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Modelling of Structural Behaviour in Strengthened Reinforced Concrete One-way Slabs using Concrete Overlay

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Abstract: Strengthening of reinforced concrete (RC) slabs using concrete overlay is one of the most popular strengthening techniques which are used for slabs. Many experimental studies were carried out to understand the behaviour of strengthened one-way slabs using RC overlay. However, the main challenge remains to predict their structural capacity after strengthening. In this paper, a numerical model is developed to simulate the structural behaviour of strengthened slab using concrete overlay. The model accounts for non-linear behaviour of concrete utilising interpolation method in Eurocode 2. The model results are compared to the experiments from literature on slabs strengthened with RC overlay using three different connecting system at the contact surface between RC slabs and RC overlay. These systems are namely; friction, epoxy adhesive material, and shear keys. The model results are compared to the experimental results in terms of deflection, cracking, and slip between the slab and overlay. This comparison shows that the model is capable of capturing the behaviour of the strengthened slab. Considerable enhancement on the structural behaviour is also confirmed using this type of strengthening technique.

Keywords: *RC one-way slabs, short-term deflection; strengthening; bond;concrete;concrete overlay; composite action.*

1. INTRODUCTION

Deterioration of reinforced concrete (RC) slab can be caused by changing in function of the building; corrosion of steel reinforcement and errors in design or construction. Strengthening of reinforced concrete slabs maybe achieved using many methods such as concrete overlay, span shortening, externally bonded steel reinforcement, and carbon fibre reinforced polymer (CFRP). The suitability of each method depends on economic indicators, possibilities and experience of the provider, and time factor[1]. Although strengthening of slabs using concrete overlay increases the dead load of the structure, this method has many advantages over the other methods such as availability and high fire resistance in addition to the fact that it does not require highly skilled labours and special equipment. Many experimental studies were carried out to investigate the structural behaviour of one-way slabs strengthened using concrete overlay[1]–[5].

On the other hand, there are very limited numerical studies on using RC overlay in strengthening either mathematical models or finite element models [6], [7]. One of the main challenges is the prediction of the structural behaviour of the strengthened element [3].

Therefore, the main aim of this paper is set to develop a numerical model to predict the structural behaviour of strengthened slabs using concrete overlay. The model considers strengthened simply supported reinforced concrete one-way slab using concrete overlay considering different connecting systems between existing and new reinforced concrete slabs. The model aims to enhance the understanding of the structural behaviour of the strengthened slab using RC overlay and to equip structural engineers with insightful details about the concrete overlay strengthening system.

2. Modelling the flexural behaviour using Eurocode 2

The Eurocode 2 [8] analysis of curvature (ψ)is based on an interpolation formula relating two states, Fig. 1: State I (un-cracked), and State II (fully cracked). In state I, both the concrete and steel behave elastically, while in state II the reinforcing steel carries all the tensile force on the member after cracking[9].The ψat each section is calculated using Equation (1).

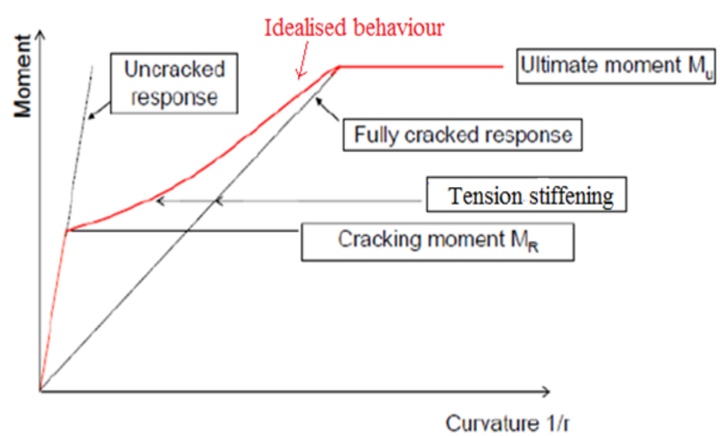

Fig. 1. Typical moment–curvature response

$$\psi_i = \frac{M}{E_c I_i} \tag{1}$$

Where M and I are the bending moment and the second moment of area of the section ;*i=1* for State I and *i=2* for State II and the Young's modulus of concrete E_c given by:

$$E_c = 22\left(\frac{fcm}{10}\right)^{0.3} \; kN/mm^2 \text{with} f_{cm} = f_{ck} + 8\; N/mm^2. \tag{2}$$

