Chapter 10
Sustainable Roof Elements: A Proposal Offered by Cementitious Composites Technology

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Abstract The use of High Performance Fibre Reinforced Cementitious Composites (HPFRCC) allows the designer to reduce the dead weight of roofing keeping concrete covering structures still more competitive in relation to steel structures in terms of costs, thermal and acoustic insulation and fire resistance. Thin slabs can be used as tertiary elements in roof decks beside the spandrel beams and the simply supported prestressed precast roof elements. Two metres wide elements, simply supported along a 2.5 m span were devised as a possible application in this paper: the high performances are mainly used for the bending behavior along the 2.5 m span and in order to drastically simplify the detailing of the support regions. The idea is that of coupling textile and Ultra High Performance Fibre Reinforced Concrete (UHPFRC) technology, by means of an interposed polystyrene layer.

A wide experimental investigation is in progress to mechanically characterize the materials in uniaxial tension and compression, in order to identify all the data needed for design like toughness, bending resistance, fire resistance and durability. As for the UHPFRC, in the research, the check of the ductility and the identification of the mechanical characteristics in tension are performed by means of bending tests carried out on unnotched specimens according to Italian Recommendations CNR DT-204 and of a new test (Double Edge Wedge Splitting test) recently proposed, while third point bending test as suggested in EN14651 is used to classify the material production.

With reference to textile materials, they are reinforced with glass fabric and randomly dispersed glass or PVA fibres. The mechanical characteristics are deduced in uniaxial tension.

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10.1 Introduction

Precast concrete roof systems are often disadvantaged compared with other structural solutions, made of timber or steel, because of the higher ratio of dead weight to live loads. An average dead weight close to 2 kN/m^2, that can be regarded as a common value for a concrete roof system consisting of precast Reinforced Concrete (RC) elements, is quite large compared to the snow load, that is close to the value of 1.5 kN/m^2 in many parts of the world. An acceptable compromise in terms of costs and weight can be achieved by adopting ultra high performance materials (Naaman and Reinhardt 2003; Reinhardt and Naaman 2007) which are more expensive, but can be much lighter. The reduction of the total weight can also result in reduced global structural cost. Preliminary results considering a composite slab made of High Performance Fibre Cementitious Composite (HPFRCC) and Textile Reinforced Concrete (TRC) are here presented to be used as secondary structural element in a prefabricated structure (Fig. 10.1).

The plate is conceived as a layered composite structure, with a High Performance Cementitious Composite in the top layer and Textile in the bottom layer. The two layers are coupled by means of a high density Polystyrene panel (Fig. 10.2), that is structurally employed to transmit very small shear stresses and is used also for thermal insulation. The low permeability of the composite (Moro et al. 2011) suggests preventing the use of a waterproofing layer over the structure, by allowing a solution that makes use only of a suitable gasket between the plates. The plates are also characterized by high fire resistance: in fact, when a fire occurs, polystyrene sublimates because the melting temperature of EPS (Expanded Polystyrene) is close to 160°C. Polystyrene is a thermoplastic substance, which is in solid (glassy) state at room temperature, but flows if heated above its glass transition temperature, and becomes solid again when cooled. If a suitable fixing device is designed to hang the

