Structural sandwich panels for roofing systems in civil applications

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Abstract. The use of composite and sandwich materials in civil engineering applications can be an efficient and sustainable alternative to the traditional materials. The design of a composite sandwich panel for applications in roofing systems such as the canopies on the platforms of train stations, made up of glass fiber reinforced polymer (GFRP) skins and a PET foam core, is herein presented, as a case study. The main advantages compared to traditional steel/concrete systems are: a high strength-to-weight ratio, durability, lightness, limited interference on railway traffic thanks to reduced installation times, factory production which reduces dangerous activities carried out on construction sites and the sustainability provided by the possibility of using recycled materials.
The design approach, developed on the recommendations provided by UNI CEN/TS 19101, an extensive experimental activity carried out on specimens and full-scale elements to characterize the mechanical and physical properties and the durability of the materials, and numerical models having different level of details developed to assess internal stressed and deformations, are critically presented and discussed. From the results, it emerges that the geometrical characteristics, i.e. the thickness of the panel, are mainly defined by the fulfilment of the limitations imposed to deformation in operational conditions, while the selection of the materials and, therefore, their mechanical and physical properties, are mainly determined by durability and fire reaction requirements.

Keywords: Composite sandwich panels, Structural design, Material properties, Civil Engineering, Canopies.

1 Introduction

The interest on composite and sandwich materials for structural applications is rapidly increasing in the field of civil and infrastructure engineering, driven by some of their peculiarities, such as high strength-to-weight ratio, durability, lightness, factory production that reduces hazardous activities carried out in the construction sites, and sustainability, provided also by the possibility of using recycled materials.

However, in spite of the profound knowledge of these materials gained in the last decades in the automotive and aerospace fields, their use in the construction industry is not straightforward because of different and various design requirements, ranging from adequate load bearing capacity at the ultimate limit state, to limited deformations in the serviceability limit state, i.e. in operational conditions, and to a durability with respect to exposure to environmental conditions, which, in some cases, can be rather aggressive. Moreover, other special requirements can apply depending on the application, such as a low reactivity to fire.

Fiber-polymer composite materials have already begun to be studied and used in the field of civil engineering for a few decades, especially in the niche sector of repairing and strengthening existing structures. In this field, they have established themselves as a minimally invasive, structurally efficient and cost-effective technology. Interest then grew over the years, extending to the use of pultruded profiles and, very recently, composite sandwiches. However, so far, the applications of composite sandwiches are sporadic, and limited to the construction of bridge decks [1] and roofing structures [2]. One of the main limitations comes from the lack of National and European reference Standards, which must be compensated by extensive experimental and numerical analyses, to check the fulfilment of all the requirements. While waiting for a Eurocode to be released, the most updated guidelines for the design of structural members in fibre-polymer composites are the JRC Report “Prospect for a new guidance in the design of FRP” [3] and the technical specifications CEN/TS 19101:2022 “Design of fibre-polymer composite structures” [4].

The design of a sandwich panel consisting of glass fiber reinforced plastic skins and a PET foam core, for application in roofing systems in civil infrastructure, is herein presented, as a case study. The paper is structured as follows. The remainder of this section introduces the rationale behind composite sandwich usage in this application, its upsides and downsides; Section 2 deals with the design of the panel; finally, Section 3 details the experimental campaign which provided the necessary material properties, verified the panel durability and its mechanical behavior.

1.1 Description of the case study

Canopies are ubiquitous in railway stations and have the main function of providing shelter to the users from bad weather along railway platforms. They also support a variety of information and lighting systems and are important for the appearance of the station. On Italian railways, the current most common design for this structure is of rather complex metallic construction, with separate elements providing weatherproofing, walkability for maintenance, structural support, and user-facing aesthetic finish.

Furthermore, the current type of canopy has no separate provisions for the electric and information systems, which are housed inside it, with obvious disadvantages for their maintenance. The main drive behind this project was to concentrate structural, aesthetic and weather protection functions in one single structural roof element, while moving the electrical and information systems in a dedicated substructure. A schematic view of the railway platform and of the canopy object of this study is visible in Fig. 1.

