported in Figure 5.

The axial load was applied to the middle axis of the panel, while the eccentric load was applied to the middle axis of only one RC layer (Figure 3). Two specimens for each group were tested.

Table 1. Identification of samples used in compression tests.

Sample	Connection	Type of Load
A-1	bent	Axial
A-2	welded	
E-1	bent	Eccentric
E-2	welded	
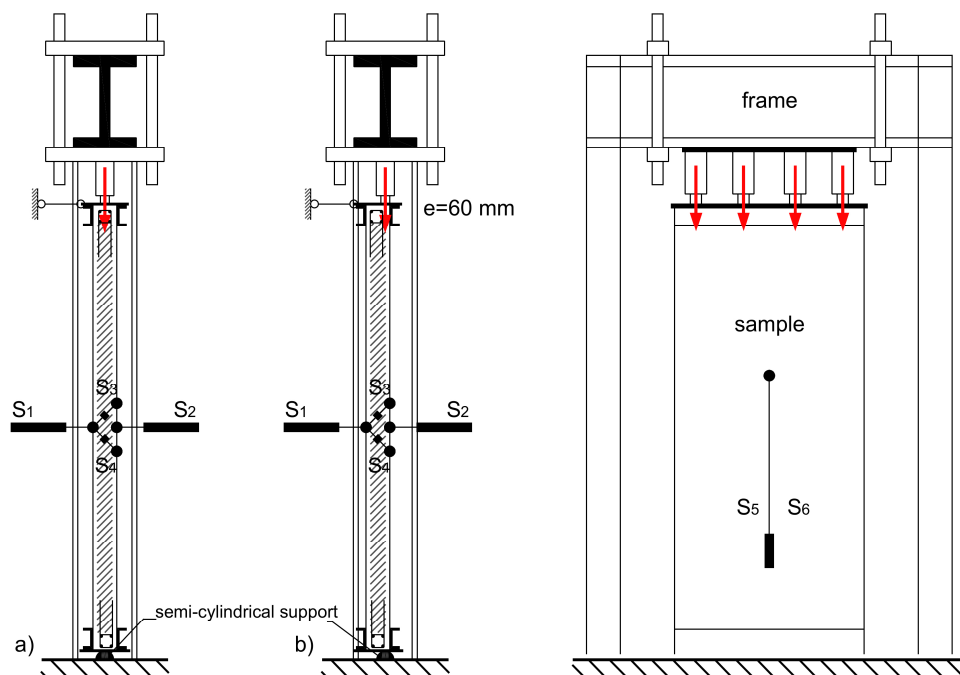
Figure 3. Test apparatus for axial compression test (**a**) and eccentric compression test (**b**).

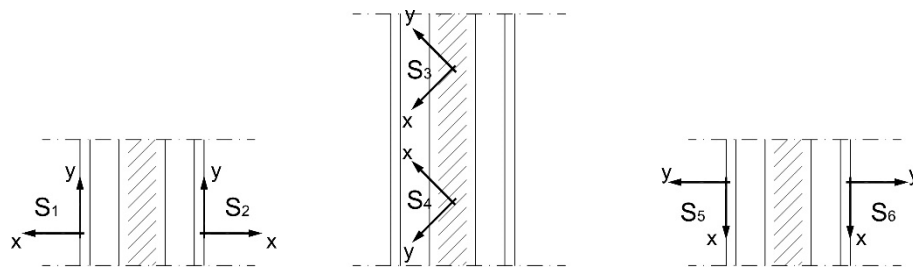**Figure 4.** Overview and details of the test apparatus used in the compression test.

Figure 5. Reference system of the transducers.

2.3. Flexural Test

Four full-scale panels (two for each group) were tested in four-points bending by varying the type of connectors (welded and bent). Sample identification and specification are present in Table 2.

The panels were placed horizontally on two steel cylindrical supports (span equal to 2820 mm) placed on the middle axis of the RC beams at the ends of the panels (Figure 6). Load was transferred to samples by means of a spreader beam fixed to a reaction frame with a spacing of 1000 mm (Figure 6). Samples were instrumented with six transducers: S_{1f} and S_{2f} placed in the middle of the RC sandwich panels on the front face, S_{3f} and S_{4f} placed in the same position on the back face of the panels, and S_{5f} and S_{6f} positioned in correspondence of the load application points.

