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Nonlinear Seismic Response of Flat Plate Systems made with Ultra Low Strength Concrete

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This paper investigates the performance of flat plates and slabs which are made with very low strength concrete (e.g. ultimate concrete compressive strength at 28 days, $f_c^{'}$≈ 10-15 MPa). Three structural systems: (i) flat plate (FP), (ii) flat slab with drop panel (FSWDP), and (iii) flat slab with drop panel and column capital (FSWDPCP)were investigated under seismic load. Two volumetric mixing ratios of 1:2:4 and 1:1.5:3 (cement: fine aggregate: coarse aggregate) and water to cement ratio (by weight) of 0.45 were used to prepare all the model concrete specimens. In order to perform dynamic tests, scaled El Centro 1940 was employed in a shake-table. Additionally,numerical models were developed by using SAP2000 to perform simulations.Later,thepredicted results have been compared with the experimentally obtained response.The experimental results have shown that the flat plate system is more vulnerable than both flat slab systems (FSWDP and FSWDPCP).It is important to note that the concrete models made with mixing ratio of 1:1.5:3 exhibits better performance in terms of reducing displacement amplitude than the mixing ratio of 1:2:4.

Keywords: Flat plate and flat slabs; Low strength concrete; Shake-table tests; Dynamic loads; Displacement.

1. Introduction

The flat plate and flat slab systems are widespread all over the world due to aesthetic consideration, the capability of minimizing total height of the structures, easier construction procedure and so on. Over the last few decades, the use of flat plate and flat slab systems have gained serious attention in Bangladesh. Basically, reinforced concrete (RC) flat plate and flat slabs, horizontal structural element, directly passes the load to the supporting column. Therefore, those systems have serious demerits that they are vulnerable to punching shear, heavy loads as well as dynamic loads. In order to keep the structure safe, drop panel and column capital/head are provided to withstand earthquake because of higher shear stress and negative bending moment than thebeam-column structural system at the slab-column connection (Nilsonet al. 2014; Graf and Mehrain, 1992). For practical application of low strength concrete is very common in developing countries like Bangladesh, Iraq, Nigeria, Turkey, and so on (Ispir et al. 2010;Ahmad,2015).

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Also, Zhang et al. (2011) studied the mechanical properties of low strength concrete. Most importantly, those structures are can be worse when they are made of low strength concrete as well as can be hazardous.

Mamede et al. (2013) performed the experimental and numerical study and has proposed an equation to predict the punching capacity of flat slabs. Punching shear behavior and effect of reinforcement on punching shear is studied by (Alam et al. 2009; Alam and Amanat, 2013;Kabir and Islam, 2012).Luo et al. (1995) showed that the probability of punching failure increased for higher peak ground acceleration in soft soil. In addition, Youssef et al. (2014) performed grillage analysis in two sets of flat plate frames considered selected parameters such as span length, bay width, column dimensions, and level of column axial load.

In the literature, the behavior of flat plate and flat slabs under dynamic/static loads are reported very well. And many analytical model and numerical simulations can be found to predict/minimize catastrophic event of earthquake. Regrettably, almost no data is available that addresses the application of low strength concrete in the flat plate and flat slabs structures and their response under dynamic loads. The lack of published test results, limited information and knowledge provide the motivation to evaluate the dynamic performance of flat plate and flat slab systems by using low strength concrete. Both experimental tests and numerical simulations are conducted for attaining the goals of this study.

The rest of the paper is structured as follows: Section 1 contains the introduction, Section 2 explains the experiment setup and test methodology. Section 3 describes the numerical simulations and Section 4 deals with the results and discussion. And Section 5 has summarized the outcome of this study and Section 6 presents the future direction of the study.

