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# Pull-out behaviour of glass-fibre reinforced polymer perforated plate connectors embedded in concrete. Part II: Prediction of load carrying capacity

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## HIGHLIGHTS

- Results of pull-out pin-bearing tests with single-hole plates are presented.
- The effect of the type of GFRP on load capacities of the connections is accessed.
- An analytical framework to estimate the load capacity of connections is developed.

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## ABSTRACT

The authors have recently proposed an innovative connector system that consists on a Glass Fibre Reinforced Polymer (GFRP) perforated plate that is embedded into Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) layers. The connection is strongly based in the mechanical interlock assured by the dowels originated from the SFRSCC passing through the holes opened on the GFRP plates. In this study, an analytical framework to evaluate the load capacity of the connections when loaded transversally was developed based on experimental pull-out tests presented in the companion paper (Part I). For a better understanding of the mechanical behaviour of the connections and to allow to make estimations of the load capacity of connection when it is conditioned by the rupture of the connector itself, pull-out pin-bearing tests with single-hole plates were executed to assess the effect of the type of GFRP on the strain distribution in the vicinity of the holes until the failure, as well as the estimated failure modes and load capacities of the connections.



## 1. Introduction

In the recent past, the authors proposed the use of an innovative type of Glass Fibre Reinforced Polymer (GFRP) connector for concrete structural sandwich panels [1,2], hereinafter referred to PERFOFRP. It consists of perforated GFRP plates, as shown in Fig. 1, that materialize the connection by means of mechanical interlock between the GFRP plate and the concrete dowels originated from the embedment of the connector into the concrete layers. The advantages of the proposed device are inherent to its material nature, of fibre reinforced polymer, since this connector reduces significantly the thermal bridge occurred when steel connectors are used, is not prone to corrosion and is lightweight. The proposed connector is particularly attractive for application in structural sandwich panels that are part of building façades, since an overall improved thermal performance can be achieved with this technology. These connectors have a relatively simple manufacturing process, are easily transported, handled and installed in the panel production process.

As observed on the first part of this paper [3], the failure of the connection when subjected to pull-out forces can occur in different modes, depending on the geometry and materials used in the connections. The pull-out experimental program evidenced that the load capacity can be conditioned by failures in the concrete or even in the GFRP connector itself, in the vicinity of the holes. Nonetheless, although the connector failure was evidenced in the post testing inspection, due to the fact that the connector is embedded in

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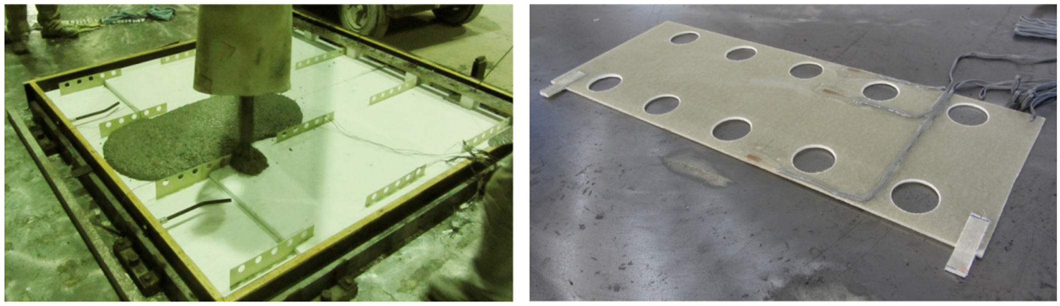

(a) (b)

**Fig. 1.** GFRP connector for concrete structural panels: (a) overall view of connectors during the casting of concrete top layer of a sandwich panel; (b) detail of one PERFOFRP connector.

the concrete, the conditions at which the rupture actually occurs and the underlying mechanisms could not yet be fully understood nor explained. Despite the relatively high tensile strength of the GFRP in the context of the materials used in concrete sandwich panels, failure through the GFRP can irremediably compromise the structural performance of this type of panels, since the these materials generally present a brittle behaviour, thus leading to an undesirable sudden rupture of the panel.