Test apparatuses designed for flexural tests are shown in Figures 6 and 7.

Thanks to the simultaneous recording of data, it was possible to identify relative displacements between the RC layers. At the end of the test, data collected from transducers in the middle of the panel (S_{1f} and S_{2f}, S_{3f} and S_{4f}) were averaged because their differences were negligible, and the average value represented the mid-span deflection (δm). The data collected from transducers S_{5f} and S_{6f} were also averaged, and the average value indicated the displacement in correspondence of the load application points (δl).

Table 2. Identification of samples used in flexural tests. Two samples for each group were tested.

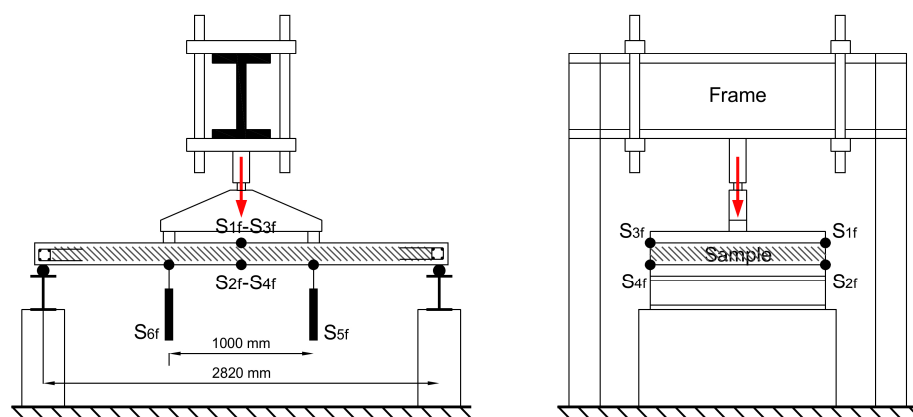| Sample	Connection	Type of Load
F-1	bent	Four points bending
F-2	welded	

Figure 6. Test apparatus for four-points bending test.

Figure 7. Overview of four-points bending test.

2.4. FE Design

An FE model able to reproduce experimental data of compression tests (axial and eccentric force) was implemented. This was done to study different configurations of the welded mesh and connectors so as to minimize the number of these last ones and the dimension of the first.

Samples were designed into a nonlinear framework with the dimensions of the tested panels, following indication from the literature [9,10,14]. RC layers were modelled with a nonlinear 3D solid able to simulate reinforcing bars [29]. In this way, welded mesh was simulated by considering the volume ratio (the rebar volume divided by the total element volume) and their orientation. Internal insulation material was simulated by a 3D non-linear solid element, and the interface contact between it and the concrete panels was simulated with a nonlinear surface-to-surface contact element.

During the definition of contact between insulation and concrete, no penetration was admitted between the two elements. This hypothesis requires a long time for computation by computer, but results in effective solutions. The normal contact stiffness factor was set to 1 because this value is appropriate for bulk deformation, it guarantees no penetration between the contact elements, and permits the convergence of nonlinear problem [30].

The connectors were simulated by using a nonlinear beam element with six degrees of freedom at each node and having a circular cross section with a diameter equal to 3 mm (like the real connectors).

Mechanical properties of the materials were resumed in Table 3. The model was restrained with a cylindrical pin at the base and a horizontal support at the top. Two rigid elements were inserted at the top and at the base of the panel and connected (with "no separation" parameter) to the faces of the sandwich panel (Figure 8). This allows for better simulating the effect of the reaction frame on the concrete layers, especially on the nodes close to the contact point. The load was applied to the rigid element at the top of the panel in the axis of the panel (axial load) and in the axis of an RC face (eccentric load).

Two configurations of welded mesh were studied: the first with 70 × 70 mm welded mesh (rebar volume ratio equal to 0.36) and the second with 70 × 120 mm welded mesh (rebar volume ratio equal to 0.29).

In the first case, connectors were located every four meshes at a distance of 280 mm, while, in the second one, connectors were placed every two meshes at a distance of 240 mm.