The mean curvature for each section is calculated using EC2 interpolation method, as shown in Fig. *1* and Equation (3).

$$\psi_{mean} = \zeta\psi_2 + (1-\zeta)\psi_1 \tag{3}$$

where:

$$\zeta = 1 - \beta\left(\frac{M_r}{M}\right)^2 \geq 0 \tag{4}$$

Where:

$\beta = 1.0$ for short term loading

$$M_r = f_{ct} Z = f_{ct}\frac{I_1}{h - x_1} \tag{5}$$

with $f_{ct} = 0.3 f_{ck}^{2/3}$ $where$ $f_{ck} \leq 50\; N/mm^2$.

3. Modelling behaviour of strengthened slab using concrete overlay

The strengthened slab with concrete overlay is expected to behave in a monolithic behaviour between new overlay and the existing slab if the fully composite action is assured by good bond or horizontal shear capacity at the contact surface. This usually could be assured at relatively low loads. With increasing loads and the longitudinal shear stress at interface, slippage at some sections may occur and thereby partial composite action takes place. With further increasing of loads, complete slippage occurs and makes both original slab and RC overlay behave independently, as shown in Fig *.2*. Therefore, the modelling strategy in this case is to simulate the behaviour at fully composite action and at independent action in addition to the behaviour at the interface between the RC slab and concrete overlay.

The section properties of strengthened slabs using overlay are firstly calculated for both un-cracked and fully cracked cases considering the equivalent section shown in Fig *.2*. The difference of the concrete properties between the slab and overlay is considered by assuming difference width of the overlay section equals to $b_e = \alpha b$ where $\alpha = \frac{E_{overlay\ slab}}{E_{original\ slab}}$.

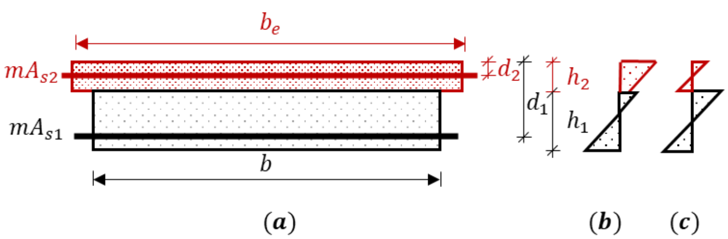

Fig .2. (a) Equivalent section of strengthened slab; (b) Fully composite action stresses; (c) Independent action stresses.

3.1 Strengthened section properties considering fully composite action

For un-cracked section, state I, the depth of neutral axis and the second moment of area are calculated asshown in Equation (*6*) and (*7*) below.

$$x_{1,comp} = \frac{0.5 b_e h_2^2 + b h_1(0.5h_1 + h_2) + mA_{s1}d_1 + mA_{s2}d_2}{b_e h_2 + b h_1 + mA_{s1} + mA_{s2}} \tag{6}$$

$$\begin{aligned} I_{1,comp} = \frac{b_e h_2^3}{12} + b_e h_2\left(x_{1,comp} - 0.5h_2\right)^2 + \frac{b\, {h_1}^3}{12} \\ + b h_1\left(h_2 + 0.5h_1 - x_{1,comp}\right)^2 \\ + mA_{s1}\left(d_1 - x_{1,comp}\right)^2 \\ + mA_{s2}\left(x_{1,comp} - d_2\right)^2 \end{aligned} \tag{7}$$

For fully-cracked section, State II, the section properties are calculated (assuming $\alpha = 1$) from Equation (8) and (9),

$$x_{2,comp} = \frac{0.5 b {x_{2,comp}}^2 + mA_{s1}d_1 + mA_{s2}d_2}{b x_{2,comp} + mA_{s1} + mA_{s2}} \tag{8}$$

$$\begin{aligned} I_{2,comp} = \frac{b {x_{2,comp}}^3}{3} + mA_{s1}\left(d_1 - x_{2,comp}\right)^2 \\ + mA_{s2}\left(x_{2,comp} - d_2\right)^2 \end{aligned} \tag{9}$$

