THE USE OF TEXTILE REINFORCED CONCRETE IN LIGHTWEIGHT CONSTRUCTION ELEMENTS

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Abstract

When textile reinforcement is used in a fine grained concrete mixture - as opposed to the use of single fibres or fibre strands mixed into the matrix - concrete composites with a significant load carrying capacity can be produced. Thin walled structural elements can be produced with a high fibre volume fraction making it possible to omit steel rebars, providing thus an interesting new construction material. In textile reinforced concrete (TRC) - as in brittle matrix composites in general - the fibres will bridge the cracks and continue to carry extra load after the matrix tensile strength is reached. In this paper the use of TRC as face material for sandwich panels will be discussed. Exemplary dimensioning of roof panels with TRC faces shows the potential of the material in construction applications.

Keywords: textile reinforced concrete; lightweight constructions

1 Introduction

High performance fibre reinforced cementitious composites (HPFRCC) aim at surmounting the most important drawback of a cementitious material: the inherent brittleness, going together with a modest and unreliable tensile strength. Reinforced concrete has addressed this problem successfully, witnessed by the fact that it is by far the most used building material: concrete represents worldwide two-thirds of the building materials. Using steel rebars as (mainly tensile) reinforcement leads however to the consequence of rather massive structural elements, due to the necessary protective concrete cover and large dead-weight of the very ineffective concrete area in the tensile part of the cross section. When using fibres, a thousand-fold scale reduction of the reinforcement diameter is obtained, while the corrosion problem is usually defined in a quite different way. It is then conceivable to think about thinner elements, taking into account that the reduction of the force level arm calls for superior material properties and/or an adapted cross section geometry, as is done when the sandwich concept is used.

Globally, one can distinguish two kinds of HPFRCC: those reinforced with discontinuous fibre systems and those with continuous fibre systems. The latter are denominated as textile reinforced concrete (TRC). Due to the pre-form of the TRC fibre system, the fibre orientations are strictly defined and relatively high fibre volume fractions can be obtained. If cheap fibres with relatively high strength and stiffness and small diameter (in order to

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increase the specific surface and optimise the stress transfer between fibres and matrix) are to be inserted in a sufficiently high amount, the use of glass fibres is a logical choice and will be discussed in this paper. TRC with glass fibres facilitates the production of very thin load-bearing two-dimensional elements, while this is less the case for discontinuous fibre systems. Thin TRC elements with glass fibres can for example be used as faces in sandwich panels for construction purposes since they provide a high stiffness to weight and strength to weight ratio and combine structural performance with thermal insulation. In this paper the global dimensioning of sandwich panels with TRC faces as roof panels will be discussed exemplarily in order to depict the potential of the material.

2 TRC (textile reinforced concrete) material behaviour

Although the behaviour of TRC in compression is linear elastic up to failure, this is not the case in tension. Figure 1 shows a typical stress-strain curve of TRC in tension. This typical non-linear behaviour is introduced by the multiple cracking of the matrix: the matrix fails already at a very low strain level of less than 0,1%. A pseudo-ductile behaviour of the composite, which makes use of the larger strain capacity of the fibres (more than 1%), is obtained by slip between matrix and fibres, together with the development of multiple cracking. When simplifying, three stages of behaviour in tension can be distinguished: the non-cracked stage (stage 1), development of multiple cracking (stage 2), and crack opening or post-cracking stage (stage 3). Within the multiple cracking stage (stage 2), a fine crack pattern is built up with increasing load. Due to the heterogeneity of the local strength of the matrix material and due to the occurrence of local internal stresses, matrix cracks occur within a certain stress range. The multiple cracking stage ends when the crack spacing is such that, at every crack, the gradual stress transfer at the fibre matrix interface is interrupted by the stress relief from the neighbouring crack. The third stage exists solely due to the fibres bridging the cracks. It ends when the fibres are pulled out of the matrix or when the fibres break. Modelling of the constitutive behaviour, based on these mechanisms, has been subject of several papers [1-3]. Based on [1, 2] a methodology was developed to determine the necessary model parameters for TRC composites [3]. The model itself is not the aim of this paper: a constitutive model shown in figure 1 and based on a stochastic cracking theory [3, 4] will be implemented in the finite element model of the studied sandwich panels.

