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TRC SANDWICH SOLUTION FOR ENERGY RETROFITTING

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Abstract.

Concerning energy improvement of existing façades, a favourable system involves prefabricated multilayer panels, made of internal insulation core and outer textile reinforced concrete layers. It is a convincing alternative to external thermal insulation composite systems (ETICS) and ventilated façades, and it meets all the requirements for façade systems. The main advantage is the possibility to apply the panel using a crane, without any scaffolding. The paper considers two solutions: the former uses expanded polystyrene (EPS) as insulating material; the latter substitutes EPS with an innovative green insulation material made of inorganic diatomite. The paper aims at comparing the solutions in terms of mechanical properties of the components and behaviour of the composite sandwich at lab-scale level. Numerical models, previously calibrated, will be instrumental for the discussion.

Keywords: Energy performance, sandwich panels, textile reinforced concrete.

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1. Introduction

In Europe, building sector uses a large amount of energy (40% of the total) and produces relevant CO_2 emissions (36%). For this reason, the focus of many European policies is to improve energy efficiency [1]. Each year, only approximately 1% of buildings are energy renovated, in the framework of a building stock that is old and energy inefficient, with the half of residential buildings dated before 1970, year in which the first European thermal Standard was emanated [2]. Hence, improvement in energy efficiency of buildings is a crucial topic.

In multi-storey buildings, façades cover a large amount of the total outer envelope surface. Hence, solutions devoted to the energy retrofitting of existing façade result particularly effective in terms of building energy saving. A convenient solution is represented by multilayer precast sandwich panels made of an inner insulation core and thin external textile reinforced concrete (TRC) layers.

TRC sandwich panels were proposed about 15 years ago by German researchers [3] and constituted a new idea in the framework of cement-based sandwich elements: TRC thickness (10-15 mm) is smaller than that of traditional R/C external claddings (>40 mm) [4], leading an important decrease in the weight of the panel. Other conveniences are durability and the good appearance, obtained using fine-grained mortar. Although connectors were introduced between the layers for a durable connection [5], advantage is taken from adhesive bond between TRC and the insulation layer to transfer the shear stresses.

2. TRC sandwich solutions

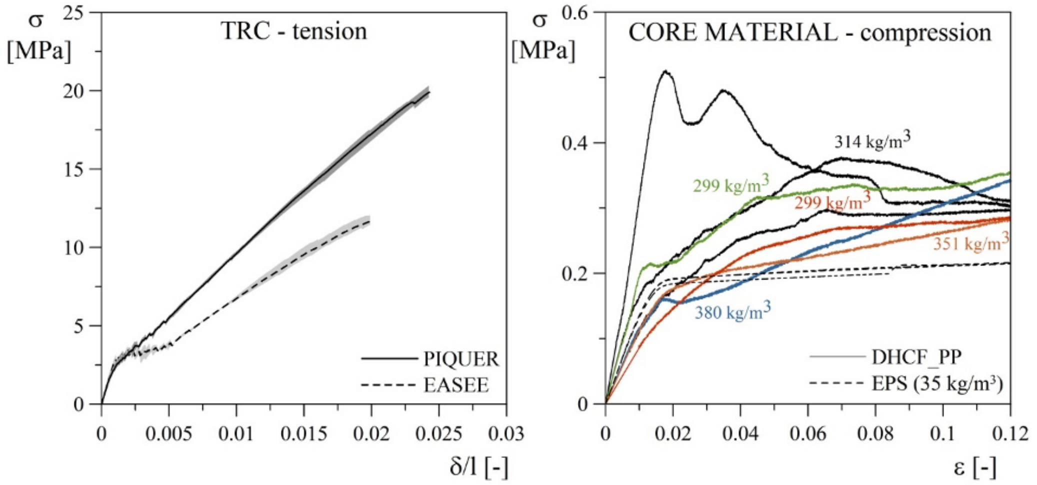
The research concerns prefabricated sandwich panels constituted by thin external TRC layers and an internal insulation core. Large size panels ($3 \times 1.5\,\mathrm{m}^2$) have been designed to reduce the manufacturing and installation costs. The installation is performed through a crane, without scaffolding, thus minimizing installation timing and inconveniences for inhabitants. Other advantages are: the integration of the insulation and finishing systems; the durability and possibility to obtain different colour and texture as finishing; the protection of the insulation core through the external, waterproofed layer of TRC; the good resistance to concentrated loads. Only the inner TRC layer is connected to the existing R/C frame; the shear transfer between the two TRC layers is entrusted to the insulation material (for fire safety, some supplementary connectors could be inserted).