3.2 Strengthened section properties considering independent action

For un-cracked section, state I, the second moment of area is calculated as:

$$I_{1,ind} = I_{1,original\ slab} + \alpha I_{1,overlay\ slab} \tag{10}$$

where $I_{1,original\ slab}$ and $I_{1,overlay\ slab}$, are calculated from Equation(11) using dimensions and properties of original and overlay RC slabs.

$$I_1 = \frac{bh^3}{12} + bh\left(\frac{h}{2} - x_1\right)^2 + mA_s(d - x_1)^2 \tag{11}$$

Where:

$$x_1 = \frac{0.5bh^2 + mA_s d}{bh + mA_s} \tag{12}$$

For Fully-cracked section, state II, the second moment of area is:

$$I_{2,ind} = I_{2,original\ slab} + \alpha I_{2,overlay\ slab} \tag{13}$$

where $I_{2,original\ slab}$ and $I_{2,overlay\ slab}$, area obtained from Equation **(14)**using dimensions of original and overlay R.C slabs.

$$I_2 = \frac{b{x_2}^3}{3} + mA_s(d - x_2)^2 \tag{14}$$

Where:

$$x_2 = \frac{0.5b{x_2}^2 + mA_s d}{b x_2 + mA_s} \tag{15}$$

Where:

$$m = \frac{E_S}{E_C} \tag{16}$$

3.3 Modelling interface behaviour between original and overlay slab

Modelling the interface behaviour is very important to determine whether the section works in a fully composite action or independently. This can be satisfied by comparing longitudinal shear stress (τ) at interface between original and overlay R.C slabs to the shear strength at that section. If the shear stress less than or equal the bond strength then the strengthened slab is considered in a full composite, otherwise slip takes place and both original and overlay RC slabs work independently. The longitudinal shear stress can be estimated using Equation(17).

$$\tau = \frac{\psi_{Mean}\ A\ y\ E}{X\ b} \tag{17}$$

Where Ay is the first moment of area considering un-cracked or fully cracked sections.

The bond strength at interface depends on connecting system between the original slab and RC overlay. BS 8110-1[10] suggests for concrete strength more than 40 MPa to take the bond strength τ_{bond} as 0.75 N/mm^2 when the overlay casted on brushed surface considering only the friction between the two layers. When shear keys are used bond strength of 2.2 N/mm^2 is suggested in addition to the shear capacity provided by the shear keys,τ_{bond}.

$$\tau_{bond} = \frac{0.6F_b\ tan\ \alpha_f}{Shear\ Area} + 2.2\ N/mm^2 \tag{18}$$

Where:$Shear\ Area = b \times segment\ length$

$$F_b = 0.95 f_y A_{sh}$$

$\tan \alpha_f = 1.4$ for roughened surfaces,[10].

3.4 Prediction of short term deflection for the strengthened slab

In this study, a model was developed to simulate the behaviour of strengthened slab. At first, the length of slab L is divided into equal number segments N. Then, bending moment is evaluated at the ends of each segment, considering the simply supported beam subjected to concentrated load at the mid. After evaluating bending moment at each section then the curvature is calculated.

After that, both cumulative slope θ and cumulative deflection δ can be calculated at each section (i) as shown in Equation (19) and (20).

$$\theta_i = \theta_{i-1} + 0.5\frac{L}{N}(\psi_{m\,i} + \psi_{m\,(i-1)}) \tag{19}$$

$$\delta_i = \delta_{i-1} + 0.5\frac{L}{N}(\theta_i + \theta_{i-1}) \tag{20}$$

Then the correct value of deflection at each section as follows

$$\delta_{correct} = \delta_i - \delta_L \frac{X_i}{L} \tag{21}$$

where δ_L is cumulative deflection at the far end (i.e. at $x = L$).

Repeating previous steps at each load level, and then the relationship between loads and maximum deflection at mid span is predicted. The flowchart in Fig *.3* summarize the steps and MS Excel spreadsheet is used to model the behaviour of strengthened slab.