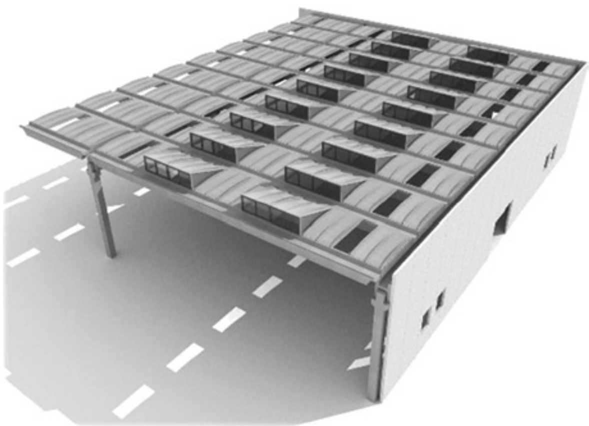


Fig. 10.1 Sketch of the prefabricated roofing adopted as a reference

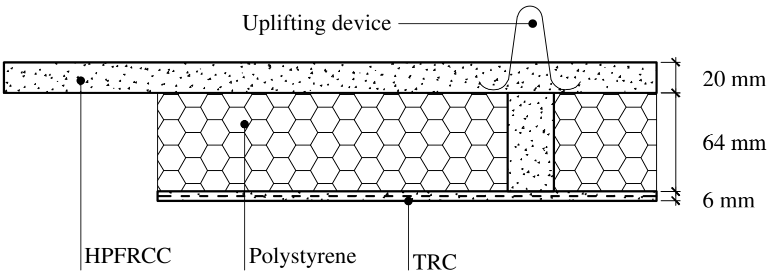


Fig. 10.2 Geometrical description of the multilayer thin plate for roofing

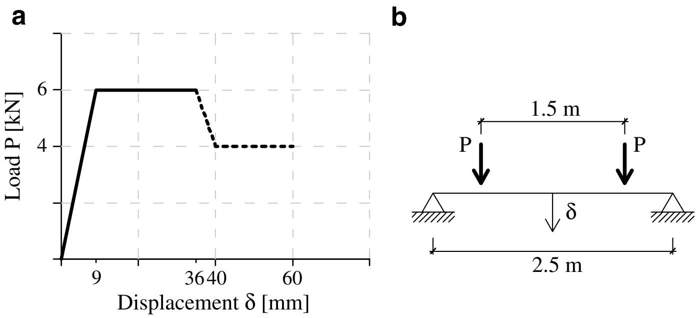


Fig. 10.3 Performance target for the roof element

textile thin layer to the upper HPFRCC plate, the empty space formed with the polystyrene melting becomes an ideal barrier against fire and the TRC panel works as a fire shield preserving the structural bearing resistance of the top HPFRCC plate. Of course a suitable escape for the smoke has to be introduced.

10.2 Research Significance

The research aims at investigating the mechanical behaviour of a layered composite structure designed to achieve the following goals: light weight, low cost, good thermal insulation, reliable waterproofing and high fire resistance. The bending resistance of the plate should guarantee a higher load for serviceability limit states and a lower load in case of fire because in that case snow load can be neglected and the bending is caused only by the structure self weight. In Fig. 10.3 a qualitative sketch of the designed bending moment performance required for a plate 2 m wide, 2.5 m long and 90 mm thick respectively at serviceability ($M = 6$ kNm) and fire load ($M = 4$ kNm) action combinations is shown.

10.3 Materials

10.3.1 High Performance Steel Fibre Cementitious Composite (HPSFRC)

The mix design of the cementitious composite (Table 10.1) was selected by comparing different solutions starting from the aggregates generally used by the precast manufacturer and limiting their maximum size to 2 mm. The composite was a self compacting cementitious material (Fig. 10.4) and some data on its fresh behaviour are available in (di Prisco et al. 2008; Ferrara et al. 2011). The steel fibre content was equal to 100 kg/m^3 (1.2% by volume); straight high carbon steel fibres, 13 mm long and with an aspect ratio (l_f/d_f) equal to 80 were used. Preliminary tests on free and restrained shrinkage (di Prisco et al. 2008), allowed estimation of the quite large strain, that was not unexpected due to the significantly large paste volume fraction which characterizes the mix composition. A cubic compressive strength of 143 MPa and an elastic modulus close to 40 GPa were measured in the preliminary material qualification. Unnotched prism specimens with a square 50 mm side cross section were tested in three point bending (span 125 mm). An average bending strength equal to 27.4 MPa was obtained, with standard deviation

Table 10.1 Mix composition

Component	Dosage (kg/m^3)
Cement type I 52.5	600
Slag	500
Water	200
Superplasticizer	33 (l/m^3)
Sand 0–2 mm	983
Fibres (l_f = 13 mm; d_f = 0.16 mm)	100

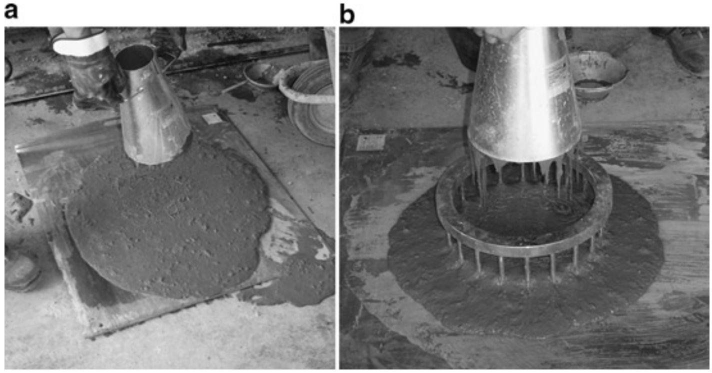


Fig. 10.4 Fresh concrete performance: (**a**) slump flow and (**b**) J-ring tests

Table 10.2 Nominal strength in bending according to UNI 11039

$f_{IF,av}$ (st.dev.) [MPa]	$f_{eq1,av}$ (st.dev.) [MPa]	$f_{eq2,av}$ (st.dev.) [MPa]
7.10 (0.14)	12.06 (1.36)	9.77 (1.83)