2. Experimental Investigations

2.1 Materials Preparation, Mix Design, and Casting:

In this experimental campaign, the first class burnt clay bricks (commonly used in Bangladesh) was used as coarse aggregates, while natural river sand (locally called Sylhet sand, which fineness modulus and specific gravity were 2.68 and 2.56, respectively) was used as a fine aggregate. The maximum size of coarse aggregate was 20 mm and the grading of the coarse aggregates was controlled as per ASTM C33.Two volumetric mixing ratios (commonly practiced mix ratio used in Bangladesh) of 1:2:4 and 1:1.5:3 (cement: fine aggregate: coarse aggregate) and water to cement ratio (by weight) of 0.45 were used to prepare all the slab model specimens. In order to monitor the compressive strength of each batch of concrete, the cylindrical (100 mm in diameter and 200 mm long) concrete specimens were made and demolded after 24 hours of casting. Then all the concrete specimens were cured under water up to the day of the compressive tests (i.e., 28 days).The compressive strength tests were performed at 28 days as per ASTM C39 by using Universal Testing Machine (UTM). During compression test, the deformation of concrete specimens was measured by a strain measurement setup with two dial gauges. The gauge length was 100 mm in the central part of the specimen. After crashing, the failure surfaces of concrete were also observed carefully. The modulus of elasticity of concrete specimens was calculated from the stress-strain curves. The maximum compressive strength of concrete is about 1500 psi (10.3 MPa) for mix ratio 1:2:4, meanwhile, compressive strength is approximately 2200 psi (15.2 MPa) for mix ratio 1:1.5:3.The summary of the compressive strength and modulus of elasticity of all concrete batches are reported in Table 1.

Table1: Compressive Strength and Modulus of Elasticity of Concretes

Mix Ratio	Models	Compressive Strength (MPa)				Modulus of elasticity (GPa)			
		1	2	3	Avg.	1	2	3	Avg.
1:2:4	FP	10.3	10.3	10.4	10.3	6.8	5.8	7.7	6.8
	FSWDP	10.4	10.2	10.3	10.3	5.8	6.3	5.4	5.8
	FSWDPCP	10.4	10.1	10.5	10.4	8.2	7.5	8.6	8.1
1:1.5:3	FP	15.2	14.8	15.1	15.0	8.6	7.8	8.1	8.2
	FSWDP	15.4	15.0	14.9	15.1	8.1	7.3	6.8	7.4
	FSWDPCP	15.5	15.2	15.0	15.2	7.4	7.3	6.9	7.2

2.2 Preparation of the Flat Plate and Slab Specimens:

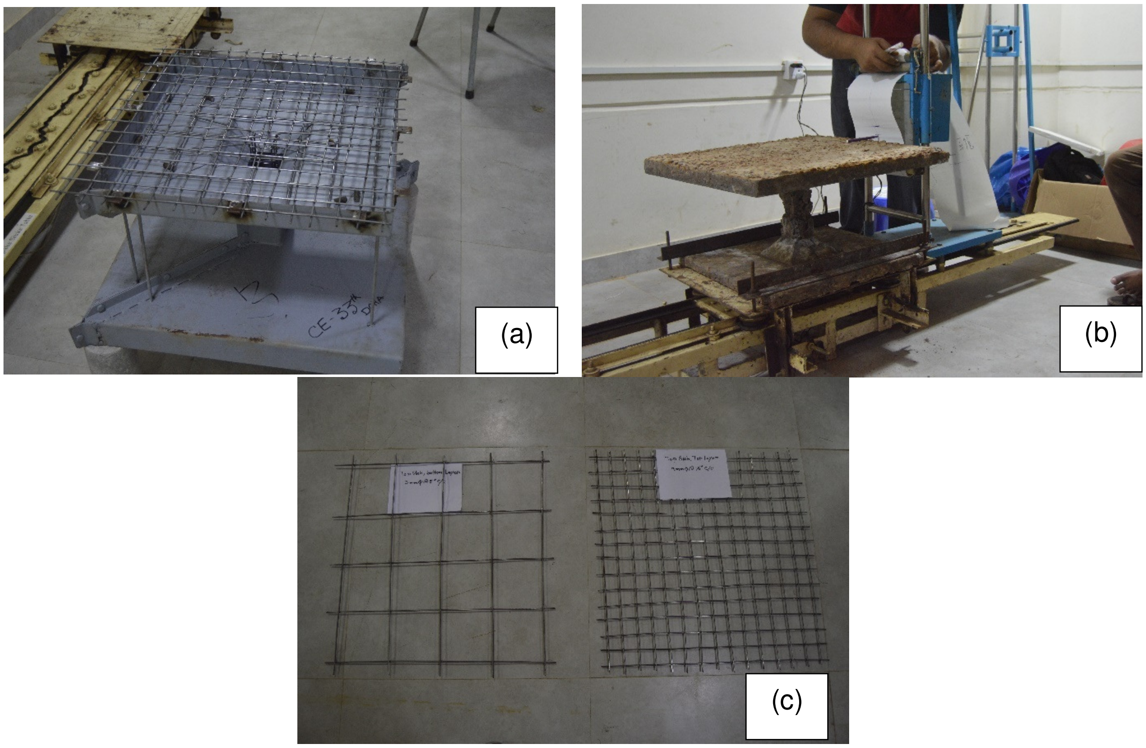
Three models of structures such as flat plate, flat slab with drop panel, and flat slab with drop panel and column capital together are considered. And each of them can be assumed as a single degree of freedom system (SDOFs).

