Composites: Part B 66 (2014) 484–493

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Tests on reinforced concrete slabs with cut-out openings strengthened with fibre-reinforced polymers

Sorin-Codruţ Floruţ [a,*], Gabriel Sas [b], Cosmin Popescu [c], Valeriu Stoian [a]

[a] Politehnica University of Timisoara, 2nd T. Lalescu, 300223 Timisoara, Romania
[b] NORUT, Rombaksveien E-6 47, N-8517 Narvik, Norway
[c] Luleå University of Technology, SE-97187, Sweden

ARTICLE INFO

Article history:
Received 2 April 2014
Received in revised form 5 June 2014
Accepted 16 June 2014
Available online 22 June 2014

Keywords:
A. Carbon fibre
C. Damage mechanics
D. Mechanical testing
Near-surface mounted reinforcement

ABSTRACT

This paper presents the results of experimental investigations on reinforced concrete slabs strengthened using fibre-reinforced polymers (FRP). Eight tests were carried out on four two-way slabs, with and without cut-out openings. Investigations on slabs with cut-outs revealed that the FRP can be placed only around the edges of the cut-out when retrofitting the slabs whereas, in the situation of inserting cut-outs combined with increased demands of capacity, it is necessary to apply FRP components on most of the soffit of the slab. The proposed strengthening system enabled the load and deflection capacities of the FRP-strengthened slabs, in relation to their un-strengthened reference slabs, to be enhanced by up to 121% and 57% for slabs with and without cut-outs respectively.

1. Introduction

The load carrying capacity of reinforced concrete (RC) slabs may be compromised for a number of reasons, including design errors, building code changes, structural damage and changes of functional use by creating new openings.

The experimental research presented in this paper deals with the structural rehabilitation of RC two-way slabs, with and without cut-out openings. One method that can be used to increase their load capacity is to apply fibre-reinforced polymers (FRP) as externally bonded (EB) or near surface mounted (NSM) reinforcement. Several guidelines for designing and applying FRPs as strengthening systems for RC structures have been published [1,2]. However, how to use FRPs to strengthen structural elements with cut-out openings is only addressed to a small extent in these guidelines due to a lack of experimental and theoretical investigations on the variations in geometry, materials and loading conditions.

Many researchers [3–10] tested the feasibility of restoring or improving the load capacity of solid slabs by means of EB FRPs. Despite the efficiency of the method, the majority of the retrofitted elements experienced debonding as a failure mode. To solve this challenge, several researchers [11–13] successfully tested different anchorage systems for FRPs applied as EB reinforcement on slabs. Furthermore, plane elements (i.e. RC walls) could also be strengthened using mechanical anchored FRPs thus being efficient in preventing debonding [14]. The NSM technique, which is relatively new compared to EB, has been proven to produce better anchoring behaviour than EB [15]. This technique introduced a new debonding mode, the slip of the reinforcement in the concrete groove. However, this failure mode is preferred to the sudden debonding of EB strips [16].

In the literature, there are several studies of slabs with cut-out openings strengthened with FRP materials [17–25]. Casadei et al. [17] tested one-way slabs with both centrally located openings and openings near the supports, strengthened by carbon FRP (CFRP) laminates. This method has been proved to be effective only for the case with openings in the sagging region. The presence of the openings in the hogging region increased the shear stress in the concrete slab, leading to premature failure [17].

Lower tensile forces in the steel reinforcement accompanied by a more favourable crack distribution were important improvements when using FRP strips for strengthening one-way slabs with a rectangular cut-out in the centre of each slab [18]. Although the method produced an ultimate bearing capacity similar to the one recorded for the control element, the elements failed due to debonding.

In another series of tests, Tan and Zhao [19] found that all the strengthened slabs with symmetric and asymmetric openings that they investigated exhibited the same load capacity as un-strengthened slabs with openings, with some cases being even higher.

* Corresponding author. Tel.: +40 256403942.
E-mail addresses: codrut.florut@upt.ro (S.-C. Floruţ), gabriel.sas@norut.no (G. Sas), cosmin.popescu@ltu.se (C. Popescu), valeriu.stoian@upt.ro (V. Stoian).

http://dx.doi.org/10.1016/j.compositesb.2014.06.008
1359-8368/© 2014 The Authors. Published by Elsevier Ltd.

Flexural failure mode was associated with small-sized openings whereas a new failure pattern with non-orthogonal yield lines initiating from the corners of the cut-out was reported for large-sized openings. The same researchers also proved that CFRP sheets are more effective compared with CFRP plates because of the premature debonding of the latter. In relation to the position of the opening, it was found that specimens with openings placed in the maximum moment zone failed in flexural mode while openings located in the shear zone failed in shear mode [20].

The location of load application and the type of the loading surface was believed to play an important role in determining the failure behaviour [21]. Using a line load configuration induces stress concentrations which can have a negative influence on the location where debonding starts [21].

According to [22], the NSM CFRP strips performed better than the EB CFRP plates when used for strengthening slabs with centred openings due to the greater resistance to debonding. When EB CFRP plates were used together with FRP anchors, the flexural capacity of the slab was fully restored.