The structural FE model is represented in Figure 8, and it is composed of 8447 elements (cubes with an edge of 40 mm) and 60,237 nodes.

At the end of the numerical simulation, the security factor was calculated as the ratio between maximum yield stress and the calculated maximum stress inside connectors from the FE model.

Table 3. Mechanical parameters used for material definition in a Finite Element model.

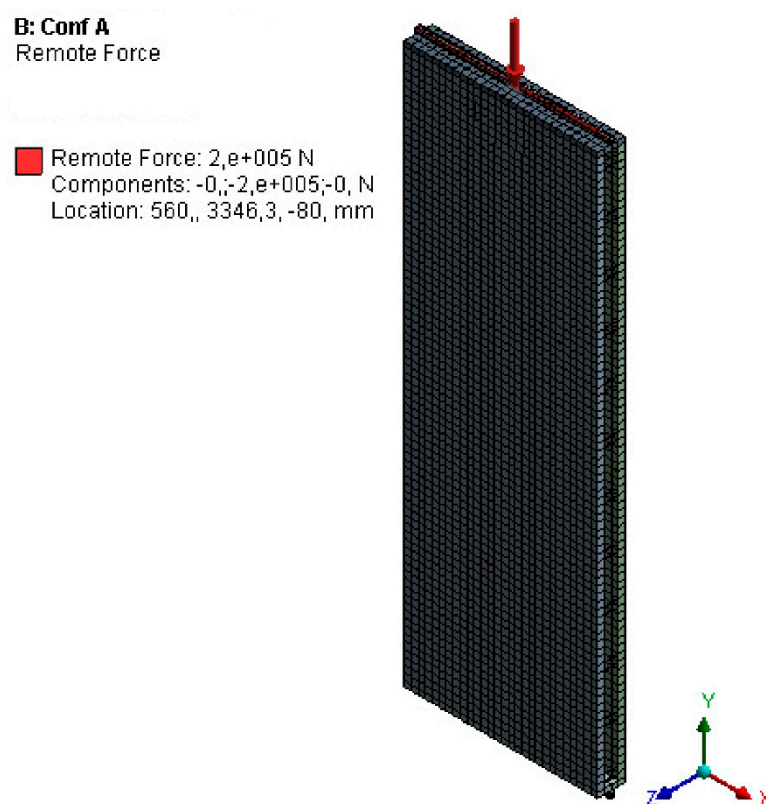| Material	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio
Concrete	2500	30,000	0.2
Steel	7850	210,000	0.3
Insulation—expanded polystyrene	15	6.5	0.12

Figure 8. Mesh of the structural Finite Elements model. Reaction frames are in blue.

3. Results and Discussion

3.1. Structural Performance

In this section, results of the axial and eccentric compression tests and then the results of flexural tests are reported and discussed. Table 4 shows the ultimate load and vertical displacement registered during the compression tests.

Values obtained from compression tests agree with results from literature [10].

As expected, samples subject to axial compression reached higher ultimate load than samples subject to eccentric load.

The failure mode of the panels varied depending on the type of load application; indeed, axial compression caused the failure of the RC layers, while eccentric load caused buckling, and samples failed because of lateral deflection.

It must take into account that axial loading was influenced by intrinsic eccentricity caused by inevitable irregularities during the production phase (i.e., planarity, geometry, defects in materials, and so on...). These imperfections produced a certain deflection also in the axial compression test, and panels reached different levels of ultimate load depending on the entity of this intrinsic eccentricity. For this reason, Table 4 shows higher standard deviations on axial load than on eccentric load.

Figure 9 shows lateral deflection of sandwich panels measured by transducers S_1 and S_2, and they show that Δh of panels subject to axial compression (Figure 9a) was close to zero up to the ultimate load.

In the case of eccentric loading (Figure 9b), a linearity between applied load and Δ*h* is visible up to about 200 kN in the case of bent connectors (solid lines) and about 350 kN in the case of welded connectors (dashed lines). After these limits, micro-cracks appeared in the concrete layers, and the panel assumed a nonlinear behavior. Final lateral deflections are similar to that obtained in previous research performed on similar panels [10], confirming that both welded and bent connectors had the same behavior.