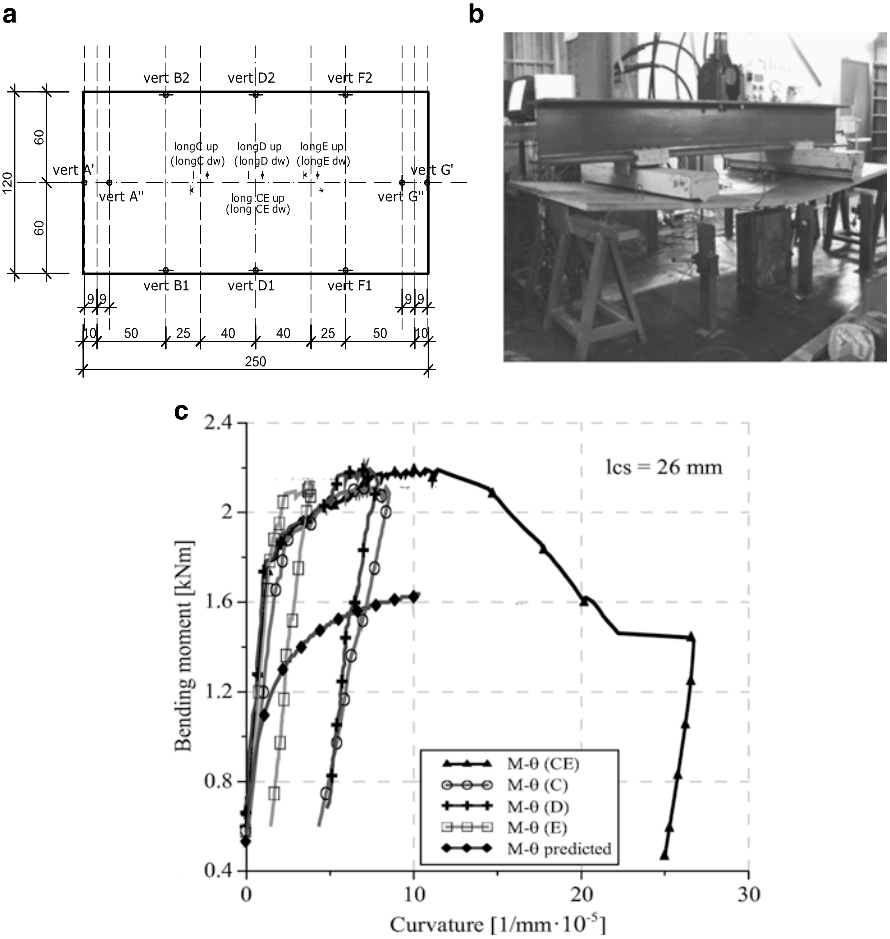


Fig. 10.5 Bending of HPFRC thin plate: (**a**) plate set-up; (**b**) deformed shape at collapse; (**c**) bending moment vs. curvature

of 1.5 MPa. To qualify the material according to Italian Standards (CNR-DT 204 2006) also four point bending tests on notched prism specimens 600 mm long, with a 150 mm side square cross section were carried out: the bending residual strength are summarized in Table 10.2. In order to ascertain the effectiveness of the bending behaviour with reference to large plates, also some tests on rectangular 1.2 m × 2.5 m plates 26 mm thick were carried out (Fig. 10.5).

Table 10.3 LOP strength and ultimate (w = 1.8 mm) residual strength in bending at high temperature (Caverzan et al. 2009a, b)

	Fibres	T = 20 °C	T = 200 °C	T = 300 °C	T = 400 °C	T = 600 °C	T = 900 °C
$f_{lf,av}$	Aligned	11.30	9.10	–	4.93	4.64	–
[MPa]	Random	11.05	–	8.20	–	4.15	0.64
$f_{eq2,av}$	Aligned	22.81	23.42	–	23.23	4.36	–
[MPa]	Random	14.00	–	14.03	–	4.99	0.34

The results obtained without any attempt to orient steel fibres highlight the favourable deflection hardening behaviour which can be achieved. Furthermore, as also highlighted in the *fib* Model Code 2010, a large safety margin can be observed when the response in bending is predicted by employing material constitutive laws identified from 4-point bending tests on notched specimens, as used for the classification of the material. A better prediction can be achieved when a tensile constitutive law is identified from bending tests performed on a "structural" unnotched specimen, characterized by the same thickness and the same casting procedure as for the structural element to be (di Prisco et al. 2009). The material used showed also very good performance with reference to fire resistance: detailed results are shown in (Caverzan et al. 2009a, b) with reference to both not aligned and aligned steel fibres: Table 10.3 provides a summary of the peak and residual strengths when the material is exposed to different high temperatures.

10.3.2 Textile Reinforced Mortar

Textile Reinforced Mortar is a relatively new material which allows producing thin structural layers characterized by a high tensile strength mainly given by an Alkali Resistant glass fabric (Hinzen and Brameshuber 2007; Brameshuber 2006; Peled and Bentur 2000; Peled et al. 1999). The reinforcement is scantly affected by aggressive environment and therefore no cover needs to be respected. This feature allows the designer to consider a reinforced skin that can exploit the largest lever arm for bending. One of the most interesting aspects is the small variability of the response when good bond between the reinforcement and the matrix is developed (Fig. 10.6; Colombo et al. 2011). Multiple cracking allows spreading the deformation as in RC structures, but a very small crack spacing prevents large crack opening up to the failure. In this preliminary study, an E-glass fabric and a commercial mortar were used. Their characteristics are specified in Tables 10.4 and 10.5.