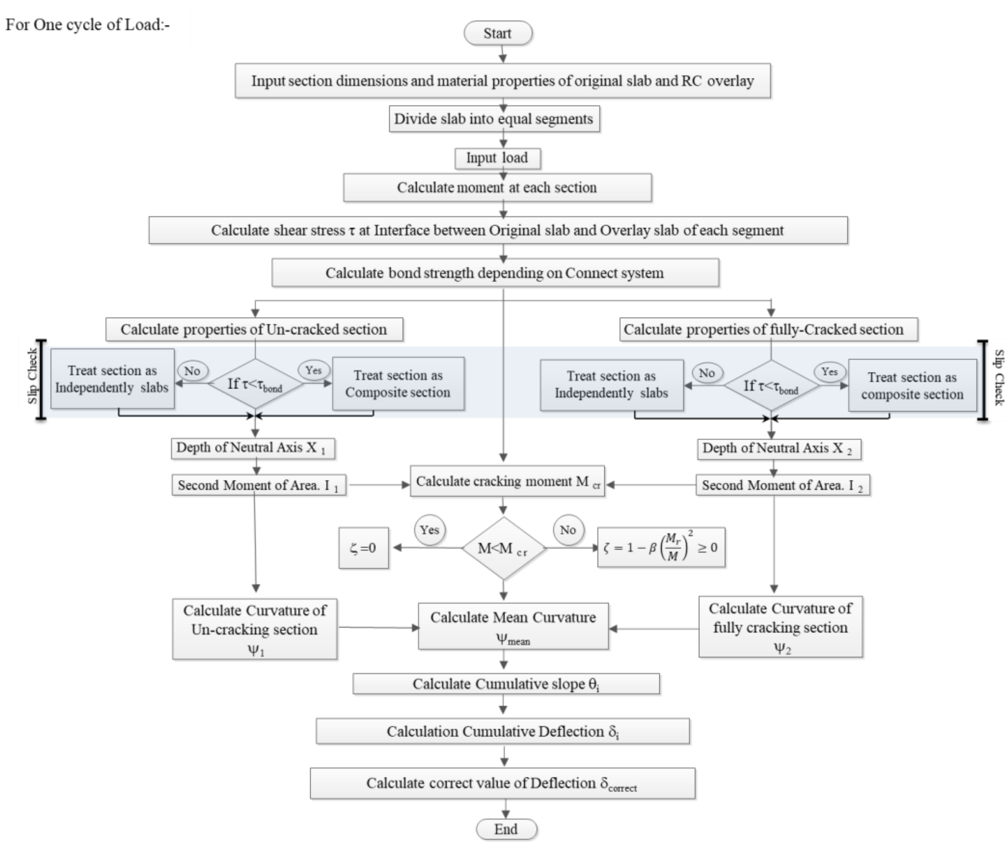

Fig .3. Flowchart of modelling strengthened RC slab using RC overlay

4. Results and discussions

The model results are compared to the previous experimental results in literature[2], [5]. The characteristics of slabs are summaries in Table 1 and the structural detailing of the strengthened original slab is shown in Fig. 4.

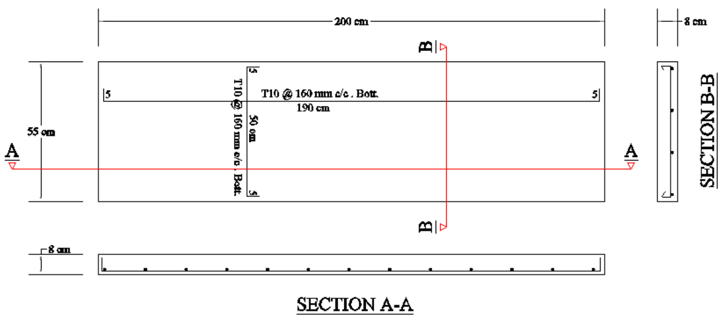

Fig .4. Structural detailing of the original slabs

Table 1: Characteristics of slabs

Type of Slab	RC Overlay: Dimensions (cm)	RC Overlay: Reinforcement	RC Overlay: Concrete compressive strength (MPa)	Bonding@ interface	Reference Slab: Dimensions (cm)	Reference Slab: Reinforcement	Reference Slab: Concrete compressive strength (MPa)
Slab 1	200 x 55 x 5	Ø6@160 mm both ways	43.25	Friction	200 x 55 x 8	Ø10@160 mm both ways	57.0
Slab 2			45.75	Epoxy Material of 36 MPa bond strength			57.0
Slab 3			50.0	Shear keys (6Ø12mm / shear span)			57.0