2.1. Panel with expanded polystyrene core (EASEE project)

The Consortium of the European project EASEE [6] developed a prefabricated TRC sandwich panel with expanded polystyrene (EPS) as insulation material. A thickness of 100 mm was considered for the core. All the details concerning the panel design, testing at different scale levels, durability, and modelling can be found in [7–12]. EASEE main output is represented by a demonstration building [11] in Cinisello Balsamo, Italy, where a 70% decrease in the thermal transmittance of the wall was achieved [13]. One of the main criticisms of this panel is that EPS may melt during fire, leading to the loss of mechanical performances of the composite solution.

2.2. Panel with diatomite core (Smart P.I.QU.E.R.)

Smart P.I.QU.E.R. project [14] was aimed at solving the criticisms of the previous project. Among the



(a) (b)

Figure 1. Test results: TRC tensile behaviour (a) and core material compressive behaviour (b).

goals, particular relevance is assumed by the development of a green insulation material, with suitable mechanical properties and good fire and insulating capabilities. At the same time, TRC layers need to be optimised, reducing the shrinkage and weight of the mortar, and enhancing the fabric fire behaviour and sustainability.

2.3. Materials

2.3.1. Textile reinforced concrete

TRC developed in the EASEE project is made by high strength fine grain mortar reinforced with one alkali-resistant glass fabric. The warp is aligned in longitudinal direction. This fabric [7] (leno-weave production; SBR coating: water resin based on styrene butadiene rubber) is characterised by a nominal tensile strength in warp direction of 820 MPa (computed on the equivalent cross-sectional area of the glass). The cementitious matrix has a water to binder ratio equal to 0.225, a superplasticiser to cement ratio of 9.3% and 1 mm maximum aggregate size. The average cubic compressive strength (f_{cc}) of mortar, measured as specified in [15], is equal to 71.89 MPa on 12 specimens, with a coefficient of variation of 9.13%.

Concerning Smart P.I.QU.E.R. project, several mortar mix-designs and alkali-resistant glass fabric reinforcements were investigated [14]. In this paper, a high-performance mortar that includes shrinkage reducing admixtures and is reinforced with one alkali-resistant glass fabric coated with a thermosetting epoxy coating is considered (see "HPC+SRA_AP1" in [14]). The epoxy coating is particularly suitable in case of fire exposure. The fabric is characterised by a nominal strength in the warp direction of 1041 MPa. The cementitious matrix used is characterised by a maximum aggregate size of 1 mm, a water to binder ratio of 0.20 and a super-plasticiser to cement ratio of 5.1%. The average cubic compressive strength (fcc) of mortar measured according to [15] is equal to 97.53 MPa on 32 specimens, with a coefficient of variation of 8.33%.

In both cases, three $400 \times 70 \times 10\text{mm}^3$ TRC samples were tested in uniaxial tension using an electromechanical press INSTRON 5867 with a maximum load capacity of 30 kN, imposing a constant crosshead displacement rate of 0.02 mm/s. The same test apparatus and modalities described in [7] are used. The test results are shown in Figure 1a in terms of nominal stress ($\sigma = P/A$, with P=load and A=specimen cross section) vs. normalised displacement (δ/l, with $\delta =$ imposed displacement and $l =$ free length) curves.

2.3.2. Core material

In the framework of the EASEE project, expanded polystyrene was used as insulation material in sandwich panels. The product EPS250, characterised by a nominal density of 35 kg/m^3, was selected. As resulting from experimental tests [10], it is characterised by a uniaxial compressive yield stress of 0.188 MPa, an estimated Young's modulus in compression of 13.7 MPa, a uniaxial tensile yield stress of 0.392 MPa, a shear yield stress of 0.160 MPa and an estimated shear modulus of 5.04 MPa.