10.3.3 Polystyrene

A careful mechanical characterization of Polystyrene was carried out (Colombo et al. 2008). The specimens were prismatic (90 × 90 × 45 mm) and both uniaxial tension and compression tests were performed. In Fig. 10.7 the strain has been

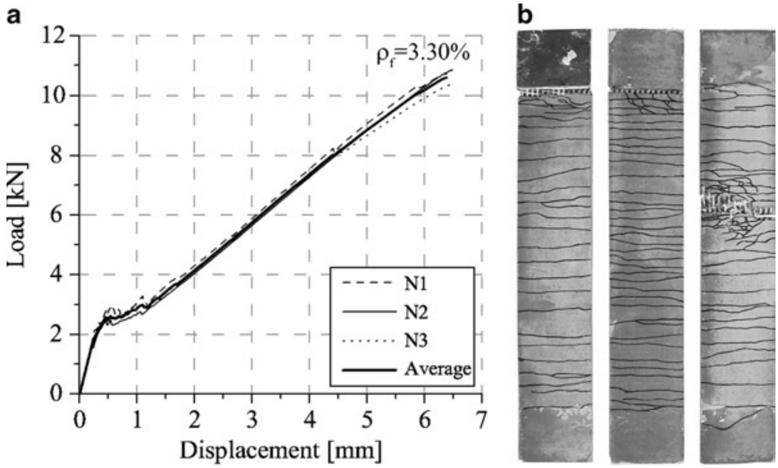


Fig. 10.6 Mechanical characteristics of a strip 400 mm long, 70 mm wide and 6.2 mm thick achieved with TRC made of AR glass fabrics: (**a**) load vs. total displacement in a uniaxial tension test; (**b**) crack pattern (Colombo et al. 2011)

Table 10.4 Geometrical characteristics of E-glass fabric used

Warp wire spacing [mm]	4.5
Weft wire spacing [mm]	5.0
Warp [Tex]	136 + 136
Weft [Tex]	320
Fabrication technique	Leno weave
Average Peak load [kN/m]	40

Table 10.5 Mortar mechanical characteristics

γ_{av} (st.dev.) [g/cm^3]	$R_{cm,av}$ (st.dev.) [MPa]	E_{av} (st.dev.) [GPa]	$f_{ct,fl}$ (st.dev.) [MPa]
2.19 (0.07)	77.50 (6.87)	29.67 (0.04)	9.52 (0.38)

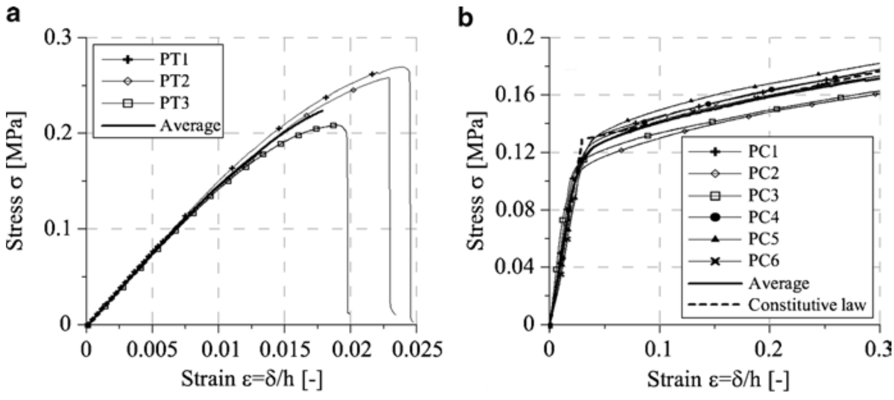


Fig. 10.7 Polystyrene mechanical characteristics: (**a**) uniaxial tension; (**b**) uniaxial compression (Colombo et al. 2008)