4.1 Behaviour of the reference slab

The load-deflection for the section at mid-span of the reference slab is demonstrated in Fig. 5 for both model and experimental results. In general, the model results are closed to the experimental results. If the service load at mid span is estimated at a deflection equal to 3.8mm $\left(i.e.\ \frac{Span}{500}\right)$ for short term, the model gives 8.0 KN. This value is used as a reference to determine the enhancement of this strengthening technique and different connecting systems.

4.2 General behaviour of RC slab strengthened by RC overlay

It is expected that the structural performance of strengthened slabs to lie somewhere between the performance of full composite action and independent action slabs. This proved by comparing load-deflection curves from the model and the experiments as shown in Fig. 6. Difference between slabs is entirely due to the difference of bonding technique at the interface. Also Fig. 6 shows clearly the enhancement of the structural performance compare to the original slab curve.

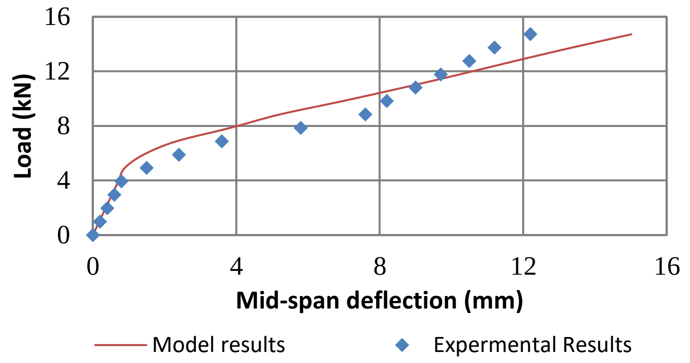

Fig .5. Load-deflection curve of the reference slab

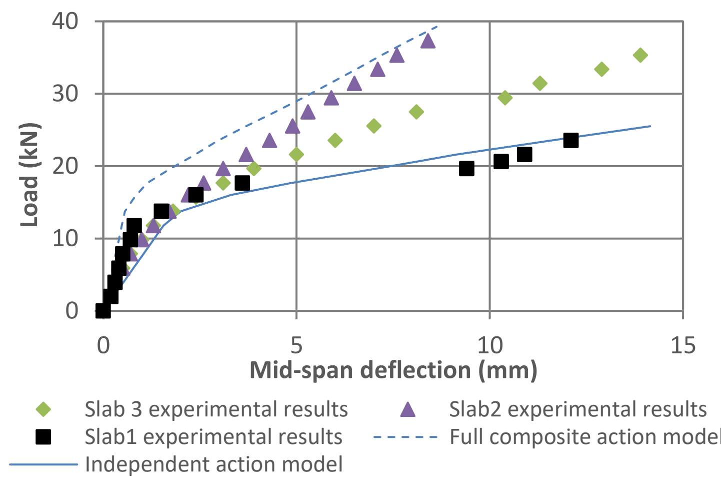

Fig .6. Expected zone of load-deflection curves of strengthened slabs

5. Influence of bonding technique between the RC slab and overlay on the structural behaviour

5.1 Bonding technique: Friction only

As mentioned earlier, Slab 1was strengthened using RC overlay without any connecting system, only friction between the two surfaces. The load-deflection from the model shows good agreement with the experimental results as shown in Fig. 7. The improvement of the strengthened slab is about 212.5% in the service load compared to the reference slab. According to this model, at the first, the slab followed full composite action curve up to 13.74 kN where flexural cracks start to propagate. Then, as the loading increased, slip between slab and overlay occurred at 15.99 kN where the strengthened slab behaviour moved toward the independent load-deflection curve. Fig. 8 shows the slip occurrence at different load level, note that the visible horizontal crack in experiment appeared at 20.6 kN.