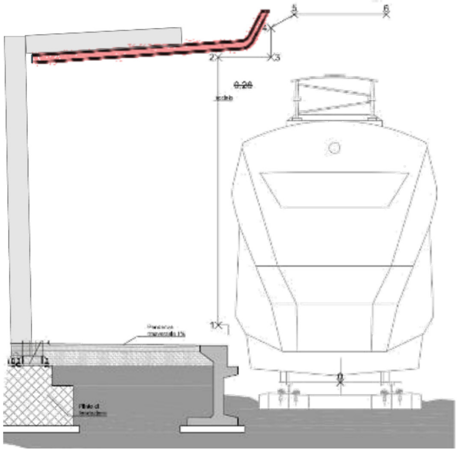

Fig. 1. Representation of the railway platform, canopy structure and of the composite sandwich roof panel (in red), in relation to the train tracks.

The advantages coming from the use of a composite sandwich, that led to its selection for this application, are multiple. Of paramount importance is the reduction of station downtime when installing the new canopies, combined with a reduction of dangerous activities carried out on construction sites. Composite manufacturing allows the production of large but lightweight structures, even relatively complex in shape, in a near-finished form. These large, pre-fabricated composite panels can be prepared off-site and quickly installed onto their support structure. A relatively limited amount of large diameter bolted connections can be used, greatly simplifying routine maintenance as well.

Being a user-facing facility, aesthetics is also an important consideration. Composite panels can be designed to have a smooth, continuous visible surface, with few panel gaps and a pleasant high-gloss finish, and their appearance can be easily customized with color and graphics. With the appropriate choice of manufacturing method, composites also allow production flexibility, in both panel size, to fit different sizes of railway platforms, and production volumes, to suit the size of the specific station where the canopies are installed and, therefore, to the size of the requested supply. The low electrical conductivity of GFRP is also a desirable property, as the panel is very close to the high-voltage overhead lines. Finally, the possible usage of recycled materials such as recycled PET foam, currently widespread in the industry, is also seen favorably.

However, the innovative application of composite sandwich materials comes with potential unresolved issues that, in the present study, were addressed by careful material selection and devising specific tests. These tests were: durability and resistance to weathering to match an expected service life of 25 years; the joining of the panels with the superstructure; the fire, smoke and toxicity (FST) requirement of category "B-s2,d0" according to fire classification for buildings EN 13501-1 [5].

2 Structure design

The canopy structure consists of a main steel structure, composed by columns and a conventional 3D truss beam, with purely structural function, supporting large overhanging composite sandwich panels, whose design process is here described. The panels (Fig. 2) measure roughly 2.5 × 4.5 m, are largely flat with a rounded upturn at the train track edge and they are connected to the superstructure via bolts along the longer sides.

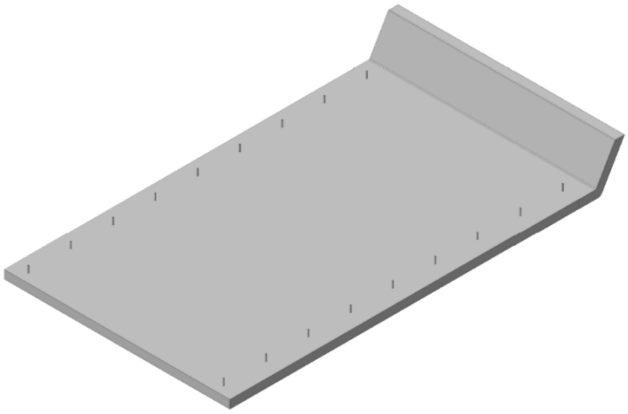

Fig. 2. Simplified 3D model of the composite sandwich roof panel.

