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Numerical simulation of the fracture behaviour of glass fibre reinforced cement

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HIGHLIGHTS

- Cohesive crack models are suitable for modelling fracture processes of GRC.
- Inverse analysis allowed the verification of constitutive relations of GRC.
- The tri-linear softening functions showed the different material properties.
- Structural design with GRC can be performed with increased safety margins.

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ABSTRACT

The exceptional mechanical properties that glass fibre reinforced cement (GRC) boasts are the result of the interaction of the fibres and the brittle matrix. While the cement mortar provides a remarkable compressive strength, the presence of glass fibres increases the material toughness under tensile and flexural stresses. In addition, the fracture energy is also enhanced due to the presence of the glass fibres that add a multiple cracking damage pattern and, hence, a large damaged surface. In order to provide available resources that may ease and widen the structural design of GRC, the assessment and verification of its constitutive relations is of high significance, given that such relations may reproduce the fracture behaviour. In this study, the softening function of GRC under flexural tensile fracture tests in an in-plane disposition has been obtained by combining numerical simulations with an inverse analysis. Such inverse analysis has been able to reach satisfactory results by varying the parameters that define the trilinear softening function proposed. The process started by means of an initial estimation of the values of the parameters. By iteratively modifying such values, a softening function capable of reproducing the fracture behaviour of GRC was found. The study shows that use of tri-linear softening functions reproduces with notable accuracy the fracture behaviour of three different formulations of GRC. The significance of this research lies in the provision of constitutive relations that can be used for future modelling and structural design, thus widening the feasible applications and reliability of GRC in the construction industry.

1. Introduction

Glass fibre reinforced cement (GRC) has been extensively used in the building industry, especially since the first alkali-resistant fibres became available in the 1970s [1].That is to say, more than 40 years of practice have shown GRC as being suitable for a wide range of applications, from telecommunication towers [2], permanent formworks [3], and cladding panels [4] to sewers. In addition, it has also had certain ornamental uses. The use of GRC in these applications has been based not only on cost-reduction concepts and the final appearance of the structures, but also on the remarkable mechanical properties of the composite material. Indeed, GRC is one of the most representative examples of the utilisation of the best performance of its two constituent materials: glass fibre and the cement mortar matrix. Generally, such properties are achieved by the union of a mortar cement matrix and a 5% volumetric fraction of chopped glass fibres. While the presence of the fibres contributes to improving the ductility and tensile and flexural strength of the material, the stiffness and the compressive properties are provided by the cement mortar [5].

It is worth noting that one of the reasons for the success and diversity of uses of GRC has involved the absence of any additional reinforcement in the elements. That is to say, the absence of steel rebar reinforcement allows GRC members to be manufactured to almost any shape and with only a 10 mm thickness. This both

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enables structural designers to create light elements and provides the material with a remarkable adaptation capacity.

However, the use of GRC in structural application has encountered two main limitations. Firstly, once the first applications were built, it was detected that the GRC properties were strongly affected as time passed. Secondly, there is a lack and subsequent need for regulations to be provided that enable evaluation and comparison of the mechanical properties.

As regards the durability problems, these were confirmed in published studies [6,7]. As the GRC ages, it becomes a more brittle material and loses the ductility that glass fibres offer to the composite material [8,9]. Some research considered that the main cause of this process is the corrosion of the glass fibres in the alkaline environment of the cement mortar matrix. Although alkaline-resistant fibres were created by industry, the reduction of GRC properties has not been fully addressed and is still termed as static fatigue [10]. Another step taken in order to address this problem was to modify the chemical composition of the cement mortar matrix by adding chemical products such as silica fume, metakaolin or acrylic resins [11,12]. In addition, there is still no standard method available to simulate the natural aging conditions of the material [13,14].

Concerning the necessity of standard procedures to assess the properties of GRC, it should be noted that this has been conventionally solved by using several test methods, not allowing a proper scientific comparison of the properties. In some published research, while its behaviour has been studied by means of four-point bending tests [15], in others this has involved tensile tests [16]. Therefore, comparison between each type of test cannot be performed easily.

In previous studies, the authors assessed the fracture energy of GRC by applying a modification of RILEM TC-187 SOC, which was a recommendation successfully used for obtaining the fracture energy of concrete [17,18]. The fracture energy of several GRC formulations was determined and the damage mechanism and patterns were described. Once the fracture energy has been determined (and in order to achieve a reliable structural design of GRC members), it is important to reproduce the fracture behaviour of GRC by using numerical or analytical methods. This task is particularly relevant because in GRC members, as there is no reinforcement in the case of the material collapse, some human or material damage might occur.