Since this study aims to optimize sustainability of sandwich panels through the two types of connectors, it was important to consider relative displacements between concrete layers because they cause stress (tensions and shear) inside the steel connectors themselves.

Horizontal separation Δc between concrete layers is reported in Figure 10, while vertical slip Δs is plotted in Figure 11 for both axial and eccentric compression.

Δc was higher on samples subject to axial loading than on samples loaded eccentrically because, during the loading increment, the insulation core tended to swell, and it pushed out the concrete layers, generating tensile stress in connectors. Conversely, the eccentric load caused a bowing of concrete layers toward the opposite side of the load axis.

This evidence was confirmed by sample A-2 that showed the lower lateral deflection, reaching the higher ultimate load and the higher separation between concrete layers.

In all cases of eccentric loading (Figure 10b), Δc was close to zero up to the plastic phase.

Figure 11a shows that samples axially loaded had a negligible slip during the first steps of load increment, and then concrete layers were subject to relative slip near the ultimate load.

In the case of eccentric loading (Figure 11b), slip developed from the beginning of the test because the imposed eccentricity caused an elevated lateral deflection and one concrete layer was subject to tensile tension and the other to compression. In this latter case, differences between curves are negligible during the elastic phase, while samples had different behavior during the plastic phase.

By comparing welded connectors (dashed lines in Figures 9–11) with bent ones (solid lines in Figures 9–11), it is possible to note a significant difference from about 150 kN, and this difference is not attributable to manufacturing defects. Weld connectors were capable of ensuring a more fully-composite behavior of sandwich panels than bent connectors, but the gap between the two cases is acceptable in terms of structural performances of the structure. The final resistance of bent connectors ensures that the steel did not reach yield stress, so that their connection of the concrete layers remained unvaried.

Results about flexural tests are summarized in Table 5, where the averaged values of ultimate flexural load, mid-span displacement (δm) and deflexion in correspondence of load application points (δl) are reported. Globally, results are in accordance with previous findings from the literature [31].

The load–deflection curves (Figure 12) overlap during the elastic phase. Furthermore, no significant difference is observed for the ultimate load, although different values of ultimate displacement were registered, showing that panels had different dissipation performances.

In summary, the mechanical behavior of the panels with bent connectors is similar to that of welded connectors only in the elastic phase, and the former have a lower axial ultimate load than the latter. These reductions (about 37% for central load and about 25% for eccentric load) are certainly important, but not so large, so that we can conclude that the load bearing capacity of sandwich panels with bent connectors is adequate for structural purposes, and the reduction is certainly justified by considering the strong advantages obtained with the major sustainability.

It is worth underlining, on the other hand, that for the flexural ultimate load, the bent connectors look 12% better than the welded connectors, although we cannot expect that this improvement is systematic.

This way, the production of RC sandwich panels with bent connectors instead of weld connectors could reduce the energy consumption of about 18% (equal to about 95 MJ for 1 ton), reduce smog, and limit costs consequently [3,4].

Table 4. Compression tests with axial and eccentric loading: ultimate loads.

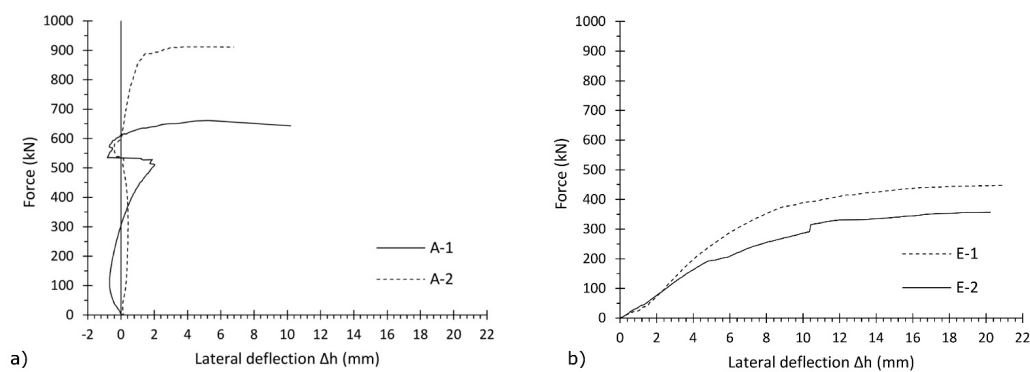| Sample	Connection	Type of Load	Ultimate Load (kN) Mean ± Stand. Dev.	Vertical Displacement (mm)
A-1	bent	axial	661.44 ± 37.33	1.92
A-2	welded		911.93 ± 45.68	1.64
E-1	bent	eccentric	356.65 ± 28.24	1.46
E-2	welded		447.48 ± 30.76	1.75