Compared to one-way slabs, less research has been carried out on FRP-strengthened two-way RC slabs with cut-out openings. Casadei et al. [23] claimed to be the first to report tests on RC slabs with openings and strengthened with CFRP laminates around the cut-out. The anchorage system prevented the premature debonding of the laminates which yielded into full utilisation of the FRPs. Enochsson et al. [24] tested two-way slabs strengthened with FRP composite materials. The tests revealed that specimens with larger openings have a higher load capacity and stiffness than the ones with smaller openings. Although this contradicted their design method, Enochsson et al. [24] have justified this as "the slabs with the large openings behave closer to a system of four beams than a slab".

Elsayed et al. [25] proved the benefits of using mechanically-fastened EB FRPs over the conventionally applied EB FRPs. The latter provided a lower performance in serviceability compared with the mechanically-fastened technique.

De Lorenzis and Teng [26] concluded that the NSM technique is less prone to debonding, can be pre-stressed more easily and is better protected against fire, chemical and mechanical damage. However, in some cases, it could be more beneficial to use both NSM and EB techniques especially when the concrete cover is limited.

In most of the above mentioned research programs, the cut-outs were created in the centre of the tested slabs and the applied strengthening techniques were either EB or NSM types. In this research, mixed retrofitting solutions (NSM + EB) are tested on two-way RC slabs with cut-out openings located on the sides of the element.

The first objective of the research program was to verify how the cut-out openings influence the loading behaviour of the slabs. This study also provides relevant information about the influence of the surface and position of the openings on un-strengthened slabs loaded with distributed loads on small areas.

The second objective was to investigate whether the FRP strengthening solutions can restore and increase the load capacity of slabs with cut-outs in comparison to that of the full slab and their corresponding unstrengthened slabs with openings, respectively.

2. Experimental tests

2.1. The test specimens

Four RC two-way concrete slabs were cast. The specimens were designed with a ratio between the clear length and clear width of about 1.55 (see Fig. 1) with dimensions of 2650 × 3950 × 120 mm. The clear span-to-thickness ratio was 20 for the short edge of the slabs. The elements replicate two-way single span simply-supported slabs, designed according to EN1992-1-1 [27]. The top of the slab was reinforced along its contour for constructional reasons only. Reinforcement at the bottom consisted of welded wire meshes made of bars with a diameter of 4 mm, arranged at a spacing of 100 mm in both directions parallel to the edges of the elements. The concrete cover provided for the outermost steel reinforcement bars (i.e. rebar placed parallel to the short edge of the slabs) had a thickness of 15 mm. The steel reinforcement ratios, based on the effective depth on the short and long edges, were 0.117% and 0.127%, respectively. The steel reinforcement ratio, based on total thickness, was 0.105%. Elements with openings were detailed in such a way as to replicate cut-outs sawn into a full element i.e. no additional reinforcement was placed around the edges of the openings.

The first specimen, denoted FS-01, was a full slab and served as the reference. The second slab, RSC-01, had a small opening. Two identical specimens with large openings were cast, designated RLC-01 and RLC-02. Details of their geometries are shown in Figs. 2 and 3.

2.2. Material properties

The average cubic compressive strength of concrete (f_{cm}) was determined based on 12 cube tests [28] at the time of testing of each slab. Three cubes were tested for each slab. All tests were carried out after 28 days. Tensile tests of the steel reinforcement were carried out on 20 samples based on specifications described in [29]. Five samples were tested for each cast slab, 4 batches in total. The properties determined were the yield stress (f_{yk}), tensile strength (f_t) and ultimate strain (ε_{uk}). Commercial CFRP products were used for strengthening the slabs. These products consisted of high strength NSM strips, plates and sheets. All the mechanical properties of these materials are shown in Table 1.

2.3. Design and detailing of the CFRP strengthening

The CFRP components were bonded to the soffit of the slabs in two directions. The CFRP components parallel to the short edge of the specimens were installed using the NSM technique and those on the direction parallel to the long edge of the slabs were installed using the EB technique.

The required amount of CFRP was determined using the following procedure. For specimen FS-01-FRP (the full slab), the capable tensile force of steel reinforcement was matched to that of the CFRP components to be installed. The strengthening for specimen RLC-02-FRP was similarly designed, with the only difference being that the NSM bars intercepted by the cut-out opening were placed in the immediate vicinity of the opening. This design procedure aimed to cover the scenario when a slab is damaged and strengthened to give a higher load capacity. For slabs RSC-01-FRP and RLC-01-FRP, the FRP system was designed so that its tensile capacity equalled that of the steel reinforcement that was removed when the slabs were sawn. This second procedure aimed to test whether the capacity of the slab can be restored to its un-strengthened, undamaged state using FRP. See Fig. 2 for the details and geometrical properties of the applied strengthening.

Strengthened reference specimens have had the suffix FRP added to their nomenclature. For example, RSC-01-FRP refers to a reinforced concrete slab with a Rectangular Small Cut-out which has been strengthened.

2.4. Test setup, loading protocol and instrumentation

It was planned to load each slab beyond the point where the tensile reinforcement yielded, then unload, apply the FRP