In the technology of the perforated composites for mechanically fastened connections this issue could be solved by establishing minimum distances from the holes to the border of the laminate to be followed in the design process. However, in the case of proposed PERFOFRP connections, the diameter of holes and the distance from border are limited by the application given to the connector. In fact, when compared with the geometries of the usual perforated plates for mechanically fastened connections, the diameter of the hole used in the PERFOFRP is larger (usually ranges between 3 and 10 mm for fastened connections) and the distance between the hole and the border is shorter [4,5]. The diameter of holes should permit the aggregates and fibres of concrete to pass through the holes and promote the expected mechanical interlocking between the concrete and the connector.

For conventionally reinforced concrete, this value could be equal to the clear distance between individual parallel bars recommended by EN 1992-1-1 [6], that is given by the maximum size of aggregate plus 5 mm (i.e.: 12 mm + 5 mm = 17 mm for the materials used in this research). Nonetheless, the steel fibres used as reinforcement of concrete has length equal to 35 mm. To avoid fibre congestion, the diameter of holes was set equal to 30 mm. The distance of hole from the border is limited by the relatively small thickness of concrete layer, that, based on the recommendations made in a first study [1,2], was set at only 60 mm. Considering a minimum cover to the GFRP of 15 mm, value also limited by the maximum diameter of aggregate used in the concrete, the length that remains for the distance from the centre of hole to the laminate border is only 22.5 mm, meaning that the distance from the edge of hole to the laminate border is only 7.5 mm. On the other hand, even with all the aforementioned constraints, in a preliminary investigation [1,2], the authors confirmed that the load capacity possible to be attained with the proposed PERFOFRP connection was enough to be used as connector for sandwich wall panels, enabling to take the advantages related to the use of this type of connector.

Although the bearing behaviour of GFRP laminates is a subject well-researched and reported in the literature [4,5,7–10], the authors considered that it was necessary to perform bearing tests that were representative of the geometry of proposed connections for a better understanding of the mechanical behaviour of the this particular type of connector. Thus, an experimental program was also undertaken in the scope of the present research, as to determine the failure mechanisms and the strain field around holes of this type of GRP connectors. More specifically, tensile tests were carried out on specimens formed by a multi-directional GFRP plate including a hole (herein designated as single-hole plate), where the hole was supported with a metallic pin to reproduce, as much as possible and in a feasible way, the anchorage conditions expected for the GFRP connector embedded in the sandwich panel concrete layers. The tests were performed for a range of laminate configurations and different positions of the hole relatively to the free-stress contour of the GFRP plate. Furthermore, the strain field in the vicinity of hole was assessed by using a full-field measurement technique, and also registering local measurements with electrical strain gauges.

Finally, based on the experimental evidence of the pull-out tests presented in the first part of this companion paper [3] and on the results from the bearing tests here presented, an analytical framework is proposed for prediction of the load carrying capacity, when subjected to pull-out loads, of connections between PERFOFRP connectors and plain or steel fibre reinforced concrete. This analytical framework emerged from the interest on a better understanding of the functionality and anchorage mechanics of the proposed connectors, which will enable the optimization of the connectors' geometry for different materials and applications (e.g.; optimization of distances between holes and from the stress-free edge).

## 2. Experimental study on the pin-bearing behaviour of perfofrp connectors

### 2.1. Expected failure modes

Despite the specificities of the PERFOFRP connectors, some similarities with the plates used in bolted joints can be still be found. For instance, apart from failure of the concrete pin in either shear or compression, it can be considered that the potential failure modes might be expected to be similar. Specific literature on strength of perforated plates for mechanically fastened joints [11,12] generally considers that the failure of the connection occurs in one of the four potential modes illustrated in Fig. 2: net-tension, shear-out (or tear-out), bearing, and cleavage.

Net-tension is a lateral failure at the minimum cross-section perpendicular to the loading direction (Fig. 2a). The stress that is introduced in net section is schematically represented in the Fig. 3a and can be determined from Eq. (1).

$$\sigma_{nt} = \frac{Q}{(W - D_h) \cdot t_p} \tag{1}$$

where $Q$ is the applied load, $W$ is the width of the specimen, $D_h$ is the diameter of the hole, and $t_p$ is the thickness of the laminate. This