Modelling of the fracture behaviour of concrete has been conventionally reproduced by means of the smeared crack approach [19] when there is no localisation of the cracks and when the crack opening is reduced. However, in the case of fracture tests where there is a clear cracking zone the so-called discrete approach has provided more accurate results. The cohesive crack model developed by Hillerborg [20] is one of the most used when studying plain concrete fracture behaviour. This model has been applied with success not only to plain concrete, but also to other brittle or quasi-brittle materials such as brick masonry [21–23]. In addition, under certain circumstances this model represents with accuracy both the fracture evident in Mode I and a fracture process generated under a Mode II without the need of using a tracking algorithm [24]. A more detailed explanation of this model can be found in any of the references provided. In addition, the applicability of this model has been shown when applied to steel and polyolefin fibre reinforced concrete [25,26]. However, the suitability of the cohesive crack approach when applied to GRC deserves thorough study. In such a sense, the good results obtained in this study highlight the significance of this research.

In order to do so, the fracture behaviour of GRC was replicated in a finite element method (FEM) program by implementing a tri-linear softening function in a user material subroutine. Moreover, the influence of two chemical additions in the fracture behaviour of GRC has also been obtained by modifying the characteristic points of the tri-linear softening function. This shows the ability of the tri-linear softening curve to reproduce the fracture behaviour of several formulations of GRC. It should be highlighted that a discussion about the experimental results and the causes of such differences are beyond the scope of this study. It is worth noting that the inverse analyses shown in this paper allowed the achievement of constitutive relations that can be used in future modelling and design procedures, providing engineers with relevant possibilities and innovative knowledge in the field. Although it is true that a complete modelling of the material behaviour is a matter that still deserves study, this study offers an approach, towards a full exploitation of the GRC properties in future structural applications.

2. Experimental results

2.1. Material manufacturing and test setup

A test campaign was carried out with GRC specimens manufactured with three different formulations: one control formulation (GRC), another formulation where the thermal treated pure kaolin Metaver® had been added [27] (GRC-M), and a formulation that had a Powerpozz® [28] addition (termed GRC-P). Powerpozz addition is a commercial pozzolanic admixture with high contents of SiO_2 and Al_2O_3. All the cement mortar formulations can be seen in Table 1.

The test boards manufactured had dimensions of 1200 mm in length, 1200 mm in width and approximately 10 mm in thickness. These boards were produced by simultaneous projection of cement mortar and chopped long glass fibres with a length of 38 mm, using the same process as that used in the GRC industry. An extensive description of the manufacturing process and the specimen preparation can be seen in reference [29]. The fracture tests were carried out in the in-plane orientation, with the fibres being almost parallel to the loading direction as Fig. 1 shows. The specimens were notched by using a water-cooled circular saw equipped with a diamond disk with a thickness of 3 mm.

The tests were conducted by following as closely as possible the recommendation RILEM TC-187-SOC [30] that employs concrete prismatic specimens with a squared (DxD) section. The span between the bearings of the test ranges from 3D to 4D. When adapting this recommendation to GRC, the relation between the

Table 1
Cement mortar formulations.

	Cement (kg)	Sand (kg)	Water (kg)	Plasticizer (l)	Addition (kg)
GRC	50	50	17	0.5	–
GRC-M	50	50	23	0.5	12.5
GRC-P	50	50	23	0.5	12.5

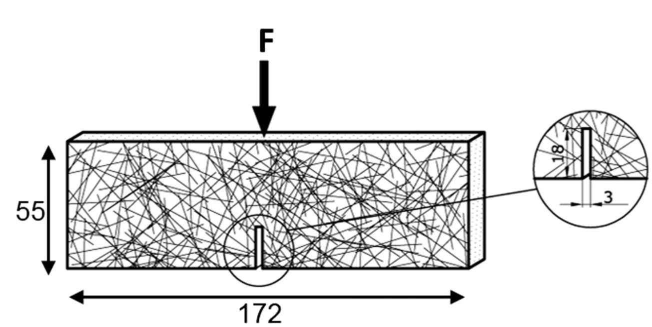

Fig. 1. Sketch of the fibres orientation in the GRC specimen. Measures in mm.