2.1 Structural design and verification

The main challenge in the design of the canopy came from the absence of officially adopted Standards for construction using composite materials. These had to be supplemented by adapting the most suitable current and prospective Standards. For the definitions of the loads and the load combinations, in-house regulations by Rete Ferroviaria Italiana (RFI) and the Italian national Standard "Norme tecniche per le costruzioni" (NTC 2018) [6] were used. For the design and verification purposes, the recent European pre-normative technical specification UNI CEN/TS 19101 "Design of fibre-polymer composite structures" [4] was used, in one of its first applications. This specification suggests the use of partial factors for verification of limit states.

After having excluded loads not significant for the application, the considered design loads were:

- Self-weight of the roof panel
- Self-weight of supported structures

- Maintenance load
- Snow load
- Wind load
- Air pressure/suction due to trains transit

These were combined into two load combinations, one for the ultimate limit state of the structure (ULS) and the other for the serviceability limit state (SLS). The requirement for the ULS is that the load bearing capacity of all the panel is larger than the applied load, while the main requirement for the SLS is that the maximum bending deflection is lower than 1/200 of the panel span between supports.

Two separate numerical models were developed to design the structure, a simplified 2D beam model and a 3D finite element model (FEM).

Beam model

A cross-section of the panel is modeled as a simply supported beam under uniaxial bending, using laminate theory and sandwich theory. This model allows the verification of limit states in a simplified manner, according to the technical specification CEN/TS 19101. The considered failure modes were face tensile, compressive and wrinkling failure, and core tensile, compressive, shear failure, as well as core indentation and axial failure or core punching.

FEM model

The 3D FEM model supplemented the simplified one, allowing verification where the beam hypothesis did not hold, such as along the non-flat parts of the panel and calculation of the bolt loads. It was developed in Ansys 2022 R2, using the Composite PrePost package. The panel was modeled with brick elements for the foam core and shell elements for the upper and lower skins, while the inserts positioned on the longer sides for bolt connections were represented by point constraints. The full layup of the composite skin was reproduced, with each biaxial ply being modeled as an orthotropic layer.

2.2 Final panel design

The structural part of the panel obtained in the design phase is constituted by a composite sandwich with GFRP skins and recycled PET closed-cell foam core. The upper and lower skins have a symmetric and balanced layup and they are made up of a fire-retard and polyester matrix and several layers of biaxial fiberglass in multiple orientations. The core has a notable thickness of roughly 40 times that of the skins, to provide the panel with the required stiffness.

Due to this non-standard thickness, a new design had to be devised for the fixing system that connect the panel to the superstructure. Inserts are molded-in the panel during production of the sandwich panel itself.

A two-layer coating system was developed to provide the necessary characteristics. The outer layer is a fluoropolymer coating, fulfilling the aesthetic, UV and weather protection functions. Immediately underneath a fire-retardant polyester gel coat is positioned, providing the panel with the bulk of its FST performance.

The panels were produced with a vacuum infusion process, followed by oven curing. This process was found to give a good compromise between part quality and productivity and can be scaled up for larger production volumes by procuring additional molds. It is interesting to remark how the foam core was supplied in pre-shaped kits by the manufacturer, already cut to accommodate the inserts and mold geometry.

3 Experimental activity

3.1 Characterization of mechanical properties

The material properties required by the numerical models were obtained via experimental characterization. Following CEN/TS 19101 recommendations, the tests were conducted according to the relevant EN ISO or ASTM standard test method, and are summed up in Table 1.

Table 1. Skin and core mechanical characterization tests.

	Test type	Test standard	Material properties obtained
Skin	Tensile	EN ISO 527-1 [7]	Modulus, ultimate strength, Poisson's ratio
	Compression	ASTM D3410M [8]	Modulus, ultimate strength
	Shear	ASTM D3518M [9]	Modulus, ultimate strength
Core	Tensile	ASTM D1623 [10]	Modulus, ultimate strength
	Compression	ASTM C365M [11]	Modulus, ultimate strength
	Shear	ASTM C273M [12]	Modulus, ultimate strength

According to the UNI CEN/TS 19101 technical specification, debonding of the skin and core is unacceptable behavior. The interface must therefore be stronger than the two substrates. This was verified performing ASTM D1623 tensile tests and ASTM C273M shear tests on specimens of the full composite sandwich. In both cases, during the experimental tests, the failure occurred in the core as requested.

