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On the efficiency of flat slabs strengthening against punching using externally bonded fibre reinforced polymers

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HIGHLIGHTS

- FRP's can be effectively used to strengthen existing flat slabs against punching shear.
- The CSCT can be applied to predict the punching strength of strengthened slabs using FRP's.
- The strengthening efficiency is more pronounced in slabs with lower reinforcement ratio and larger column sizes.
- The strengthening efficiency is less pronounced in actual continuous flat slabs.

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ABSTRACT

One possibility for strengthening existing flat slabs consists on gluing fibre reinforced polymers (FRPs) at the concrete surface. When applied on top of slab–column connections, this technique allows increasing the flexural stiffness and strength of the slab as well as its punching strength. Nevertheless, the higher punching strength is associated to a reduction on the deformation capacity of the slab–column connection, which can be detrimental for the overall behaviour of the structure (leading to a more brittle behaviour of the system). Design approaches for this strengthening technique are usually based on empirical formulas calibrated on the basis of the tests performed on isolated test specimens. However, some significant topics as the reduction on the deformation capacity or the influence of the whole slab (accounting for the reinforcement at mid-span) on the efficiency of the strengthening are neglected. In this paper, a critical review of this technique for strengthening against punching shear is investigated on the basis of the physical model proposed by the Critical Shear Crack Theory (CSCT). This approach allows taking into account the amount, layout and mechanical behaviour of the bonded FRP's in a consistent manner to estimate the punching strength and deformation capacity of strengthened slabs. The approach is first used to predict the punching strength of available test data, showing a good agreement. Then, it is applied in order to investigate strengthened continuous slabs, considering moment redistribution after concrete cracking and reinforcement yielding. This latter study provides valuable information regarding the differences between the behaviour of isolated test specimens and real strengthened flat slabs. The results show that empirical formulas calibrated on isolated specimens may overestimate the actual performance of FRP's strengthening. Finally, taking advantage of the physical model of the CSCT, the effect of the construction sequence on the punching shear strength is also evaluated, revealing the role of this issue which is also neglected in most empirical approaches.

1. Introduction

Fibre Reinforcement Polymers (FRP) can be used as a technique to strengthen existing two way flat slabs against punching shear failures developing at slab–column connections [1–12]. For this purpose, FRP strips are usually glued on the top surface of the slab (Fig. 1). Different potential failure modes can be governing for members strengthened with FRP's as described in Smith and Teng [13]: (1) FRP rupture, (2) crushing of the compressed concrete, (3) shear failure, (4) concrete cover separation, (5) plate end interfacial debonding and (6) intermediate crack induced interfacial debonding. In this paper, the shear failure mode will be investigated in detail. The influence of FRP reinforcement on the punching shear

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strength is explained in Fig. 2 with the help of the Critical Shear Crack Theory (CSCT) [14]. In Fig. 2a, a conventional reinforced slab (without any FRP strengthening) is presented. Punching failure occurs for a given deformation level (rotation ψ_R of the slab at the connection), when the shear demand equals the available shear strength (V_R). According to the CSCT, the shear strength decreases for increasing opening of the flexural cracks (related to the rotation and size of the slab) as wider cracks have a lower capacity to transfer shear stresses. If the member is strengthened during its service life by gluing FRP strips on the surface of the slab (refer to Fig. 2b), the flexural behaviour would be stiffer (lower crack openings developing for the same level of load) and thus the punching shear strength can potentially be increased ($V_{R,st}$). It is to be noted that the increase on the flexural stiffness leads however to a reduction of the deformation capacity at failure [14,15]. As Fig. 2b shows, the strength and deformation capacities are also dependent on the level of load at the moment of strengthening [16]. Strengthening for levels of load similar to the strength of the unstrengthened slab (V_R) leads to a poor efficiency of the system (low increase of strength), whereas the efficiency in terms of strength is larger for strengthening occurring at low load levels ($V_{R,st(1)} > V_{R,st(2)}$ in Fig. 2b).

This behaviour (increasing shear strength but decreasing deformation capacity of the strengthened slabs) can be considered as peculiar to this type of strengthening, whereas other approaches for strengthening (such as post-installing shear reinforcement) are aimed at increasing both the failure load and deformation capacity [16–18]. Despite this physical reality, most design approaches based on empirical formulas do not acknowledge for the reduction of the deformation capacity and the influence of the level of load at the moment of strengthening, and may potentially lead to unsafe or unexpectedly brittle designs. In this paper, the topic of punching strengthening of flat slabs with glued FRP's is investigated on the basis of the mechanical model of the CSCT. Suitable load–rotation curves are developed and the approach is validated through comparisons to available test data from the literature. The mechanical model of the CSCT is finally used to investigate the influence of FRP strengthening on actual (continuous) flat slabs, where moment redistributions occur due to cracking and flexural reinforcement yielding. This investigation will focus on the punching strength of the connections strengthened using FRP's with sufficient bonded length, and other potential failure modes (such as debonding or laminate failure) will not be investigated.