The scaled El Centro 1940 seismic data was used to perform the shake-table dynamic tests. Original duration El Centro has been scaled to 25secto cope with the current facility of the laboratory. Interested reader may get further detail via Islam and Anam 2015; Hossain and Ahmed 2016. Experimental setup and formwork with slab reinforcement are shown in Fig. 1(a-c). The prototype models were scaled down by a factor 10 assuming a slab span of 20ft×20ft(610 cm x 610 cm) standing on 25 in×25 in(63.5 cm x 63.5 cm) columns. The models are considered for numerical simulations as similar as experimental setup in terms of material properties and structural dimensions. Support condition remains fixed in all cases/models.

A detail dimensions of prepared models are given below:

I. **Flat plate**: size 24 in x 24 in (60.96 cm x 60.96 cm) slab standing on 2.5 in x 2.5 in (6.35 cm x 6.35 cm) column as well as slab thickness was 2 in (5.1 cm).
II. **Flat slab with drop panel**: size of slab and column remain same as described above. Additionally, 8 in x 8 in (20.32 cm x 20.32 cm) with 0.45 in (1.143 cm) depth drop panel added with flat plate.
III. **Flat slab with drop panel with column capital**: as described above that the slab and column size remain same and further, a 6 in x 6 in (15.24 cm x 15.24 cm) column capital added with flat slab consists of drop panel.

Figure 1: Experimental Setup: (A) Formwork and Detailing; (B) Shake-Table Test; and (C) Detailing of Top and Bottom of the Specimen.



3. Numerical Implementations

In order to perform numerical simulations and compare with the experimental results, numerical computations were carried out by using SAP2000. The basic formulation of any dynamic system is known as the equation of motion (Chopra, 1995; Miah, 2015). All of the flat slab systems are considered to be single-degree-of-freedom (SDOF) system. And the aforementioned SDOFs can be described via the equation of motion as given by:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = -m\ddot{x}_g \tag{1}$$

where m, c, and $k$represents mass, damping and stiffness of the system, respectively,$\ddot{x}_g$ represents the ground acceleration, t indicates the time vector,x, $\dot{x}$and $\ddot{x}$ indicates the displacement, velocity, and acceleration vector accordingly. The damping of the system is assumed to be Rayleigh damping and given by

$$c = \alpha \times m + \beta \times k \tag{2}$$

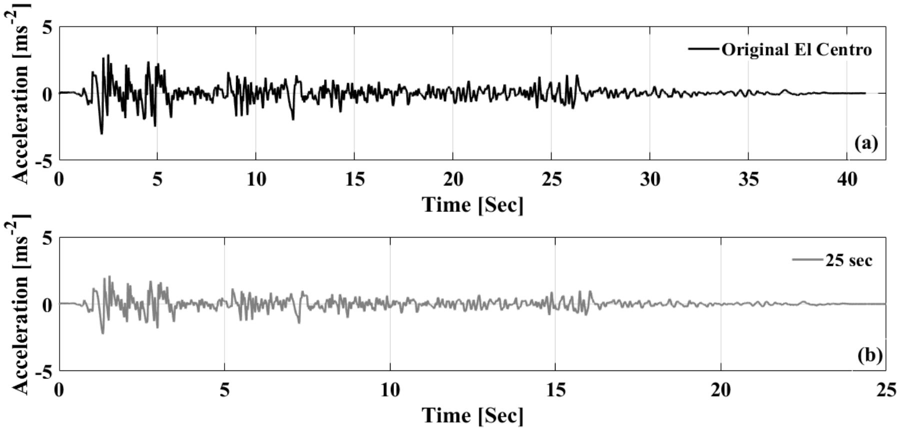
where α and β are constants. It should be noted that the parameters α and β have been regulated the damping to attain similar damping of lab structures.