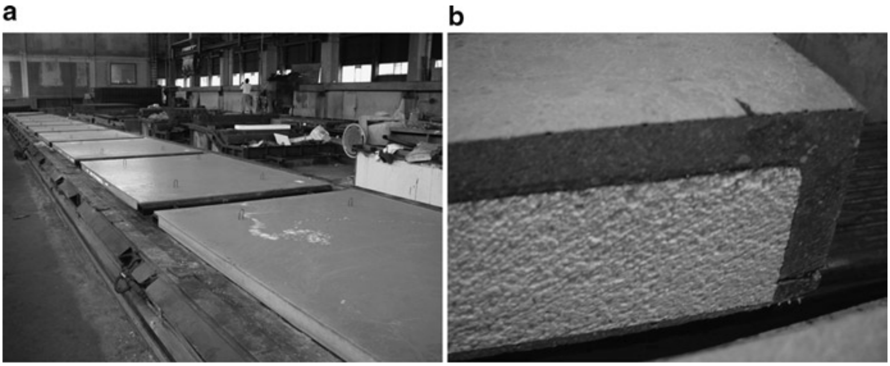


Fig. 10.8 Casting of full scale multilayer plates

calculated dividing the relative displacement of the press platens by the total specimen length. As expected, the material exhibits a quite low strength, but while in compression its behaviour is elastic–plastic, in uniaxial tension is elastic-brittle, with a strong non-linearity close to the peak. It is interesting to observe that the compressive yield strength ($f_{py}=0.12$ MPa; Fig. 10.7b) is lower than the tensile one ($f_{pt}=0.2$ MPa; Fig. 10.7a), even if the compressive behaviour guarantees a larger ductility due to the hardening branch that plays the key role in the mechanical behaviour of the layered panel. Furthermore, also the Young's modulus in tension is larger than in compression ($E_{Pc}=4.35$ MPa; $E_{Pt}=14.7$ MPa).

10.4 Experimental Investigation

In order to understand if the conceptual design, as highlighted in the Research Significance Section, could achieve the declared goal, a preliminary experimental investigation on small prismatic specimens and full scale plates was carried out. This investigation was instrumental to anticipate the rising of unexpected structural problems, if any, related to delamination, shear failure, deformability or other mechanical problems concerning the use of unconventional materials. The specimen production was also instrumental to highlighting any constructive difficulty. Ten plates 2.0 m × 2.7 m and 90 mm thick were produced (Fig. 10.8a). The thickness of the three layers was 20, 64 and 6 mm respectively for HPFRCC, polystyrene and TRC materials (Fig. 10.8b). Two different E-glass fabrics and different devices to guarantee the transmission of shear stresses between the two cementitious layers were investigated. A plate was first sawn to obtain several prismatic specimens devoted to investigate the specific behaviour of the composite structure. This procedure guarantees the most realistic situation in the sense that the material properties as well as the casting procedure are exactly the same of the full scale manufactured slab, and for this reason the representativeness of these test specimens is very high.

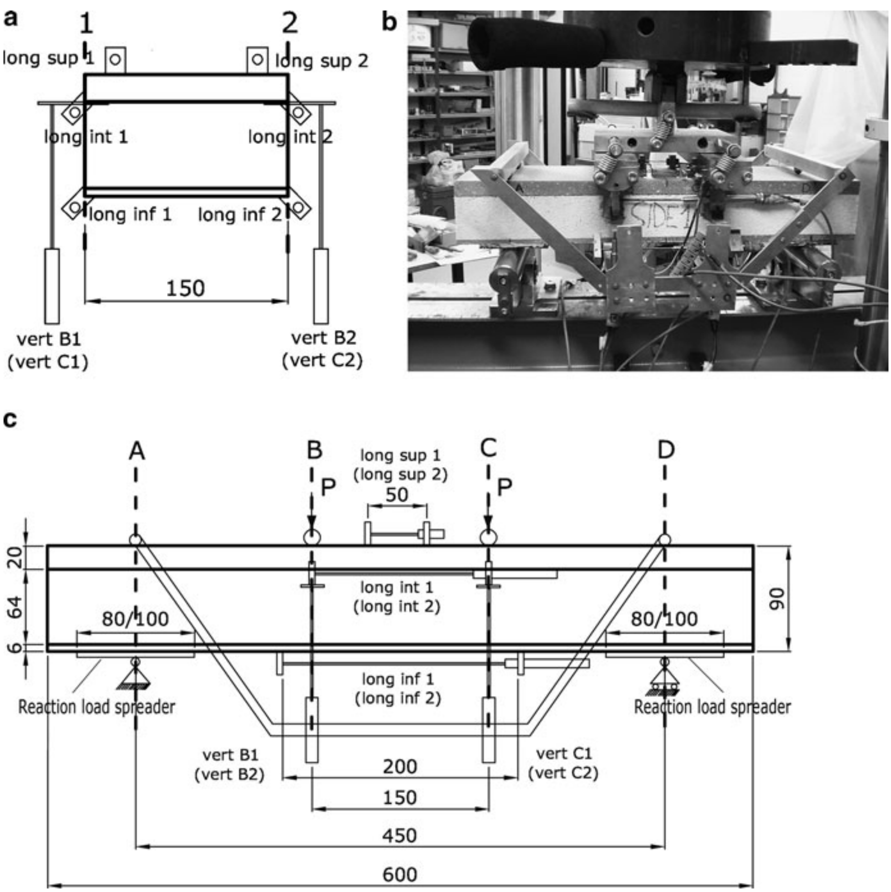


Fig. 10.9 Composite beam specimen: (**a**) geometry; (**b**) test set-up; (**c**) instrumental equipment

10.4.1 Composite Beam Specimen test

Fifteen tests were carried out on prismatic layered specimens 150 mm wide according to a four point bending set-up: the details of the geometry and of the instrument equipment are shown in Fig. 10.9. Two thin steel plates were glued to the TRC bottom layer in the zones close to the supports in order to diffuse the localized stress and prevent any spurious localization due to the reduced load span here adopted with respect to the one introduced in the full scale plate test (Fig. 10.9c). The vertical displacements of two points close to the intrados of the UHPFRCC layer and in correspondence with the loading knives were recorded; besides vertical deflections, also the relative horizontal displacements between two points located close to the top and the bottom fibres to evaluate the curvature in the central zone between the loading knives were used. The tests were also instrumental in the evaluation of the scattering in the response, both in relation to the peak and the ductility.