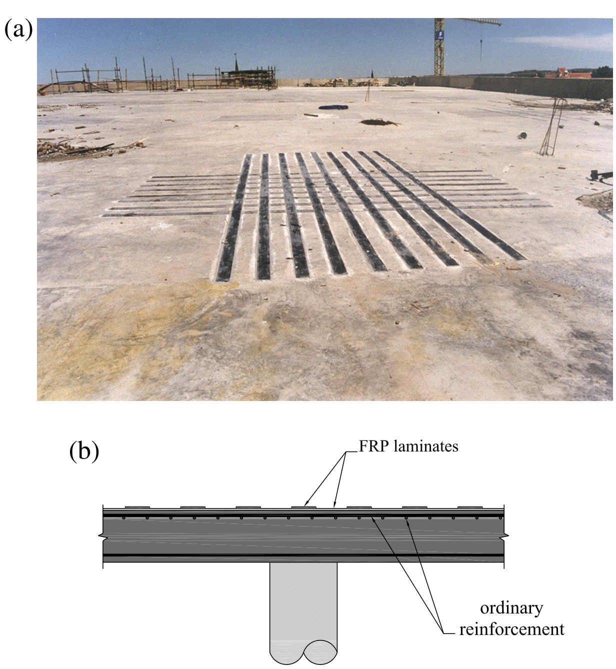

Fig. 1. (a) Practical application of bonded FRP's for slab strengthening (courtesy of VSL), and (b) cross-section of a strengthened slab.

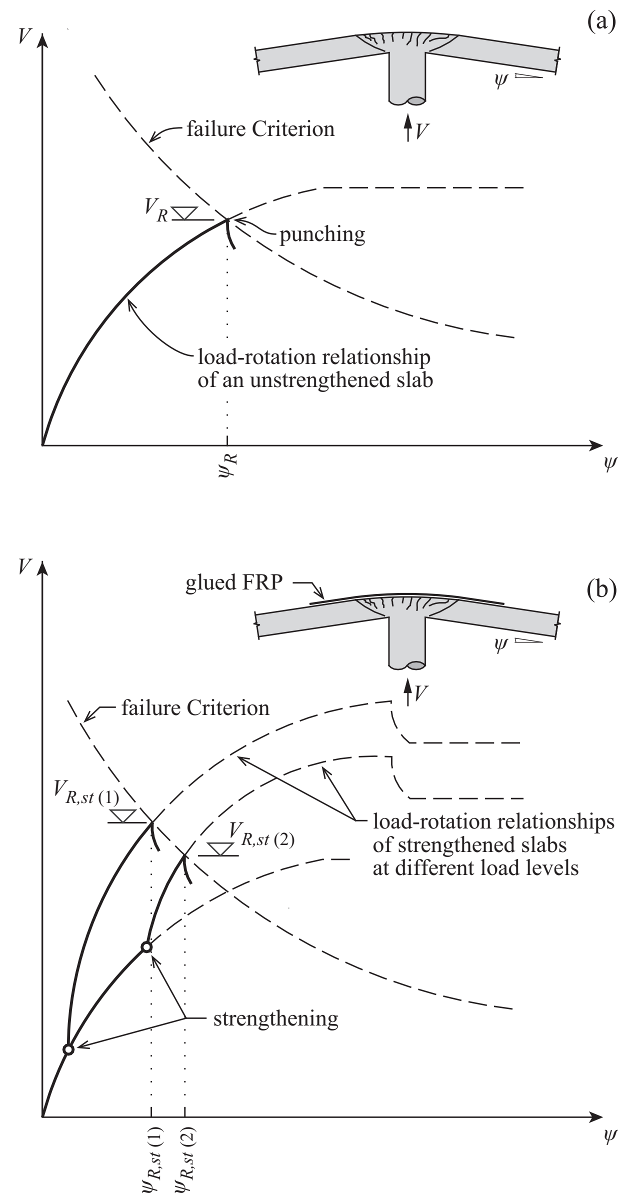

Fig. 2. Behaviour of flat slabs: (a) unstrengthened; and (b) strengthened at various load levels.

2. Mechanical behaviour of flat slabs strengthened with post-installed glued FRP strips

In the following, the mechanical behaviour of concrete slabs strengthened with FRP's glued on the surface is investigated on the basis of the mechanical model of the CSCT. This approach is selected as it allows relating the shear force that can be carried by the concrete to the activation of the glued strengthening and available reinforcement.

2.1. Failure criterion of concrete according to the CSCT

The fundamentals of the CSCT to slabs without transverse reinforcement have been presented in detail elsewhere [14]. According