EXTENSION OF MCFT APPROACH FOR PREDICTING SHEAR STRENGTH CONSIDERING COMPRESSIVE MEMBRANE ACTION IN LATERALLY RESTRAINED RC SLABS

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1. INTRODUCTION

Accurate estimation of residual bearing capacities in structural safety assessment is crucial for cost-effective maintenance. As Walraven (2010) found, many existing reinforced concrete (RC) slab bridges in the Netherlands have significantly insufficient shear strength compared to the predicted capacities calculated using design codes. Although it is common practice to strengthen these slabs, there is no evidence showing the lack of shear strength observed during the investigation. That may be due to the hidden reserve capacity enhanced by an internal arching or compressive membrane action (CMA). Consequently, executing a more accurate assessment could determine the true strength of the slabs and possibly eliminate the need for strengthening. Despite the recognition of CMA's advantages, few shear equations have accounted for it. This study aims to predict the shear strength of laterally restrained RC slabs by extending the well-known approach for shear strength prediction, the modified compressive field theory (MCFT) developed by Vecchio and Collins (1986). The extension is then validated with experimental results conducted by Hon (2003).

2. CMA IN LATERALLY RESTRAINED RC SLABS

2.1 CMA in RC bridge deck slabs

CMA occurs in RC slabs that are subjected to vertical loads, such as wheel loads, and have been adequately restrained against lateral expansion. In the case of RC bridge deck slabs, surrounding slabs or adjacent span members can provide this lateral restraint. The restraint at the slab's boundaries induces in-plane compressive forces within the slab, resulting in an arching force, as shown in Fig. 1(a). This arching force, depending on the degree of lateral restraint, can improve the load-carrying capacity of RC slabs as shown in Fig. 1(b).

(a) (b)

Fig. 1 CMA in RC bridge deck slabs: (a) arching force; (b) strength enhancement due to CMA

2.2 Prediction of arching capacity

Rankin and Long (1997) proposed an approach to assess the ultimate strength of RC slabs with arching action. The total ultimate load capacity is calculated by summing the loads carried by the bending and arching actions. The strength enhanced by the arching action P_a (N) can be computed using Eq. (1), which relates the arching moment ratio M_r and the ratio of the half span of elastically restrained L_e to the half span of an equivalent rigidly restrained strip L_r.

$$P_a = k(0.21 f_c^{'} d_1^2 M_r)(L_e / L_r) \quad (1)$$

Where $f_c^{'}$ is the compressive strength of concrete (N/mm^2), and d_1 represents half of the depth of the section available for arching (mm). k is static moment coefficient (e.g., k = 4/L for a slab strip under concentrated midspan loading).

3. EXPERIMENTAL DATA USED

The experiment of Hon's study (2003) was used to validate the extension of the MCFT-based shear equation for predicting shear strength in laterally restrained RC slabs with CMA. The specimens were tested with horizontal restraint at various depths, using a restraining frame. In the present study, only the slabs that failed in shear with restraints at depths of 105 and 140 mm were employed for validation.

4. EXTENSION OF MCFT APPROACH

4.1 MCFT-based shear strength equation

The MCFT approach was derived by Vecchio and Collins (1986) to predict the shear strength of RC members V_c (N). When effective width b_v and effective shear depth d_v are known, V_c can be estimated using Eq. (2). The shear resistance depends on the ability of diagonally cracked concrete to transmit tension and shear stresses occurring in the critical section

Keywords: Shear strength, MCFT, Laterally restrained RC slabs, Compressive membrane action
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which is denoted as the factor β. This factor for members without transverse reinforcement is expressed in Eq. (3). It can be calculated from the longitudinal strain ε_x and the crack spacing parameter S_{xe} (mm).

$$V_c = \beta\sqrt{f_c'}b_v d_v \tag{2}$$

$$\beta = [0.4/(1+1500\varepsilon_x)][1300/(1000+S_{xe})] \tag{3}$$

Where ε_x is half of the strain in the longitudinal tension reinforcement ε_s. $S_{xe} = [35S_x/(a_g+16)]$ in which S_x taken as the greater of d_v, 0.9 of effective depth d, and 0.72 of member height (mm), and a_g is the maximum aggregate size (mm).

