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An experimental and theoretical study of sandwich panels with TRC facings: Use of metallic connectors and TRC stiffeners

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TRC composite material, made from a combination of fine-grained cement matrix and textile reinforcement, possesses properties, particularly mechanical ones, which makes it a suitable candidate a priori for the manufacture of low-thickness facings in applications such as sandwich panels. The aim of this study is to supplement and enrich as far as possible the rare studies dedicated to the subject. The aim, more precisely, is to add to the experimental database but also to attempt to make a useful contribution regarding damage and failure mechanisms as observed in the interplay between local and global levels. In addition, the possible use of discrete connectors and stiffeners designed to improve the mechanical properties of the panels is envisaged from a technological viewpoint and the consequences of the technological processes involved are assessed.

Finally, a simple calculation model designed to help engineers with pre-dimensioning will be proposed and validated and its limits will be determined on the basis of a comparative theoretical/experimental study.

1. Introduction

Sandwich panels result from the assembly of two facings made from high mechanical efficiency materials with a core (rigid or flexible material) whose main function is to separate the facings to maximize the stiffness of the sandwich structure. In this way, the use of metal facings combined with honeycomb cores enabled the production of light, robust structures used almost exclusively in the aeronautic field (especially before the 1960s [1]). Since the 1960s, and more precisely, with the development of cement-fibre or polymer-fibre composite materials, sandwich panels were introduced for several other applications, particularly as building materials, resulting in structures with efficient high stiffness-to-weight ratios. In addition to these advantages, they also offer beneficial properties in terms of thermal and acoustic insulation, easy manufacturing, time-saving installation, etc.

The diversity of the materials used in the manufacturing of the facings for the building industry is currently rather limited (e.g., [2,3]). Materials such as glass fibre reinforced concrete (GFRC) or fibre reinforced polymer (FRP) are often used as facings for these types of panels. Sandwich panels with GFRC facings are generally thick and often reinforced by metallic frames to increase their stiffness, which makes them rather heavy structures. FRP composites, which possess more efficient mechanical properties, can be an effective alternative to GFRC. However, this material is associated with toxicity problems due to the epoxy resin, and also shares common disadvantages with GFRC, such as reduced resistance at higher temperatures in the case of fire; FRP also has a significant ecological footprint [4].

1.1. Bibliographic study

In this context, to address the previously mentioned issues, a new composite material known as textile reinforced concrete (TRC) is of increasing interest in the scientific community in relation to new construction [5–9] or building rehabilitation projects [10–13]. Indeed, these new-generation composite materials provide gains not only by offering structural performance levels representing a complete break with those of traditional fibre-cement [14,15] but also by overcoming temperature and fire resistance problems [16–19], while simultaneously being more in phase with sustainable development and hygiene and safety standards [20–22]. Finally, these materials prove to be less prone to problems of indentation in comparison to those made from steel or aluminium. The use of TRCs in the manufacturing of sandwich panels is very

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recent; few scientific studies can be found in the literature on the subject [5,7,14,23–25].

The pioneering works in this field include Wastiels et al. [14], who concentrated principally on the optimization of TRC-facings sandwich panels on the basis of the mechanical performance/weight criterion. To achieve this, they proposed using a non-alkaline cement matrix reinforced by E-glass fibres (10–20% in mass). This work was continued by Cuypers et al. [5] who made use of a numerical-experimental approach to highlight the appropriateness of using TRC for sandwich panel facings. Two facing configurations (phosphate matrix reinforced by glass-fibre textiles) and three core configurations (40 kg/m^3 polyurethane foam with different thicknesses) were used. Firstly, an experimental campaign to study the core/facing interface subjected to shearing forces was conducted, which demonstrated the strong adherence between the facing and the core (sandwich panels were fabricated by using the contact moulding technique); failure occurs in the foam close to the interface. Subsequently, the manufactured sandwich panels (six configurations) were subjected to cyclical 4-point bending tests. This experimental study shows that the non-linear behaviour of the facings under tension leads, at a global level, to complex (non-linear) behaviour of the panel, with a gradual translation of the neutral axis towards the facing under compression. At a local scale, a comparison between the experimental results and the proposed theoretical calculations reveal a significant difference on the order of 35%. Finally, it should be noted that the damage of the foam and the failure of the panels were not studied.