The Newmark-beta method is a technique for numerical integration to solve differential equations. The early mentioned method was introduced by Newmark in 1959 and detail can be found in (Newmark, 1959). It is broadly used in the numerical evaluation of the dynamic response of structures and solids such as in finite element analysis to model dynamic systems. In this study, Newmark-beta method was employed in conjunction, the Newton-Raphson iterations were used for better accuracy (Clough and Penzien, 1993; Miah et al. 2016). For numerical simulations, theinitial condition of the aforementioned model was unstressed state and history type was transient. To consider the geometric nonlinearity, (P-Δ) effect was applied.

4. Results and Discussion

In order to evaluate the seismic behavior of flat plate and flat slabs, nonlinear time history analysis was performed. Afterward, the experimental and numerical responses (e.g. displacement)were compared. Numerical simulations were accomplished by using SAP2000.The ground motion was modified in terms of peak and duration according to the structural size and demand of lab facility. As it is mention earlier that duration of El Centro calibrated from 40.96sec that has been scaled to 25 sec. Original data and the scaled of El Centro is depicted in Fig.2.

Figure 2: Input Excitation for Dynamic Tests:(a) Original El Centro data; and (b) Scaled El Centro for 25sec.



Figures 3-5 represent the experimental and numerical response (i.e. evolution of displacement) of flat plate, flat slab with drop panel, andflat slab with drop panel and column capital to mix ratio of 1:2:4. The solid linere presents the experimental response and the dashed lineshows the numerical responses. For simplicity, the curves lines remainsame for Figs. 6-8 for mix ratio of 1:1.5:3. In addition, a zoomed view of 1-5 second also sub-plotted for better visualization of the data.

It can be seen that the experimental results are quite in good agreement with the numerical results carried out by SAP2000, see Figs. 3-8.

Figure 3: Displacement Response of Flat Plate for Mix Ration of 1:2:4: (a) Full-Time History; and (b) Zoomed View of 1-5 sec.

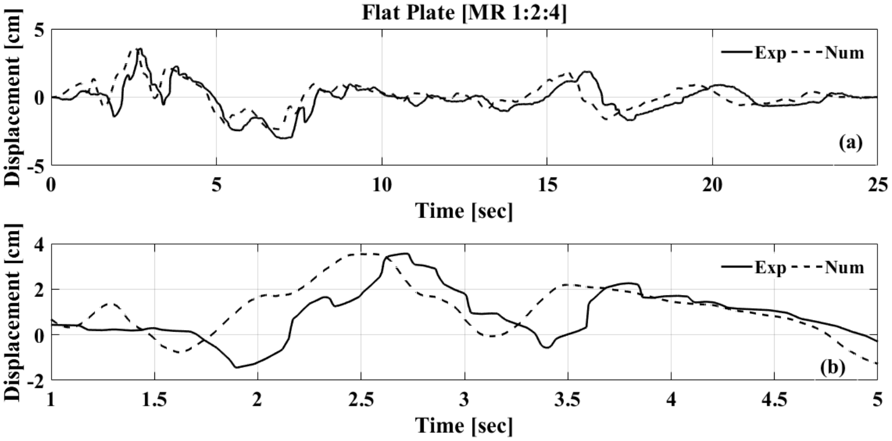


Figure 4: Displacement Behavior of flat Slab With Drop Panel as a Function of Time for Mix Ration of 1:2:4: (a) Full-Time History; and (b) Zoomed View of 1-5 Sec.