4.2 Extended MCFT approach

The MCFT approach identifies ε_x as an essential factor in predicting shear strength when the geometrical and material properties of the member are given. This is because it accounts for the effect of externally applied load P_u, causing the moment M_u and shear V_u, and amount of longitudinal reinforcement A_s on V_c of the section. Since Hon (2003) found that slabs with higher compressive membrane force had lower strain in the steel reinforcement at the bottom mid-span, it is possible that ε_x is affected by arching force N_a. Therefore, for laterally restrained slabs, ε_s can be estimated by incorporating arching moment M_a, as shown in Fig. 3(a). By analyzing the geometry of deformation and equilibrium of internally sectional forces at the ultimate state, the lever arm h_a for calculating M_a can be determined, as illustrated in Fig. 3(b).

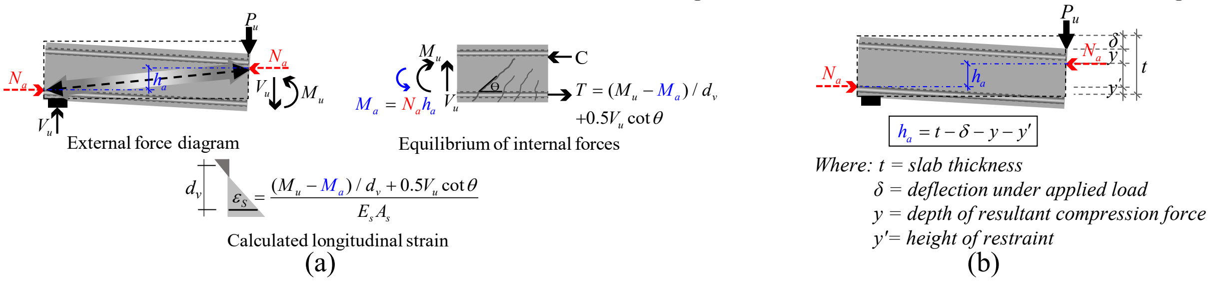
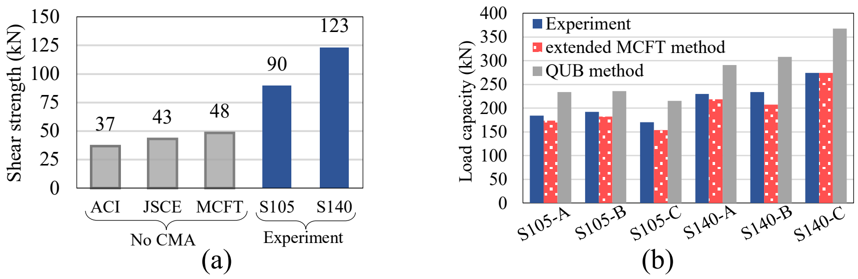


Fig. 3 Influence of arching force: (a) calculated longitudinal strain; (b) lever arm for arching moment calculation

4.3 Shear strength and load capacity prediction

Fig. 4 compares Hon's experimental results with the calculations in this study. The difference in shear strength obtained from practical design codes (ACI and JSCE) and the MCFT method (Fig. 4(a)) suggests that CMA enhances the shear strength of laterally restrained slabs. The load capacities in Fig. 4(b) predicted by the extended MCFT method ($P_{ext\text{-}MCFT} = 2V_c$) agree well with the experimental results (P_{exp}) but may slightly underestimate them due to the approximation of the lever arm for the arching moment. Whereas, Rankin and Long's method (P_{QUB}) tends to overestimate load capacities, possibly due to the approximate depth of concrete available for arching and the suitability of the method for predicting flexural capacity. Summary of results are also tabulated in Fig. 4(c).



Slab	P_{exp} (kN)	$P_{ext\text{-}MCFT}$ (kN)	P_{QUB} (kN)	$P_{ext\text{-}MCFT}/P_{exp}$	P_{QUB}/P_{exp}
Slabs restrained at depth of 105 mm					
S105-A	184.1	173.4	233.9	0.94	1.27
S105-B	191.9	182.0	235.7	0.95	1.23
S105-C	170.4	153.9	215.5	0.90	1.26
Slabs restrained at depth of 140 mm					
S140-A	229.7	218.5	290.9	0.95	1.27
S140-B	234.2	207.7	307.8	0.89	1.31
S140-C	274.1	274.5	368.0	1.00	1.34
			Average	0.94	1.28

(c)

Fig. 4 Comparison of experimental and predicted results: (a) Shear strength; (b) Load capacity; (c) results summary

5. CONCLUSIONS

The study aims to extend the MCFT approach to predict the shear strength of laterally restrained RC slabs, such as bridge deck slabs, by including the influence of CMA. Results show that CMA significantly enhances the shear resistance of the section and improves the reliability of shear strength prediction. The study concludes that the MCFT method is suitable for estimating shear strength considering the CMA effect, as the predicted values agree well with experimental results.

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