As already anticipated, one of the main aims of the Smart P.I.QU.E.R. project was to develop a core material that could be more sustainable and more suitable in case of fire with respect to EPS. Hence, a novel lightweight sustainable insulation core (DHCF) was developed by Verdolotti and other authors [16] using diatomite (natural source) as matrix. Short fibres were added to guarantee a ductile behaviour of the insulation material both in compression and in bending, in order to guarantee a proper global behaviour of sandwich panels. These fibres also contribute to the enhancement of thermal performances of the material, by reducing the thermal conductivity. Polypropylene (PP) fibres were selected among different kind of reinforcement tested (jute, waste synthetic, mixed and hemp fibres, as such and chopped).

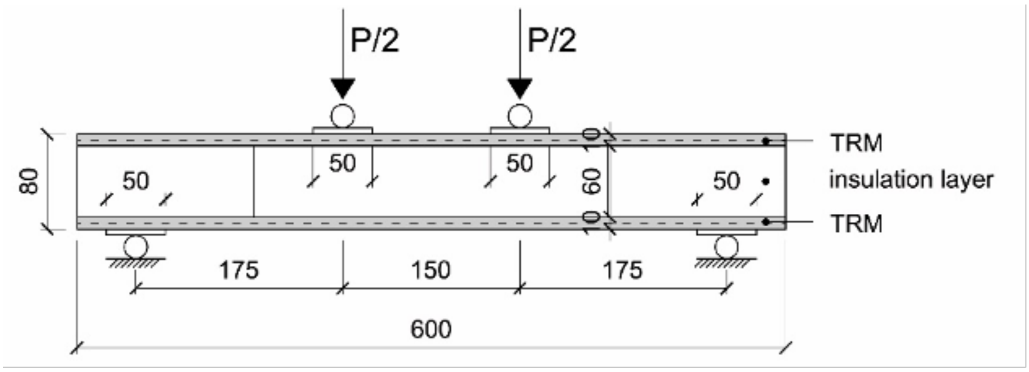


FIGURE 2. Four-point bending test set-up (Smart P.I.QU.E.R.).

This choice was related not only to the proper thermal and mechanical performances of the foam in which PP fibres are included, but also because they are the only ones that allow the production at industrial level by means of an industrial plant. Considering that the level of the plastic plateau is related to specimen density, a target density of 300 kg/m^3 was fixed to guarantee comparable performances of the core material with those of expanded polystyrene. The core mix design is collected in Table 1.

Diatomite (wt%)	19.57
Polysilicate (wt%)	65.24
Si (wt%)	0.046
Catalyst (wt%)	8.39
Vegetable (wt%)	5.82
PP fibres (wt%)	1

TABLE 1. DHCF_PP mix design.

Compressive tests were performed on EPS specimens with a size of $100 \times 100 \times 150\,\mathrm{mm}^3$, and DHCF specimens with a dimension of $40 \times 40 \times 40\ mm^3$. The tests were displacement controlled by imposing a constant displacement rate of the machine crosshead equal to 1e-3 mm/s and 2e-3 mm/s respectively. The compressive behaviour of both expanded polystyrene and diatomite-based insulation material is shown in Figure 1b where the nominal stress σ vs. nominal strain ε curves are plotted ($\sigma = P/A$, P = load, A = unloaded specimen cross-section; $\varepsilon = \delta/h$, δ = top displacement, h = specimen height).

3. EXPERIMENTAL BEHAVIOUR OF LAB-SCALE SANDWICH BEAMS WITH DIATOMITE-BASED CORE

A wide experimental campaign on lab-scale sandwich specimens were developed within the EASEE project. A four-point bending set-up was adopted for both deep ($550 \times 150 \times 120\ mm^3$) and slender ($1200 \times 300 \times 120\ mm^3$) sandwich beams, with EPS 100 mm thick. Detailed description of experimental procedures and results can be found in [8]. Hence, this Section is focused on the experimental tests performed at lab-scale level within Smart P.I.QU.E.R. on beams in bending.

3.1. TEST SET-UP

Four-point bending tests were performed on sandwich beams using the same electromechanical press INSTRON 5867 already mentioned. Two nominally identical specimens with size of $600 \times 150 \times 80\ mm^3$ and the warp of the glass fabric aligned in the beam longitudinal direction were tested. The specimen geometry and the test set-up are shown in Figure 2. The insulation panel densities are collected in Table 2.

Specimen	$\rho_{1st\_measure}$ (kg/m^3)	$\rho_{2nd\_measure}$ (kg/m^3)
PIQUER1	330 (31 days)	303 (125 days)
PIQUER2	348 (28 days)	297 (122 days)

TABLE 2. Density of the insulation core.