5.2 Bonding technique: Epoxy material

In Slab 2, an epoxy material was used as a bonding agent to connect between the RC overlay and the original slab. The service load of this slab reached 26 kN compared to 8 kN in the reference slab with 532% improvement. This due to the epoxy material bond strength (i.e. 36 MPa) that was enough to safely transfer the shear stresses at the interface between existing and overlay concrete slabs (the maximum shear stress was 7.21 MPa), slip did not occur and slab have behaved in fully composite action as shown in Fig. 9.

5.3 Bonding technique: Shear Keys

Total of 12∅6 mm shear keys (6 per shear span) at the interface are used in Slab 3. Fig. 10 shows the load-deflection curve of strengthened slab. The model predicts the service load at 22 kN with an enhancement of 275 % compared to the reference slab. In this case, the first slip observed in the model at a load equal to 19.62 kN compared to 25.5 kN in the experiment. The difference in the slippage load in this slab compare to Slab1 (i.e. 15.99 kN) mainly could be attributed to the difference between the two connecting systems. It is important to note that the bond strength in the segments where shear keys are installed is calculated according to Equation (***18***).

6. Comparison between numerical and experimental results in all slabs

Fig. 11 and Fig. 12 (a and b) show the results of load-deflection curve, service load, and slippage load, respectively. The Figs show the strengthened slabs in comparison to the reference slab in flexural behaviour, service load, and slippage load. It is found that the model results are in a good agreement in comparison to the experimental results. It is clear that the enhancement in the flexural capacity has been significantly influenced by the connecting technique between the RC overlay and the original slab. For slippage load in Fig. 12b, as expected, the values predicted by the model is smaller than those observed in the experiments. This is because the horizontal cracks only appears when becomes visible which is usually less than the theoretical values, however, the difference does not exceed 25%. Both model and experimental results show that the use of adhesive epoxy materials has a superior performance and the strengthened slab works in a fully composite action. The use of any of the three connecting techniques may also depend on the budget of the project and the desired strength.

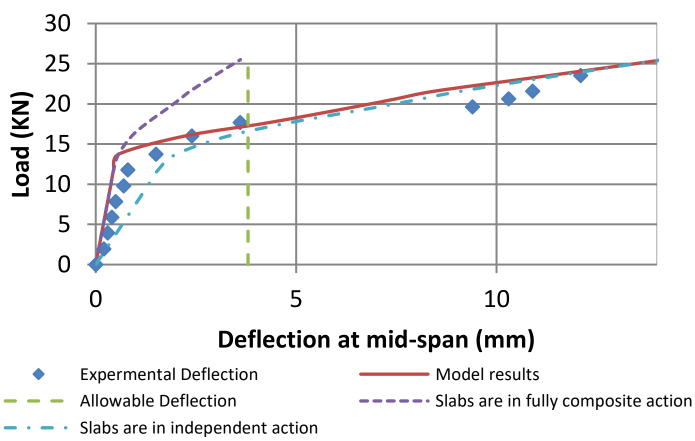

Fig .7. Load-deflection curves of slab 1 (Friction only)