Figure 9. Lateral deflection Δh of panels tested under axial compression (**a**) and eccentric compression (**b**).
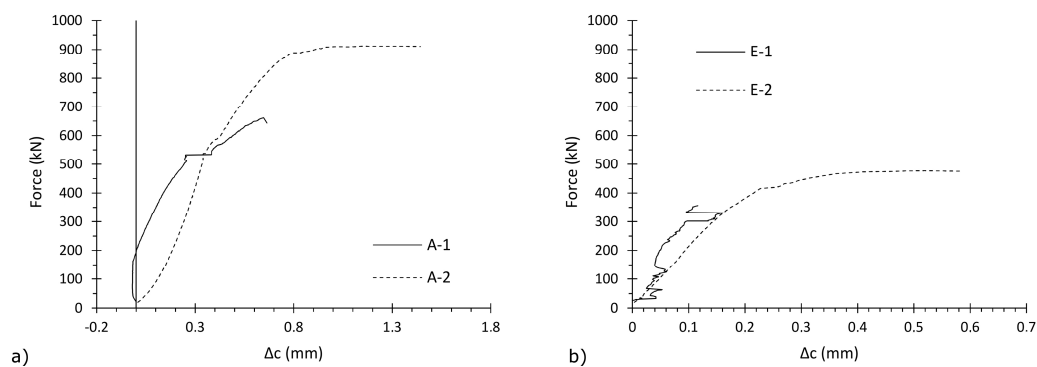

Figure 10. Relative transversal displacement between concrete layers Δc under axial compression (**a**) and eccentric compression (**b**).
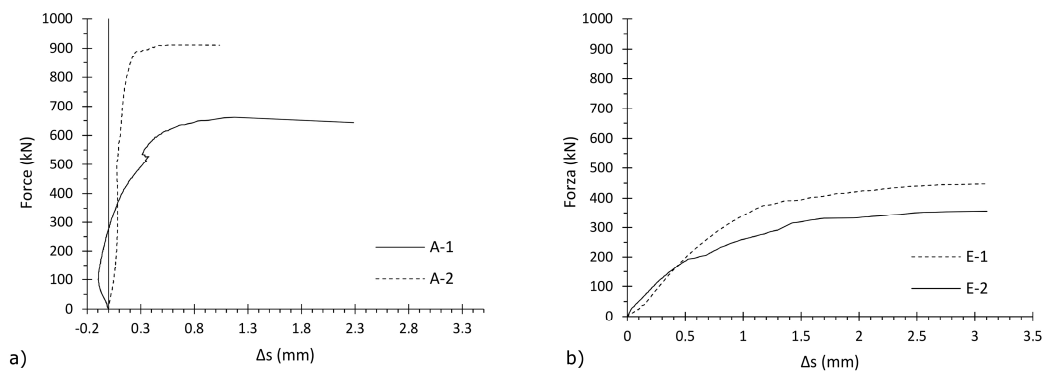
Figure 11. Shear deformation Δ*s* under axial compression (**a**) and eccentric compression (**b**).

Table 5. Average values and standard errors measured during four-points bending test.