The insulation layer of full-scale panels designed in the Smart P.I.QU.E.R. project is obtained placing side by side different core panels with size of $600\times600\times100\mathrm{mm}^3$. For this reason, some cuts are introduced in the insulation layer also in the lab-scale beams (Figure 2). With the aim of reducing stress concentration, 50 mm wide steel plates are glued on the specimen over the cylindrical supports and under the loading-knives. The loading and the supporting cylinders are free to rotate on their axis and in the plane perpendicularly to the longitudinal axis of the specimen. During the initial phase of each test, specimens were instrumented with displacement transducers in order to measure: the specimen deflection under the loading knives, the deflection of the upper TRC layer under the loading knives, the superior longitudinal displacement on the compressed side inside the constant bending moment region, and the crack opening displacement on the tense side. However, these aspects are not treated in this paper. Tests were displacement-controlled, considering the machine crosshead displacement (stroke) as feedback parameter. An initial stroke rate of 2E-3 mm/s

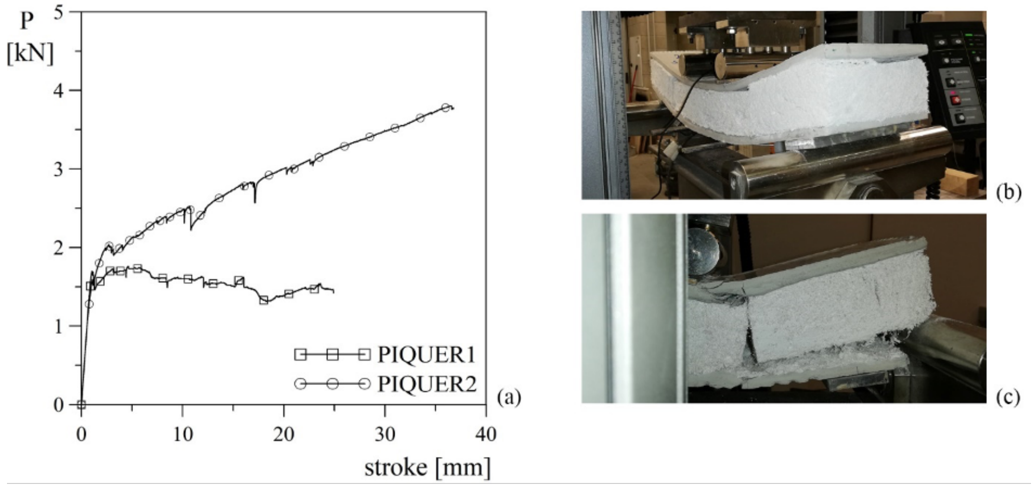


Figure 3. Experimental results (Smart P.I.QU.E.R.): load vs. stroke curves (a) and pictures of specimen PIQUER 2 during the test (b) and at failure (c).

was imposed; then, after crack formation, the rate is increased up to 5E-3 mm/s.

3.2. Experimental results

The test results are shown in Figure 3a in terms of load (P) vs. stroke curves. Looking at the results, it is interesting to note that specimen PIQUER1 experienced a premature shear failure of the core, thus leading to a localised failure and preventing the multi-cracking of TRC layers that guarantees the hardening behaviour of the sandwich solution. In fact, while performing a check before testing, core panel used to cast specimen PIQUER1 presented - to the touch - some softer regions at the edges. On the contrary, specimen PIQUER2 showed a ductile hardening global response, experiencing multi-cracking of TRC faces. A picture of this specimen during testing is shown in Figure 3b. The final failure is related to the debonding between the beam core and the lower TRC layer (Figure 3c).

4. Numerical modelling of the tests and comparison between the two sandwich solutions

4.1. Geometry and constraints

Abaqus /CAE 6.14-5 was adopted for the modelling of the panel. Yz symmetry was exploited, and half of the beam was reproduced, thus minimising the numerical effort (Figure 4a).

As shown in the figure, the panel layers (TRC and core), and the steel plates are modelled as solid and homogeneous. Perfect bond is assumed at core/TRC interfaces and between the panel and steel plates. The interaction between adjacent core panels is characterized by a hard contact in the normal direction and by a frictionless contact in the tangential direction.