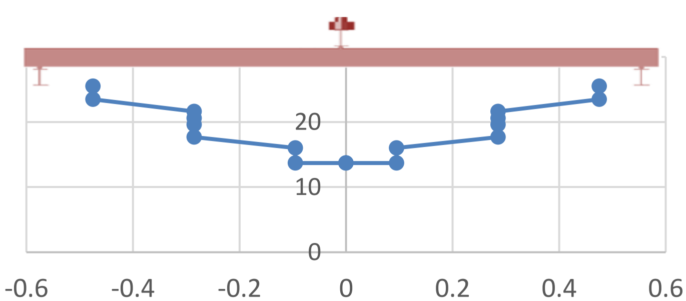

Fig .8. Slip occurrence at different load levels

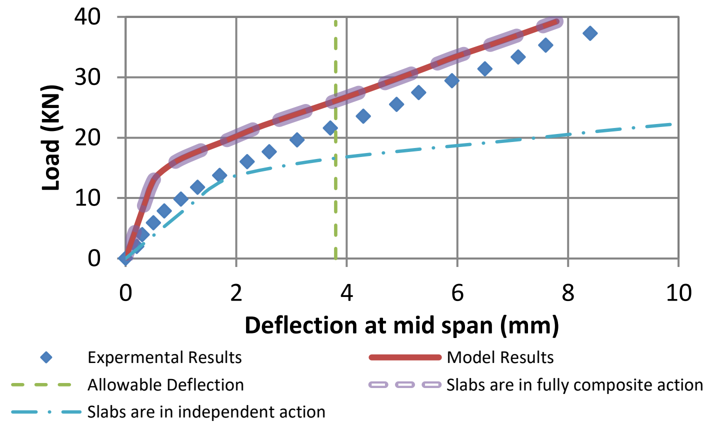

Fig .9. Load-deflection relationship of slab 2 (Epoxy)

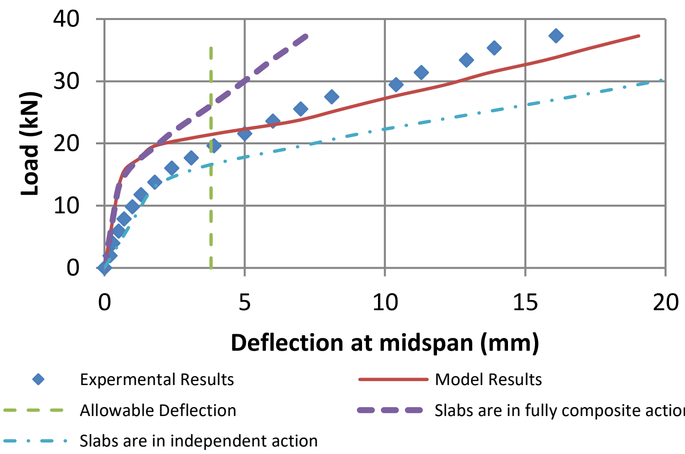

Fig .10. Load-Deflection relationship of slab 3 (Shear keys)

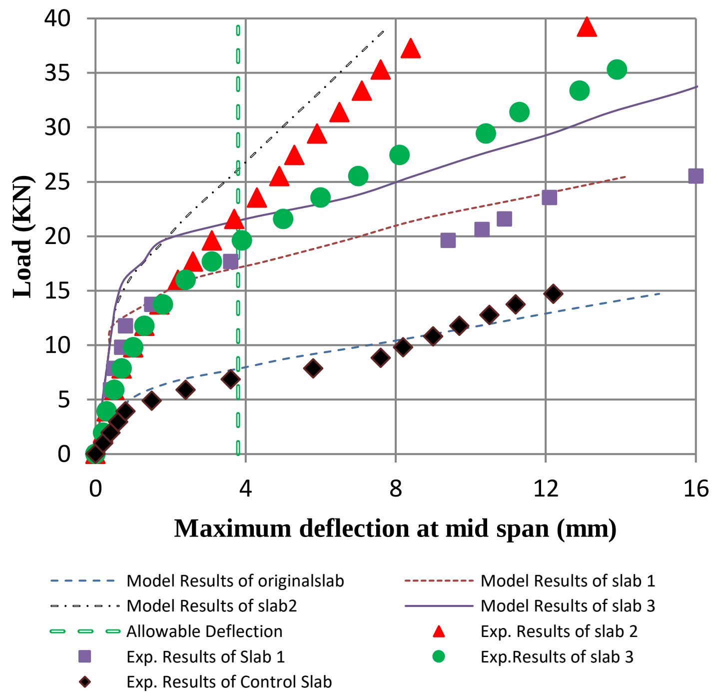

Fig. 11. Load-deflection curve of strengthened slabs compared to the reference slab