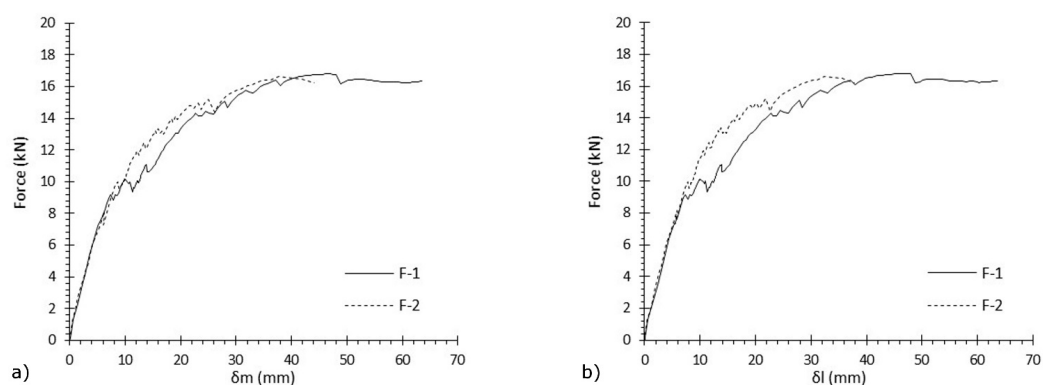| Sample	Type of Connection	Ultimate Flexural Load (kN) Mean ± Stand. Dev.	δm (mm)	δl (mm)
F-1	bent	16.82 ± 0.83	56.62 ± 1.21	49.88 ± 0.83
F-2	welded	17.03 ± 1.27	50.70 ± 1.78	43.38 ± 0.03

Figure 12. Load-deflection plot on mid-span (**a**) and in correspondence of load application points (**b**).

3.2. FE Results

In order to further optimize sandwich panels, the FE model was used to study different configurations of connectors as described in Section 0.

Von Mises stress inside the most stressed connector was resumed in Table 6. In all cases, stresses were much lower than the maximum yield stress of steel wires equal to 737.73 MPa.

Table 6 shows that the higher the mesh spacing, the higher the stress inside connectors; more precisely, stress increase of about 15% in the case of axial loading and 18% in the case of eccentric loading. This phenomenon is understandable because the 70×120 mm mesh is less rigid than the 70×70 mm mesh, and the relative displacement between concrete layers is greater than in the other case. Under these conditions, connectors were subject to higher stress to ensure the integrity of the system.

Results from the FE model confirm that the substitution of welded connectors with bent ones does not compromise the mechanical resistance of the sandwich panel. Stress inside connectors remains lower than yield stress and also in the case of a 70×120 mm welded mesh.

However, it is important to underline that welding generates induced stresses and local effects (reduction of section, imperfections, stress concentration, and so on), which cannot be properly taken

into account through an FE analysis at the panel scale [22,24,28,29]. A complete understanding of local behavior around the contact area between connectors and welded mesh is possible only through future experimental campaigns or local FE models.

Table 6. Stress in connectors at the ultimate load.

Configuration	Type of Load	Mesh Spacing (mm)	Stress (MPa)	Security Factor
A	axial	70×70	336.01	2.19
B		70×120	389.72	1.89
C	eccentric	70×70	357.95	2.06
D		70×120	420.95	1.75

4. Conclusions

Welded connectors usually connect the RC skins of structural sandwich panels. A different, simpler and cheaper type of connector was experimentally tested and compared to those in this paper. Numerical simulations were also carried out to optimize the dimension of the welded mesh and the number of connectors.

Results from (axial and eccentric) compression tests have shown that the new proposed connectors seem to be able to guarantee a good structural response of the full panel, even if its final strength is higher when using the traditionally used welded connectors.

Flexural tests showed the same trends of compression tests, and results are fully in line with other findings from the literature. These tests confirm the possibility to substitute welded connectors with bent connectors without compromising the global mechanical resistance of the RC sandwich panel.

FE results suggests that is possible to vary the number of connectors and the dimension of the welded mesh to obtain different RC skins with different levels of automation and manufacturing costs by, however, maintaining a good structural performance.

This way, the use of bent connectors instead of weld ones seems to be a more sustainable way for producing RC sandwich panels. In fact, it could reduce the energy consumption (about 18%), reduce smog, and limit costs consequently. In addition, the production of RC sandwich panels with bent connectors, by requiring a low level of automation and no qualified labor, could allow their production on site and their diffusion in developing countries.

The RC sandwich panels with bent connectors studied in this paper were prototypes, so further research in this field, coupled with the optimization of manufacturing processes, could further reduce the gap between RC panels with welded connectors and have a more and more sustainable building product.

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