3.2 Durability testing

A number of durability tests were devised to verify the panel's resistance to weathering, chemicals, and cyclic loading. In general, the tests were devised as ageing of a rectangular sandwich specimen, fully covered by composite skin with the same layup as the full-size panel. After ageing, the specimens were cut to standard size and tested in bending with a test procedure derived from ASTM C393 [13]. The results were compared to control specimens. The only exception to this test procedure was represented by the UV resistance tests, where the specialized test machine required rectangular coupons of the skin, which were tested after ageing in uniaxial tension. The ageing procedures are summarized in Table 2. No appreciable degradation of mechanical properties was observed in any of the performed tests.

Table 2. Ageing procedures for the durability tests

Test type	Test description
Freeze-thaw cycles	4 h @ -18°C followed by 10 h @ 38°C and 95% RH; 100 cycles
Humidity resistance	95% RH @ 38°C for 1000 hours
Cyclic loading	Sinusoid load between ±40% failure load; 100 000 cycles
Alkali resistance	Immersion in pH 10 solution for 1000 hours
Saltwater resistance	Immersion in 35 g/l NaCl solution for 1000 hours
UV resistance	Per UNI EN ISO 16474-3 [14]

3.3 Tests on the co-cured joining inserts

Due to their unique design, it was necessary to assess the load-bearing capability of the inserts. To this aim pull-out tests up to failure were performed, on a section of the full-size sandwich with a joining insert at its center.

Durability test was also performed on a specimen that was subjected to 240,000 load cycles with a semi-amplitude 3 times the expected alternating load. All specimens, including the one which underwent alternate load cycles, showed linear load-curves well past the maximum load at ULS. The failure occurred in the sandwich, not in the insert, by core shear combined with core-insert interface failure. Reloading after first failure shows significant residual load bearing capability, providing an additional margin of safety.

3.4 Tests on the full panel cross-section

Bending tests were conducted on sandwich beams with the same length as the span between the supports, representative of a cross-section of the panel.

A first series of tests was performed on a beam in the 4-point bending configuration, supported on rollers, in order to verify bending behavior and assess the failure mechanism. Beam deflection was measured by five LVDT transducers. The deflection was found to follow a third-degree polynomial, indicating bending behavior prevailing on shear. Failure was due to a combination of face wrinkling and core shear failure.

A second series of tests was performed on a beam representing a cross-section of the panel including the bolted connections. Deflection was measured at the center of the beam. The beams were subjected to 120,000 sinusoid loading cycles with a semi-amplitude equal to 35% of the design bolt load at ULS, and then linearly loaded up to first failure. This failure occurred in the upper skin. The lower facing was found to still have load bearing capacity due to membrane behavior; no reduction in the mechanical properties due to cyclic loading was observed.

4 Conclusions

The case study of the design of a composite sandwich panel for structural application in railway canopy roofs herein presented, attests to the potential of using these materials in the infrastructure and civil engineering fields. In particular, the material and process allow for freedom in shape and production of quick-to-install large, prefabricated elements, fulfilling mechanical and durability requirements analogous to traditional metallic and concrete structures.

The following main conclusions can be drawn:

- The design of the geometry of the structural element, i.e. thickness of the single constituents and of the full sandwich, are defined by the fulfillment of the SLS requirements, rather than the ULS ones. This is a consequence of the strict limitations typically imposed by Standards to the deflection of structural elements and the low rigidity of fibre-polymer composite materials, with respect to the more conventional steel and concrete. Therefore, the exceptional strength of the composite material is not fully exploited, neither at the ULS.
- The selection of the materials and, therefore, their mechanical and physical properties, are mainly determined by requirements other than the load bearing capacity, such as, for instance, durability, low electrical conductivity, and fire reaction requirements.
- The lack of Standards poses a big obstacle to the diffusion of fibre-polymer composite materials in a field like civil engineering, where every project can be considered as a prototype. An extensive experimental and modelling activity is required, independently of the size of the project. This implies that current applications necessarily remain limited to a few case studies.

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