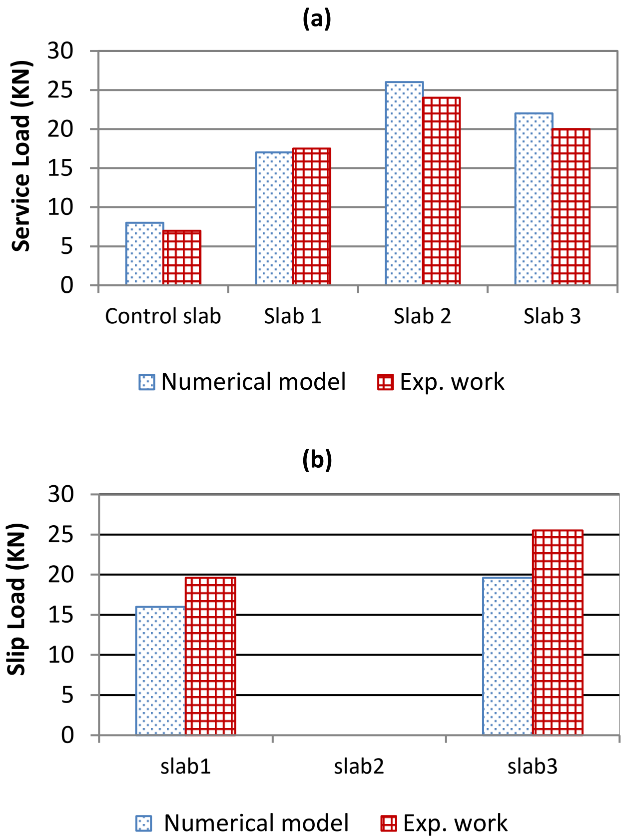

Fig. 12. Comparison of slabs in terms of: (a) Service load; (b) Slippage Load

7. Conclusions

The Numerical Model is developed to simulate the behaviour of strengthened simply supported RC one-way slab, using reinforced overlay considering different connecting systems between existing and new reinforced concrete slabs. The connecting techniques namely are: 1) friction only; 2) epoxy adhesive material; and 3) shear keys. The main outcomes from this study are:

- The developed numerical model is capable of predicting the behaviour of strengthened one-way slab using RC concrete overlay, good agreement has been found between the numerical mode results compared to experimental results.
- The service load of strengthened slabs increased by 212.5%, 325% and 275% for those slabs strengthened using; friction, epoxy material and shear connector respectively, as compared to the control slab.
- The use of epoxy having strength greater than the expected horizontal shear stress achieved full composite action.
- The slippage load obtained from this study does not exceed 25%, when compared with visible horizontal cracking load obtained from experimental work in reference.
- The structural behaviours in strengthened RC slabs with overlay depends entirely on the used bonding technique between the two surfaces.

Conflict of Interest

The authors declare no conflicts of interest.

Nomenclature

α_f: The angle of internal friction between the faces of the joint
δ: The cumulative deflection at $\frac{x}{L} = 1$
δ_i: Cumulative deflection for each section
$\delta_{correct}$: corrected deflection
$\psi_1, \psi_2, \psi_{mean}$: Curvature of un-cracked, fully cracked sections, mean, respectively
θ_i:Cumulative slope for each section
τ_{bond}: Horizontal shear capacity/strength of the interface
ζ: Distribution factor
A_s : Area of steel reinforcement, $A_{s1}, A_{s2}$are used for the original slab and concrete overlay, respectively.
A_{sh}: Cross-sectional area of shear keys
b, b_e: Width original R.C slab and concrete overlay respectively.
d : Depth of steel reinforcement, $d_1, d_2$are used for the original slab and concrete overlay, respectively.
E_c, E_s: Elastic modulus of concrete and steel, respectively
f_{ck}: Characteristic compression cylinder strength of concrete at 28 days
f_{ct}: Mean value of tensile strength of concrete
h : Thickness of slab, $h_1, h_2$are used for the original slab and concrete overlay, respectively.
I_1, I_2: Second moment of area for un-cracked and fully-cracked sections, respectively
L: Length of beam
M_r:Cracking Moment
m: modular ratio between steel and concrete
x_1 , x_2: Distance from extreme fibre in compression to the neutral axis for un-cracked and fully-cracked sections
$x_{1,comp}$: Distance from extreme fibre in compression to the neutral axis for un-cracked section considering fully composite action
$x_{2,comp}$: Distance from extreme fibre in compression to the neutral axisfor fully-cracked section
Z: Section modulus

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