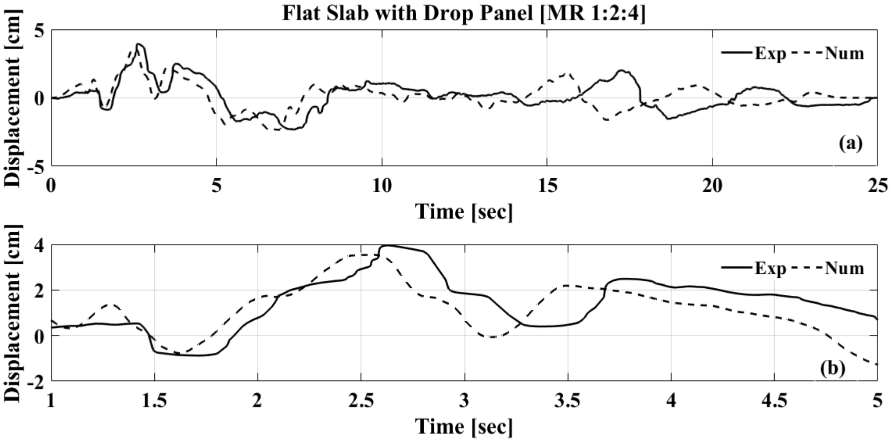


Figure 5: Evolution of Displacement of Flat Slab with Drop Panel and Column Capital for Mix Ration of 1:2:4: (a) Full-Time History; and (b) Zoomed View of 1-5sec.

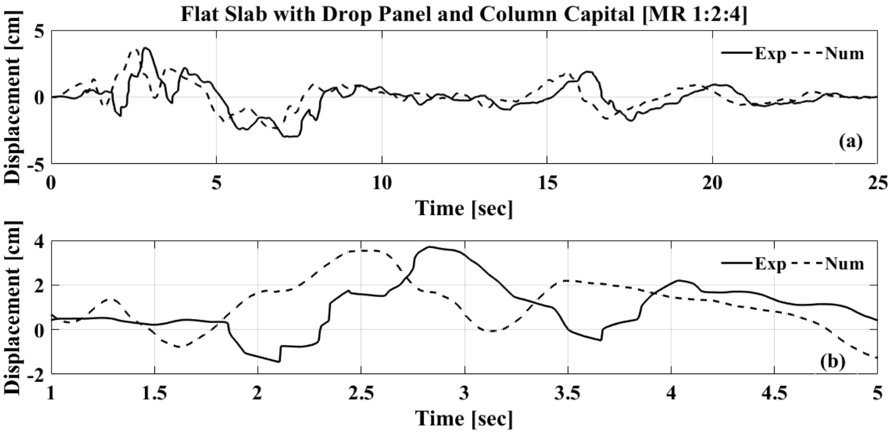


Figure 6 represents the comparison of the experimental and numerical response of flat plate for mix ratio of 1:1.5:3. Herein the responses of flat slab with drop panel as well as responses for flat slab with drop panel and column capital is given in Fig. 7 and Fig. 8, respectively. Once again, it is found that experimental observations and numerical responses are almost identical. The mix ratio between 1:1.5:3 and 1:2:4, the responses are little dispersed.

Figure 6: Displacement Response of Flat Plate for Mix Ration of 1:1.5:3: (a) Full-Time History; and (b) Zoomed View of 1-5 sec.

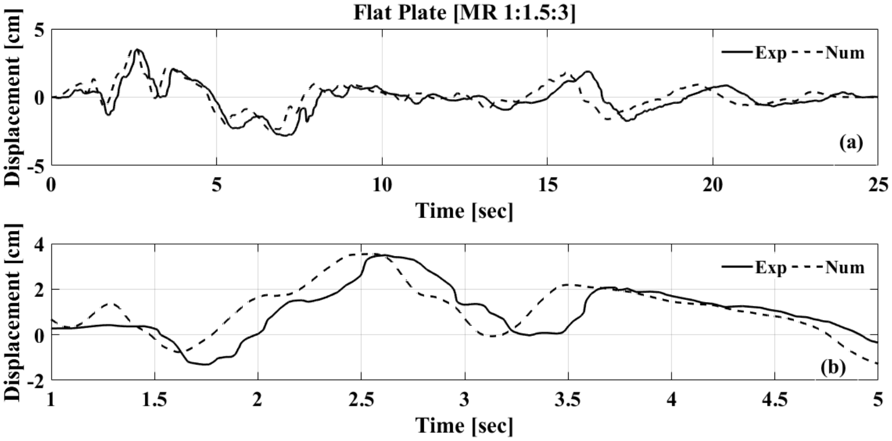
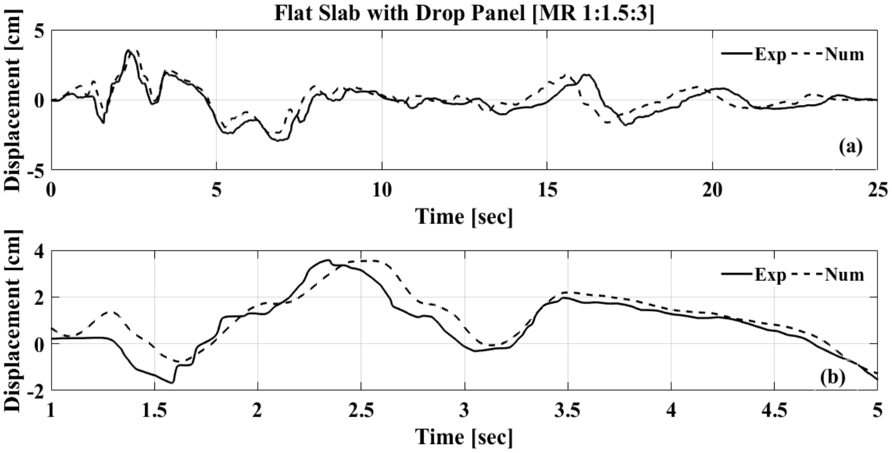