Hegger et al. [7] conducted an experimental study on sandwich panels with TRC facings (cement matrix made from small-grained aggregates (~5 mm), reinforced by glass and carbon fibre meshes), with a high quality surface. Extruded polystyrene foam was finally chosen for manufacturing the sandwich panels. Moreover, techniques for improving the core/facing connection were proposed with the aim of promoting load transfer from the facings to the core. To accomplish this task, discrete connectors (Glass Fibre Reinforced Polymer, GFRP, pin-connector designed mainly for work under tension) and continuous connectors (carbon meshes whose fibres are oriented at a 45° angle to absorb shearing forces) were designed. One of the most original aspects of the study concerns the advantages of using continuous connectors, which provide a very significant improvement in the global behaviour of the sandwich panel (load–deflection curve) of approximately 500% for the load and 800% for the observed deflection. Regarding the panel failure mode with continuous connectors, in addition to the significant increase in ductility, core cracking no longer leads to panel failure. However, the use of such connectors was only possible at the expense of resorting to facings of considerable thickness (30–40 mm), thus necessarily limiting the advantage of TRC facings solutions, which are especially suitable in the case of reduced thicknesses and weight. Finally, this study does not make any significant contribution to the understanding of the local behaviour of the panels.

Shams et al. [23] studied the mechanical behaviour of different sandwich panels (one panel for each configuration), whose facings were fabricated by combining one cement matrix (from a total of two matrixes) premixed with short glass fibres and a fabric made of an AR-glass fibre (from a total of three fabrics) preimpregnated with epoxy resin as reinforcement. The chosen core is a polyurethane foam of varying densities. The resulting sandwich panels (24 panels) were subjected to 4 types of tests to study the influence of the following criteria on the bearing capacity of the beam: the geometry, the nature of the material and the reinforcement ratio. The findings of this experimental campaign confirmed the advantages of using TRC as a material in the manufacturing of sandwich panel facings; a priori, they meet the specification requirements for lightweight construction. Moreover, the authors recommended the use of metallic connectors to ensure firm connection between the facings and the used cores. The findings of this experimental campaign were then used by the authors to validate an analytical calculation model designed to account for the load–deflection response of panels subjected to unidirectional bending.

This short bibliographical study shows that TRC may be considered as a highly promising alternative to existing solutions in the case of sandwich panel facings for building exteriors. Although the existing scientific studies are scarce and incomplete, they help to highlight, sometimes in an implicit way, a number of technological, technical and scientific obstacles. One of the foremost of these is the core/facing connection (or interaction), which largely conditions sandwich panel behaviour. Thus, even if long-term behaviour (creep) or the consequences of indirect stresses (mortar shrinkage, hygrothermics) and even behavioural singularities related to the connectors must necessarily be addressed for the proposed solutions to be considered as credible, it is still necessary for the existing studies to be filled out in the quasi-static field, firstly by enhancing the experimental data-base and secondly by attempting to contribute usefully to the issue of damage and failure mechanisms, as observed in the interaction between local and global levels. Therefore, from a technological point of view, the use of a discrete connection or of stiffeners is considered.

To study the influence of these technological enhancements on the mechanical behaviour of TRC-facings sandwich panels, sandwich panels with facings made from a non-combustible ettringite matrix reinforced by AR glass-fibre textile were built. Thus, three sandwich panel configurations were chosen, one as the reference configuration and the other two designed to improve the panel mechanical performances by (i) improving facing/core interaction via discrete metallic connectors and (ii) improving the interaction, including the stiffness, of the sandwich structure by use of stiffeners made from TRC, without increasing the panel weight considerably.

Finally, to valorize the use of TRC composites, a simple analytical dimensioning model limited to the elastic linear field is proposed and validated. The model is based on the Timoshenko beam model [26,27], which given the approach described in this paper, proves to be entirely compatible with programming language, and may be considered potentially as a fast, efficient tool for pre-dimensioning under unidirectional bending.

2. Experimental approach

2.1. Description of the studied sandwich panels

2.1.1. Materials

The facings of the sandwich panels are made from the TRC composite: the matrix used consists of an ettringite binding agent (tensile bending strength: 8.5 MPa), whose other properties are presented in [28,29]. For the reinforcement textile, two layers of textile of type AR-glass fibre MAT (produced by chopping a CEM FIL and forming it into a mat with a suitable binder, a nominal weight = 120 g/m^2, a fibre diameter = 14 μm, and textile without any coating, shown in Fig. 1(c) are used. For the core, 50 mm-thick polyurethane foam with a density of 35 kg/m^3 is used. The mechanical properties of the facings were obtained by mechanical characterization tests (three parallel piped specimens made of TRC composite submitted to quasi-static and monotonic direct tensile tests); the used test protocols are described in [11]. Laws of tensile and compressive behaviour were obtained and are shown in Fig. 1 picture (a) and (b). The mechanical properties of the polyurethane foam were calculated by means of theoretical models developed by