Concerning constraints, displacement orthogonal to the symmetry plane are prevented, the lower steel plate is constrained in the vertical direction on the bottom face and a vertical displacement δ is imposed on the loading line. The mesh is shown in the same figure: eight-node linear hexahedral elements (C3D8R - Continuum, 3-D, 8-node - reduced integration) are used.

4.2. Constitutive laws

In this Section, a description of the constitutive laws adopted for each material is proposed.

The elastic phase of TRC is defined introducing a Poisson's ratio of 0.2 and a Young's modulus of 30 GPa (according to literature results [17] on mortar characterized by equal maximum aggregate size and compressive strength).

The plastic behaviour of TRC is modelled through Abaqus Concrete Damage Plasticity model. No damage curve is inserted; hence, the model behaves as a plasticity model. In compression, an elastic-perfectly plastic behaviour is assumed, imposing a yield strength of 97 MPa according to the values shown in Section 2.3.1. The stress-irreversible strain relationship (Table 3) adopted in tension is extracted from the experimental results of PIQUER specimens shown in Figure 1a, considering strains computed basing on the measurements of displacement transducers applied on TRC. TRC tensile behaviour is assumed homogeneous over the layer thickness; this assumption is reliable according to [10].

Point	Yield stress	Cracking strain
T1	2.5	0
T2	5	0.00275
T3	20.81	0.017

Table 3. TRC plastic tensile constitutive law.

Concerning the core material, the elastic phase is defined introducing a Young's modulus of 20 MPa

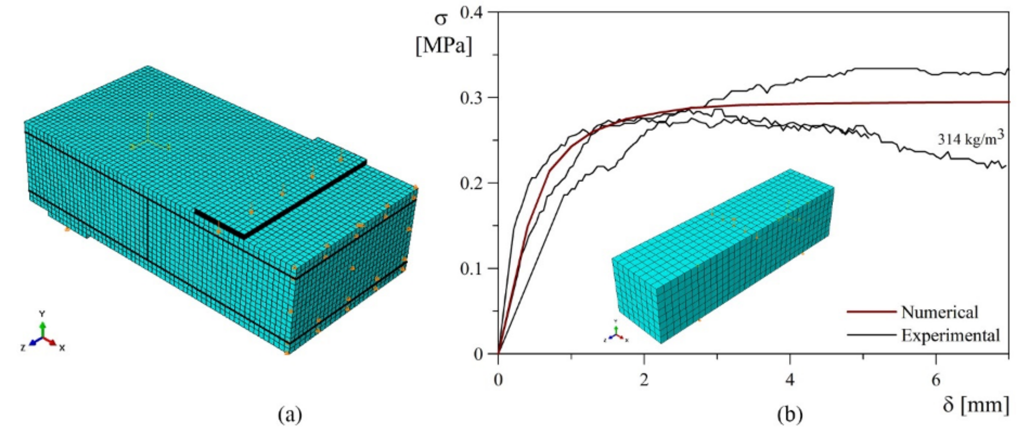
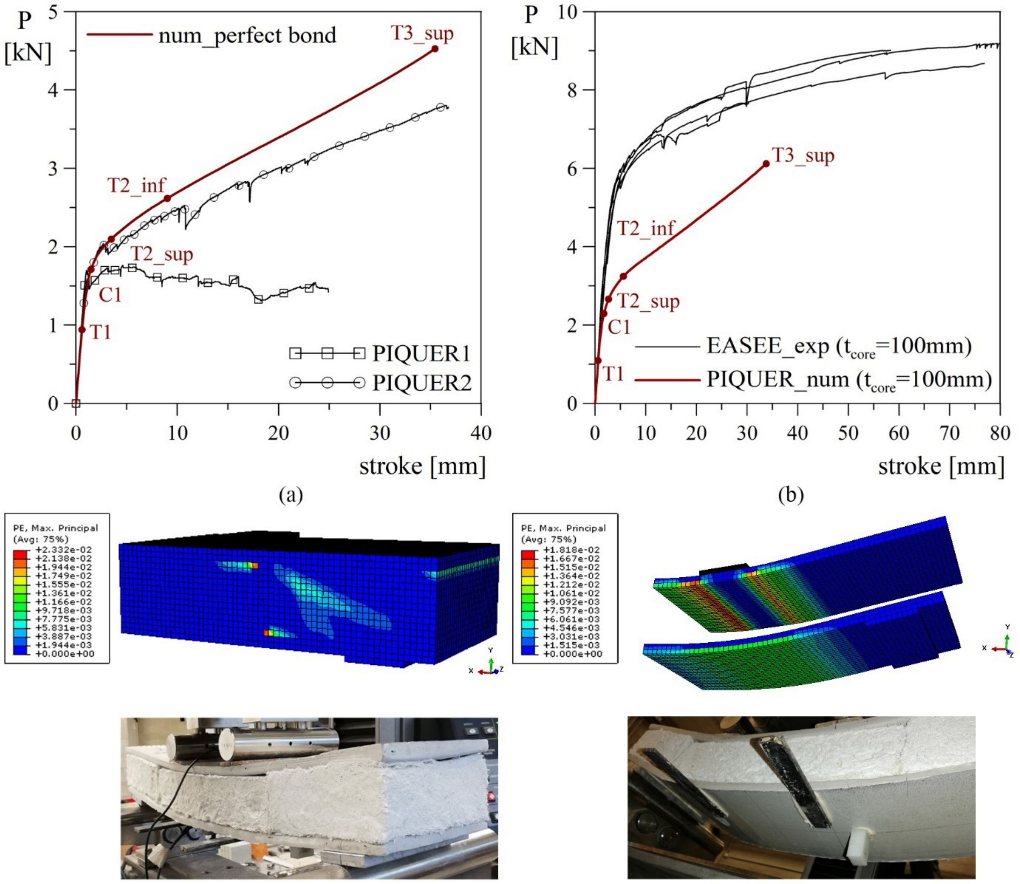