Figure 7: Displacement Behavior of Flat Slab with Drop Panel as a Function of Time for Mix Ration of 1:1.5:3: (a) Full-Time History; and (b) Zoomed View of 1-5 Sec.



In order to better understanding the response of three different structural systems, Fig. 9 and Table 2 are prepared. In terms of the evolution of displacement, no significant differences have been observed among three different structural systems. For example, maximum response determined during dynamic tests of flat plate, flat slab with drop panel, and flat slab with drop panel and column capital are, respectively, 3.54 cm, 3.56 cm, and 3.54 cm for positive displacement and 2.72 cm, 2.85 cm, and 2.87 cm for the negative displacement of the mix ratio of 1:1.5:3, see Table 2. While a bit scattering was observed for the mix ratio of 1:2:4. However, a significant different response was observed for the flat plate system in terms of stability of the structures during the dynamic tests. It has been found that the flat plate system is more vulnerable than FSWDP and FSWDPCP. During the dynamic tests, the flat plate system was cracked and partially damaged, resulting spalling of concrete (detachment of some chunk or debris of concrete) from the surface of the plate close to the joint (see Fig. 10), while no similar cracking or damage of this type was observed for flat slab with drop panel and column capital.

Figure 8: Evolution of Displacement of Flat Slab with Drop Panel and Column Capital for Mix Ration of 1:1.5:3: (a) Full-Time History; and (b) Zoomed View of 1-5 sec.

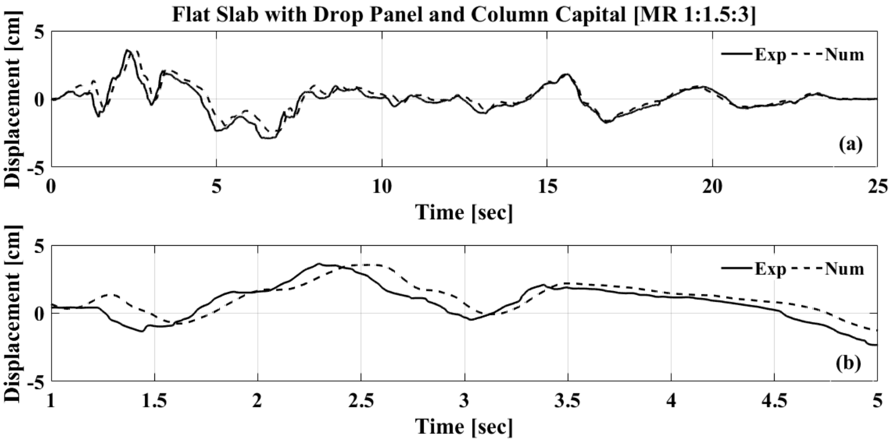
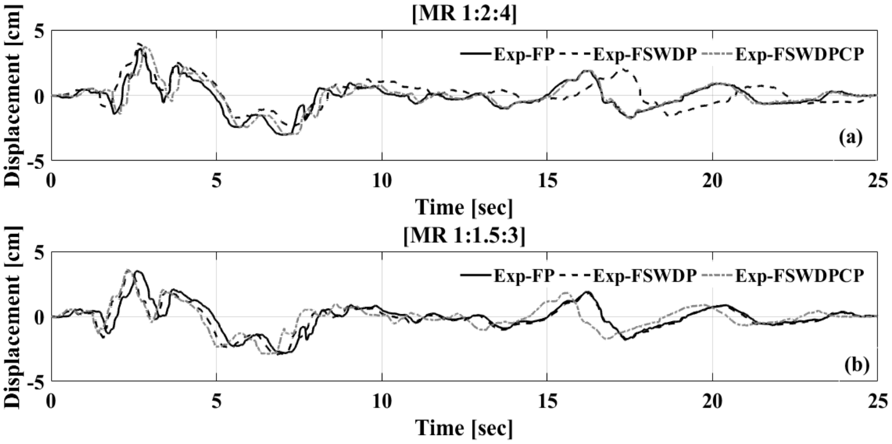