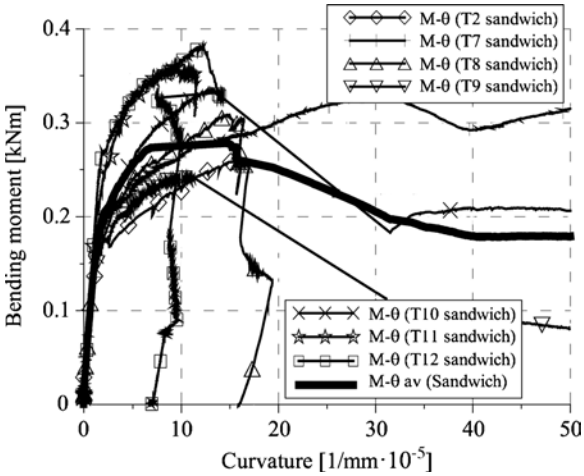


Fig. 10.10 Bending moment vs. curvature of composite beam specimens

The comparison between seven tests carried out on sandwich prismatic specimens with the same E-glass fabric and described in terms of bending moment versus curvature are shown in Fig. 10.10. A double plateau is clearly observed: the first one corresponding to the bending contribution of the TRC and the second one corresponding to the bending of the HPFRCC layer alone, which remains active when the crack propagates through the polystyrene layer. Although the small sizes of the prism specimens cannot guarantee a good repeatability of the response, the global ductility obtained with the use of a brittle glass fabric is quite high, since a peak curvature equal to 10^{-4} mm^{-1} has been reached, while the curvature measured at the failure of the top HPFRCC plate is much higher, reaching a value close to five times the peak one. The average was computed by a first normalization of each curve with respect to each peak. The initial stiffness is not affected by any tolerance or defect and is always the same, thus showing that no sliding or delamination occurs up to the onset of cracking of the TRC layer, that is for a bending moment close to 55% of the average peak value.

10.4.2 Full Scale Structure Tests

The full scale plate tests were carried out at different ages in order to evaluate the effect of aging on the mechanical degradation of the E-glass material used in the TRC layer, even if a careful protection made of a suitable dressing was adopted. The four point bending set-up used is described in Fig. 10.11: five cross sections (A–E) were instrumented to measure vertical deflections at the supports, at midspan and under the loading knives at the slab intrados. Four LVDT transducers were positioned at the supports (long A2(E2)sup, long A2(E2)inf; Fig. 10.11) to measure the relative sliding of the top and bottom cementitious layers to the polystyrene one. No significant sliding was observed up to the peak. The test was displacement controlled and the feedback parameter was the midspan deflection. The employed hydraulic jacket