Figure 4. FE model: geometry and constraints (a) and validation of core material model considering three-point bending (b).



(a) (b)

(c) (d)

Figure 5. FE model results: numerical response compared with experimental results (a) and with EASEE bending behaviour (b); failure modes for specimen PIQUER2 showing core strut yielding at point C1 (c) and TRC multi-cracking at point T3_sup (d).

(according to experimental results in compression shown in Figure 1b) and a Poisson's ratio of 0.2.

The plastic behaviour of the core material is introduced using Abaqus Concrete Damage Plasticity model. Also in this case, no damage curves are introduced. An elastic-perfectly plastic behaviour is assumed both in tension and in compression: a compressive yield strength of 0.30 MPa is used according to experimental results shown in Figure 1b (average value for specimens of the same batch of core sample PIQUER2); a tensile yield strength of 0.053 MPa is adopted according to average experimental results of tensile tests performed on core specimens.

With the aim of checking the validity of the material model adopted for the core, a three-point bending test performed on core prismatic specimen with size of $160 \times 40 \times 40 mm^3$ was modelled. Experimental and numerical curves are compared in Figure 4b, demonstrating that the adopted material model is reliable.

Steel is assumed elastic with a Young's modulus of 210 GPa and a Poisson's ratio of 0.1.

4.3. Numerical results

The numerical response is shown in Figure 5a in terms of load (P) vs. stroke. A good correlation is found with respect to the behaviour of specimen PIQUER2 that showed a hardening behaviour. A perfect overlapping is obtained in the initial phase of the test; the divergency of the two curves while the test is progressing could be related to a bond weakness at TRC-core interfaces, leading to the final failure due to debonding already underlined in Figure 3c.

In order to investigate the failure mechanisms occurred for a specimen characterised by a good TRC-core bond, critical points of material constitutive laws are underlined on the numerical curve. In particular: T points refer to the TRC layers (Table 3), with subscript "inf" related to lower TRC layer and subscript "sup" related to the upper TRC layer; point C1 indicates the yielding of the strut in the core material. It is worth noting that the change in the slope of the global response corresponds to point C1 (Figure 5c), when both TRC layers are already cracked (Figure 5d).

In Figure 5b the numerical response of PIQUER specimens, in which the core thickness was enhanced to 100 mm, is compared with the experimental behaviour of EASEE sandwich beams characterised by the same cross-section and size.

5. Conclusions

The bending behaviour of sandwich solutions developed within the EASEE and Smart P.I.QU.E.R. projects was compared at lab-scale level. Even though the response of the PIQUER sandwich beam showed lower maximum load and final displacement, a ductile hardening behaviour and a reasonable sustained load are guaranteed by the solution. It is worth noting that a good bond at TRC-core interfaces must be guaranteed to obtain a proper behaviour of the composite.

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