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Alexandria Engineering Journal

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ORIGINAL ARTICLE

Prevention of premature failures of plate bonded flexurally strengthened RC slab using end anchor and connector

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Received 24 February 2016; revised 7 September 2016; accepted 24 September 2016

KEYWORDS

RC slab;
 Strengthening;
 Debonding;
 Premature shear;
 End anchor;
 Embedded connector

Abstract Flexural strengthening of reinforced concrete (RC) slab using externally bonded plate is found to be the most common and popular in retrofitting of deficient structure. However, premature failures due to plate end debonding of steel plate and shear could be the major drawbacks of the system to obtain the highest flexural capacities. The aim of this research was to propose a comprehensive strengthening technique to eliminate premature failures of flexurally strengthened RC slab. In the experimental programme, five full scale RC slabs including un-strengthened control slab and flexurally strengthened slabs using steel plates were fabricated and tested. The strengthened slabs were further strengthened with end anchor and embedded steel bar connector to eliminate premature end peeling and shear failure respectively. Theoretical and numerical models were also provided to design and to analyse the structural behaviour of steel plate strengthened slabs. Results showed that end anchor and embedded connectors prevented premature end peeling and shear failure of flexurally strengthened RC slabs completely and allowed the slab to fail by flexure with the maximum strength and ductility, whereas, their corresponding strengthened slabs without end anchor and embedded connector failed with premature plate end debonding and shear respectively. Both premature failures were found to be brittle in nature. The proposed theoretical model predicted the capacities of strengthened slabs satisfactorily. The results based on the numerical analysis were found to be comparable with the experimental findings.

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1. Introduction

Strengthening of reinforced concrete slab for flexure is crucial to enhance the capacity of deficient slab. The slab could be deficient because of underdesign or lack of quality control. Furthermore the existing slab might be required to strengthen due to increase of design action in the design code or changes of utility of floor. In terms of economy and environmental

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

<http://dx.doi.org/10.1016/j.aej.2016.09.018>

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Nomenclature

d	effective depth of slab	$V_{Rd,c}$	shear force resisted by concrete
f_{bd}	bond strength of concrete	ρ	steel ratio
M_s	moment resisting capacity of beam	M_{pt}	moment capacity of strengthened slab based on tensile strength
A_s	cross sectional area of flexural bar	f_{tk}	tensile strength of flexural steel bar
f_{yk}	yield strength of flexural bar	$f_{tk,p}$	tensile strength of steel plate
f_{ck}	concrete compressive strength based on cylinder test	V_p	shear strength of flexurally strengthened slab
b	width of slab	V_{ec}	shear force need to be resisted by connector
z	moment arm	f_{bd}	bond strength of concrete
x	depth of neutral axis	r	radius of connector
M_{RC}	moment resisted by concrete	N_c	number of connector for single row
M_d	design moment	s	spacing of connector
M_p	moment need to be resisted by steel plate	M_{cs}	failure moment of control slab
t	slab thickness	M_{ss}	failure moment of strengthened slab
A_p	required cross sectional area of steel plate	V_{ss}	shear failure load of strengthened slab with connector
$f_{yk,p}$	yield strength of steel plate		
V_{max}	maximum shear resisting capacity of slab		

aspects, strengthening of slab is the most acceptable way rather than demolish. A significant number of research works have been conducted over last decade on strengthening of reinforced concrete slab using various methods to enhance flexural capacities of deficient slabs [1–11]. Amongst the existing methods, externally bonded plate using steel plate and carbon fibre laminate is found to be the most effective and popular method to strengthen the slab for flexure. It has been investigated that the plate bonding method could achieve the maximum capacity of strengthened slab. However, premature plate end debonding failure was found to be the major weakness of this method to obtain the highest flexural strength [12]. In most of the cases the debonding of plate caused premature failure which was brittle and catastrophic in nature.

Researchers investigated that because of the discontinuity of the plate, excessive shear and normal stresses developed at end of the plate which caused cracks [13,14]. Finally the cracks lead to debond the plate either at the level of concrete adhesive interface or at the level of internal flexural reinforcement. Since, this debonding failure was found to be premature and brittle in nature, elimination of the plate end debonding failure is vital to obtain the full strength and ductility of flexurally strengthened RC slab. Furthermore, in general the slab is not critical for shear; however, once the slab is being strengthened for flexure, it could fail by premature shear. In that case, strengthening of slab for shear would be crucial to avoid premature shear failure to obtain the maximum flexural capacity of strengthened slab. Although the structural behaviour of flexurally strengthened RC slab using externally bonded plates is well known, solutions on preventing those premature failures are seldom found. The main aim of this research work was to investigate the performances of end anchor and embedded connector to eliminate premature plate end debonding and shear failures of flexurally strengthened RC slab. Comprehensive theoretical model is proposed to design and analyse the slab for flexural and shear strengthening using externally bonded steel plate and embedded connector respectively. Finally, the slab specimens were modelled using ABAQUS to investigate the structural behaviour numerically.

2. Proposed design model for flexural strengthening of RC slab using externally bonded steel plate

2.1. Flexural capacity of un-strengthened control slab

The flexural capacity of control slab based on yielding of steel bar could be theoretically predicted using Eq. (1) of EC2 (2004):

$$M_s = A_s f_{yk} \left[d - \frac{0.588 A_s f_{yk}}{f_{ck} b} \right] \quad (1)$$

where,

$$x = \frac{A_s f_{yk}}{0.85 f_{ck} (0.8) b} = \frac{A_s f_{yk}}{0.68 f_{ck} b} \quad (2)$$

$$z = d - 0.4x = \left[d - \frac{0.588 A_s f_{yk}}{f_{ck} b} \right] \quad (3)$$

2.2. Design flexural strength of strengthened slab

The slab could resist the moment until it fails by crushing of concrete. Thus, the maximum moment resisting capacity of slab is as follows:

$$M_{RC} = Cz = 0.85 f_{ck} b (0.8) x [d - 0.4x] \quad (4)$$

As per EC2, the maximum depth of neutral axis, $x = 0.45d$. Thus,

$$\begin{aligned} M_{RC} &= Cz = 0.85 f_{ck} b (0.8) (0.45d) [d - 0.4(0.45d)] \\ &= 0.251 f_{ck} b d^2 \end{aligned} \quad (5)$$

If $M_s < M_{RC}$, in that case the slab can be strengthened for flexure.

Since, slab could resist moment as long as it fails by crushing of concrete; thus, the maximum moment resisted by concrete could be used as the design moment of strengthened slab.

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