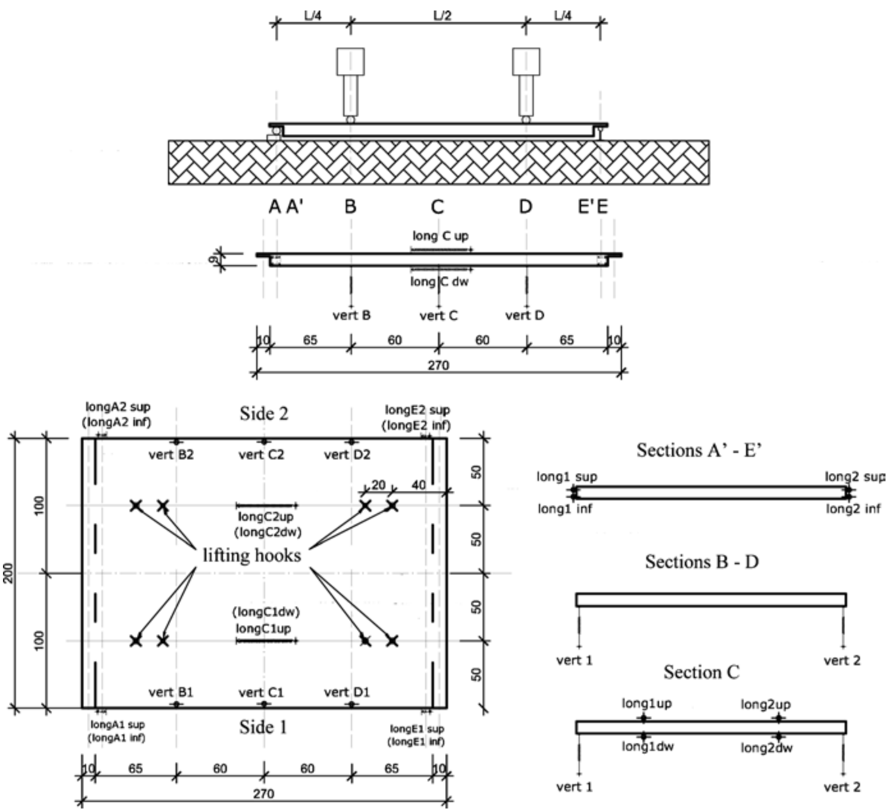


Fig. 10.11 Full scale plate set-up

(MTS®) had a load capacity of 250 kN available at the Department of Structural Engineering; two loading knives 120 cm long and acting over suitable timber beams were used in order to distribute over the whole plate width the total load. The two load devices guaranteed separately both the rotations around a knife axis (roller) and about longitudinal axis parallel to the longitudinal symmetry one (Fig. 10.12a).

Three load stages were imposed: an adjustment stage by imposing a loading and unloading cycle up to 6 kN (corresponding to a moment given by a uniformly distributed load of 1.25 kN/m^2); a second stage with three loading and unloading cycles between zero and a maximum load respectively equal to 3.0, 6.0, and 9.0 kN. In this phase the structural response remains quasi-linear. This was followed by a monotonic loading stage, in which a peak load equal to 15.26 kN was reached at a deflection equal to 40 mm. A further cycle in the cracked regime was imposed up to a deflection of 60 mm. Finally a third stage characterized by a progressive reduction of the load displacement controlled was imposed. The final load reached corresponded to about 20% of the peak load. It is worth remarking that all the tests were performed at an environment temperature equal to about 28°C. The graphs here proposed concern only the first two stages. The E-glass fabric, as expected progressively lost its

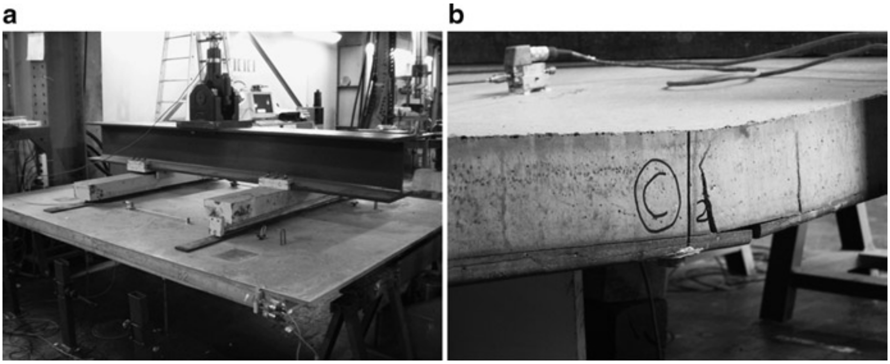
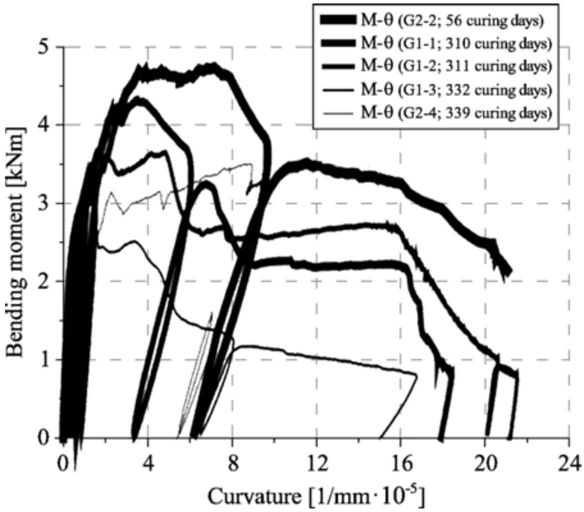


Fig. 10.12 Full scale plate testing: (**a**) bending test arrangement; (**b**) localization at failure

Fig. 10.13 Bending tests carried out at different ages



tensile strength due to Alkali attack, despite the suitable dressing used (Fig. 10.13). The best behavior was obtained in the earliest test and the load vs. vertical displacements as well as the load vs. longitudinal relative displacement, useful to compute the load vs. curvature response, are shown in Fig. 10.14. The total load is equal to about twice as much as the serviceability loads anticipated as design target. As remarked above, the double plateau values correspond first to the bearing capacity of the composite plates and, after the crack propagation, only to that of the top HPFRCC plate. Although the E-glass fabric was elastic-brittle, a suitable coupling of the layers allowed a ductile behaviour as planned in the preliminary design.

The comparison between composite beam and plate behaviour (Fig. 10.15a) highlights that the plate, due to its larger size and consequently to its higher expected defect distribution, shows a reduced ductility and a smaller bending strength. Moreover it is also worth noting that the larger shear load introduced in the beam due to its reduced span, does not at all affect the bending behaviour.