In the past the limited durability [5,6] prevented the use of glass fibre reinforced concrete for structural applications, but recent developments in glass-fibre compositions, sizing, matrix mixtures and textile production increased the durability and global performance [5,6] in such a way that proper performance of the materials can reasonably be expected throughout the lifetime of a construction. Since durability is however still an important consideration for cement matrix composites, a non-alkaline cementitious matrix called Inorganic Phosphate Cement (IPC) will be used in this paper to override the durability challenge. Due to the non-alkaline environment of the matrix, the fibres hardly lose any strength as a function of time [6]. The particular material that will be used in this analysis is thus composed of an IPC matrix and will be reinforced with 12% of in-plane randomly oriented fibres. The stress-strain behaviour of this material combination in tension is shown in figure 1 and will be implemented in the finite element model as such. From statistical analysis of the failure strengths of 116 similar composite specimens, a characteristic failure strength (5% probability of failure) in tension was obtained, leading to a design failure stress of 19MPa after application of a material safety factor of 1,5. The compressive behaviour of the IPC matrix is linear elastic up to failure and the design failure stress in compression can reasonably be chosen to equal 50MPa [4].

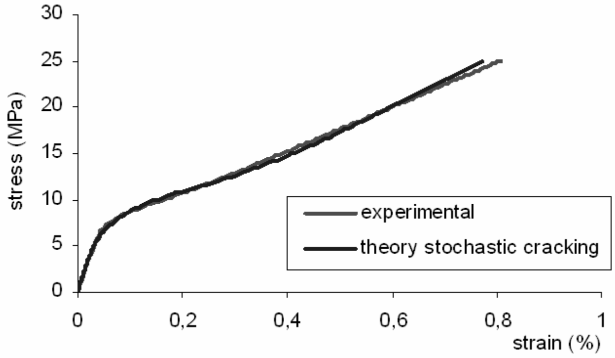

Fig. 1 Typical stress-strain behaviour of TRC under tensile loading (fibre volume fraction is 12% in volume, 2D-randomly distributed for in plane isotropy)

3 Roof Panel Design

3.1 Global dimensions and loading

A dimensioning example of roof panels with TRC faces will be used in order to show the potential of the material. Flat roof panels, acting as simply supported wide beams will be analysed and the effect of increasing span and core thickness will be discussed. The loads, which are considered to act on the sandwich panels, are own weight, snow load and wind load. The span of the panel is varied from 2m to 4m with steps of 0.5m. The width of the panels is 60cm. Since for each span several combinations of face and core thickness can lead to satisfying solutions, the necessary thickness of the faces is determined in combination with a polyurethane core with a thickness of 40mm, 60mm, 80m and 100mm. The thickness of the TRC layers is assumed to increase in a discrete way by 1mm per extra layer of textiles. The TRC material is modelled as described in the previous section. The core material is insulation polyurethane foam of 40kg/m^3, which is assumed to behave linear elastic in shear as long as the maximum shear stress stays below 1/3rd of the failure shear stress (which was tested and found to be 0,2MPa). The shear stiffness of the core was 8Mpa. In an earlier publication, sandwich panels which were very similar to the ones discussed in this paper were tested [7]. For panels with a span of 2m and various core and face thickness it was shown that the finite element predictions showed good similarity with the experimental curves under four-point bending.
The FEM-simulation program Ansys, version 7, is used to dimension the TRC faces. Element “Shell 91” is used and the sandwich option is activated: the element stiffness and the evolution of the stresses along the thickness of an element are calculated according to the sandwich theory. The number of elements along the whole sandwich is increased until convergence is reached for the displacements and stresses. The minimum thickness needed for the TRC faces is calculated for each combination of panel length and core thickness. This dimensioning takes into account the limitations in ultimate limit state (ULS) design (the stresses in the materials should not exceed the design strength of the used materials)

and in serviceability limit state (SLS) (the deflections of the sandwich panels should not exceed a certain limit, here chosen as span/250). If a transversely loaded sandwich panel is studied, the most common failure types, which will be taken into account in this paper, are: face fracture in tension, face fracture in compression, core fracture in shear, face wrinkling (in compression) and core-face interface failure. In previous publications it has been verified that the strength of the core-face interface of the studied panels is usually higher than the strength of the core material. Therefore, core-face interface failure is not further considered as possible failure mechanism. For all case studies in this chapter, it is considered that the sandwich panels are used in buildings, situated at the Belgian coast. The magnitudes of the design snow/wind/temperature/own-weight loads are determined for a return period of 50 years, which is assumed to be the design lifetime of the panels. No extra service loads, like extra roof covering, are considered since these loads do not occur inevitably, in contrast to the environmental loads.