Figure 9: Displacement Comparison of Experimental Response among Flat Plate, Flat Slab with Drop Panel, and Flat Slab with Drop Panel and Column Capital.



As concern the mix ratio, the concrete models made with mixing ratio of 1:1.5:3 exhibits better performancein terms of reducing amplitude than the mixing ratio of 1:2:4. As an example, the maximum positive response determinedduring dynamic tests of flat plate, flat slab with drop panel, and flat slab with drop paneland column capital are, respectively, 3.54 cm, 3.94 cm, 3.67 cm for the mixing ration of 1:2:4 and 3.54 cm, 3.56 cm, and 3.54 cm of the mixing ration of 1:1.5:3. This behavior could be due to the higher compressive strength of the mix ratio 1:1.5:3 (approx. 15.2 MPa) than the mix ratio 1:2:4 (approx. 10.3 MPa). It is believed that the high strength concrete gives lower displacement than the low strength concrete due to denser microstructure and a strong interfacial transition zonebetween the cement paste and aggregates.

Table 2: Comparison of Maximum and Minimum Peak Displacements of All Tests

Type of Structures	Experimental $^{(+)}$ (cm)		Experimental $^{(-)}$ (cm)		Numerical $^{(+)}$ (cm)		Numerical $^{(-)}$ (cm)	
	1:2:4	1:1.5:3	1:2:4	1:1.5:3	1:2:4	1:1.5:3	1:2:4	1:1.5:3
FP	3.54	3.54	3.02	2.72	3.54	3.54	2.37	2.32
FSWDP	3.94	3.56	2.31	2.85	3.56	3.48	2.37	2.36
FSWDPCP	3.67	3.54	2.97	2.87	3.53	3.54	2.37	2.27

Figure10: Crack Formation of Flat Plate slab After the Dynamic Test

Last but not least, for visualization purpose of cracks marked with red colored lines are depicted in Fig. 10.

5. Conclusion

This study investigates the performances of flat plate and flat slabs made with low strength concrete both experimentally and numerically. To do this end, locally available materials are used by considering appropriate volumetric mix design ratio, that provides low strength. Compressive strength and stress-strain behavior of concrete are evaluated. The maximum compressive strength of the concrete is observed ~1500psi (10.3 MPa) and 2200psi (15.2 MPa) for mixing ratio of 1:2:4 and 1:1.5:3, respectively. Later, the aforementioned concrete has been used to cast three models for each mixing ratio. All of the models have gone through the shake-table tests. In shake-table, scaled El Centro 1940 earthquake is employed for the duration of 25sec. Further, same ground motion is used for numerical simulations. And a set of representative models are created for simulations purpose in SAP2000.It is observed that the experimental responses of the tested models have agreed well with the numerical results. It is found that the flat plate system is more vulnerable than other two flat slabswith drop panel and column capital. Further, it is observed that theflat plate system was partially damaged due to punching shear. In contrast, almost no visible crack or damage was noticed for the flat slab with column capital and drop panel. The structure made with mixing ratio of 1:1.5:3 exhibits lower amplitude in comparison to the mixing ratio of 1:2:4.

6. Recommendations for Future Work

This study has motivated to perform further study to retrofit the partially damaged structure and evaluated their performance. This is an ongoing research project where further work is planned in the direction of strengthening of structures made with extremely low strength concrete. After that, the dynamic test will be performed on the retrofitted model slabs and the responses will be monitored via the linear variable differential transformer (LVDT) type sensor as well as accelero meters. The outcome will provide a guideline to the designers for designing structures with low strength concrete.

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