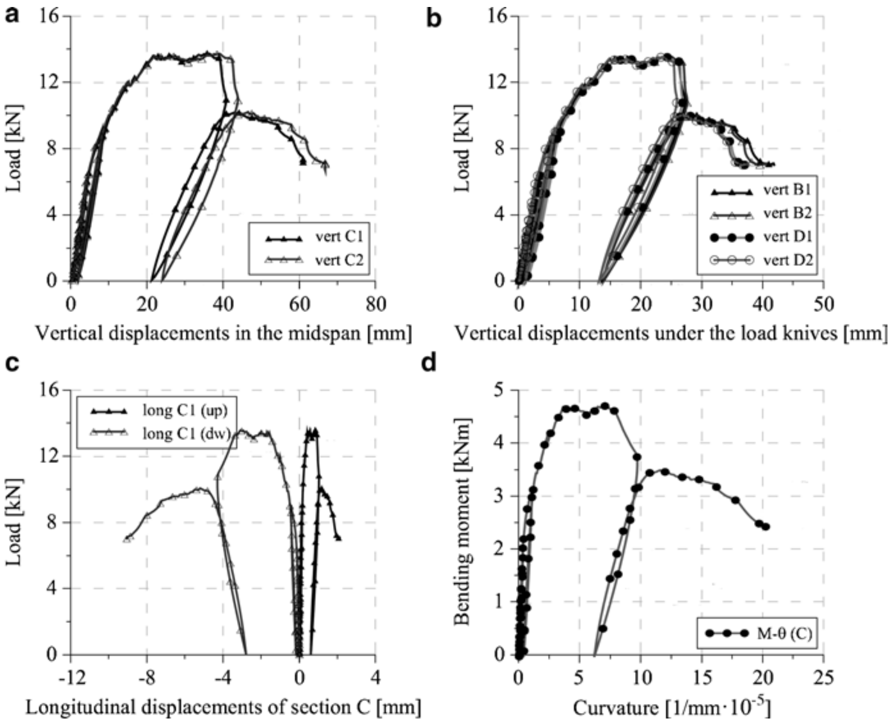


Fig. 10.14 Bending behaviour of full scale composite plate G2-2 (56 curing days): (**a**, **b**) load vs. deflection in the midspan and under the load knives; (**c**, **d**) load vs. longitudinal displacements and bending moment vs. average curvature at midspan

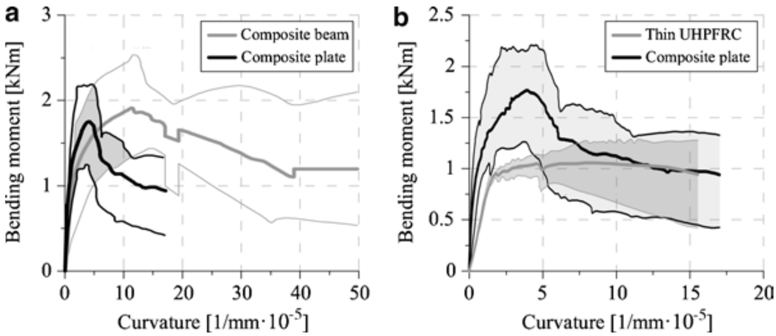


Fig. 10.15 Test comparisons on bending behaviour: (**a**) composite beam vs. composite plate; (**b**) thin UHPFRC vs. composite plate

Finally, the comparison between the behaviour of composite and simple UHPFRCC plates (Fig. 10.15b; (di Prisco et al. 2008)) highlights the TRC contribution, which is limited to a larger initial stiffness and the first plateau bending performance.

10.5 Technological and Design Problems

During the production of full size composite plate, several technological problems were met. The most crucial concerns with the ability to guarantee the robustness of the fresh state performance of the employed HPFRCC, which is, as a matter of fact, necessary not only for successful casting but also with reference to the expected day by day variability of mechanical performance (Ozyurt et al. 2009). As known, it is mainly affected by the actual water/binder ratio, which needs a careful control of the aggregate moisture content. Some difficulties also arose with reference to filling all the gaps between the moulds and the polystyrene panels; these gaps, because of the fibre length, cannot be made thinner than 10 mm. In the proposed experimental campaign no effort to orientate the fibres in the top plate was performed. During the production a special care has to be devoted to shrinkage, especially when the mortar used in TRC is not the same used for HPFRCC material.

10.6 Concluding Remarks

An original idea to build light, waterproofing, thermal insulated and fire resistant roof plates has been presented in this paper. The main result is the possibility to use layered plates without any special gluing, obtained just using the chemical and mechanical bond strength obtained between polystyrene and high performance mortars due to hydration of Portland cement. In the tests no delamination problems were met and the results confirm the achievement of the declared goals. The mechanical response of the overall composite structures shows a quite good ductility, while it has been proved once again that E-glass fabrics must be substituted by AR glass fabric to prevent significant performance decreases in the time of the structural behaviour. Further research aimed at improving bending performance by means of oriented fibres in the top layer as well as larger reinforcement ratios of AR glass fabrics in the bottom layer is in progress.

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