3.2 Load combinations

Within the chosen lifetime of a construction (element) it is very unlikely that all variable loads occur with their maximum power at the same moment in time. Therefore, combination coefficients are used to include the probability of simultaneous occurrence. The total load on the structure, used for design calculations, is the sum of the characteristic loads (own weight/wind/snow/temperature) after these loads are multiplied with the combination coefficients (and with safety coefficients in ULS). According to the value of these combination coefficients, several load combinations are to be considered. The designer can obtain the combination coefficients from Eurocode 1, or from the European Recommendations for Sandwich Panels [8]. Although the philosophy for the determination of the load combinations is similar in these documents, the proposed values of the combination coefficients are obviously dissimilar. This discrepancy is highest within serviceability limit state design and SLS will thus be discussed in detail here to show the differences. The frequent design load combination S_d can be determined in SLS as follows:

$$S_d = G_k + \psi_{11} Q_{k1} + \sum_{i>1} \psi_{2i} Q_{ki} \tag{1}$$

where:

G_k = own weight of the construction (element)
Q_{k1} = characteristic value of the dominant variable load
ψ_{11} = combination coefficient of the dominant variable load
Q_{ki} = characteristic value of the other variable load(s)
ψ_{2i} = combination coefficient of the other variable loads

The combination factors defined by the European Recommendations for Sandwich panels are higher than the factors defined by Eurocode 1. In most design cases (Eurocode 1), the own weight of the construction (element) contributes considerably to the total design load S_d. The own weight of the construction is thus generally a major contribution term in S_d, compared to the variable loads. Therefore, only the variable load with the largest effect is considered in S_d as extra load. The European Recommendations for Sandwich panels are formulated for lightweight panels: when it is assumed that the own weight contributes only slightly to S_d, the contribution of the variable loads (wind, snow and temperature) in S_d gains importance. It can reasonably be assumed in this paper that the own weight of the studied panels stays relatively low. The determination of the load combination factors will thus be done as depicted in the recommendations for sandwich panels in SLS and ULS. This assumption will be discussed after all simulations are performed.

Table 1: comparison of combination coefficients

	wind	snow	temperature
ψ_{11} Eurocodes	0,2	0,5	0,5
ψ_{11} Recommendations [8]	0,7	0,5	0,5
ψ_{2i} Eurocodes	0	0	0
ψ_{2i} Recommendations [8]	0,49	0,25	0,25

3.3 Results

In table 2 the minimal thickness of the faces is depicted for each combination of span and core thickness, such that none of the limit states is violated. For all analyses it was found that the thickness of these panels was determined by serviceability limit state design rather than ultimate limit state design. This was mainly due to the non-linear behaviour of the face in tension. The sandwich panels were found to lose stiffness gradually upon loading.

Table 2: calculated thickness of the faces (in mm)

Face (mm)				
span (m)	core thickness (mm)			
	40	60	80	100
2	3	2	1	1
2,5	5[1]	3	2	1
3	8[1]	4	3	2
3,5	-[2]	6	4	3
4	-[2]	9[1]	5	4

[1]: the ratio of the face thickness to core thickness is essentially too high in order to use a sandwich element hypothesis with complete confidence. The in-detail analysis of the finite element model should be interpreted with care

[2]: the ratio of the face to core thickness is too high for sandwich action and the typical advantages of the sandwich action are not exploited.

Table 3: own weight of calculated sandwich panels (in kg/m²)

Weight (kg/m²)				
span (m)	core thickness (mm)			
	40	60	80	100
2	7,6	6,4	5,2	6,0
2,5	11	8,4	7,2	6,0
3	17	10	9,2	8,0
3,5	-	15	11	10
4	-	21	13	12

The own weight of the panels is depicted in table 3. It can be seen in this table that the maximum contribution of the own weight found within this series of simulations was 210N/m^2, which is indeed low.

4 Conclusions

In this paper several test cases were studied to illustrate the potential of sandwich panels with TRC composite faces for building purposes. It is shown that relatively lightweight panels could be produced for various spans. It was also stated that the dimensioning of these panels should be done with care. More precisely the determination of the load combination factors should be done taking into account the fact that the live variable loads have a large contribution into the total loading of the construction.

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