An Effective Retrofitting Scheme for Flat-Slab Systems Made with Unconventional Type Concrete

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Abstract—**This study investigates static and dynamic performances of flat-plate and flat-slab systems made with unconventional type concrete (i.e., low strength concrete) both experimentally and numerically. To do this end, in a first step, the specimens are tested under both static and dynamic loads. Later, all of the specimens are retrofitted (i.e., partially damaged specimens after dynamic load) via the use of ferrocement technique and tested again under dynamic loads to investigate the performances of the retrofitted specimens. Total six slabs with columns are made for two different concrete mix design ratios such as 1:1.5:3 and 1:2:4 (cement: fine aggregate: coarse aggregate). The models are: flat-plate labeled as M1, flat-slab with drop panel namely M2 and flat-slab with drop panel and column capital termed as M3. And their performances are evaluated by performing static and dynamic tests via shake-table. Additionally, numerical simulations are performed by using SAP2000 and compared with the experimentally obtained response. It is observed herein that the punching shear failure occurred at the slab-column connection for most of the un-retrofitted cases, while the performances have improved significantly due to retrofitting. The outcome will assist the real engineering problem to mitigate the damage of flat-slab systems in general.**

Index Terms—**flat-slab system, punching shear failure, dynamic loads, shake-table tests, ferrocement**

I. Introduction

Flat-plate (FP) and flat-slab (FS) systems are typically used as a horizontal structural element that directly passes the load to the supporting columns. The aforementioned systems have significant demerit during earthquake due to concentration of excessive shear stress and negative bending moment at the slab-column joint. The drop panel and column capital/head are provided to withstand against early mentioned issues. The work in [1], studied the problem where edges restrained and unrestrained reinforced concrete (RC) slabs are constructed and tested. In [2] performed an experimental investigation on RC structures by using ferrocement jacket and good improvement is reported. While in [3], studied the mechanical properties of low strength concrete. The punching shear strength of RC flat-slabs with and without shear reinforcement is investigated and the necessity of reinforcement is reported in contrast no steel on structures [4]. A detailed study for various retrofitting schemes for flat-slab structures via using ZEUS-NL and DRAIN-2DM are studied and fragility curves are proposed [5]. Several strengthening techniques for RC slabs with or without cut-outs are performed and reported that the retrofitting scheme always comes with an economical consideration [6]. Shear bolts are used to improve performance of RC slabs [7], meanwhile, column jacketing, shear walls, RC column jackets, and confinement has studied in [8]. Additionally, an experimental study for retrofitting damaged flat-slabs due to punching shear by using prestressed vertical type bolts are performed [9]. The effect of catastrophic or unforeseen events both the structural robustness and vulnerability of FS is presented in [10]. The paper revealed that weakness of flat-slab can be identify using fuzzy numbers. Modeling effects of a 50 storey RC tall building with flat-slab is investigated [11]. And three laterals load resisting systems: (a) core wall only, (b) core wall with flat-slabs, and (c) core wall with flat-slabs and damper outriggers, have considered for analysis. The results stated that the flat-slab with early mentioned systems (a-c) have significantly contributed to the energy dissipation of the structural systems and also disclosed that the inter-story drift has decreased.

Herein, the seismic performance of flat-plate and flat-slabs are evaluated by conducting experimental tests. Finally, the experimentally obtained results are compared with the numerical one and quite good agreement is observed. The rest of the paper is structured as follows: immediate next section describes the problem statement including experimental and numerical implementations. After that section, the results and discussion are presented and the last section of this paper summarizes the outcome of this study.

Manuscript received November 30, 2018; revised December 30, 2019.

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doi: 10.18178/ijscer.9.1.19-24

II. Problem Description

In this study, three models of six slabs with columns are considered and each of them is assumed to be a single degree of freedom system. In order to evaluate the response of the flat-plate systems, slabs are made with commonly used concrete mix ratios in Bangladesh (e.g., 1:1.5:3 and 1:2:4) (see Table 1). More specifically, three models are cast for each mix ratio, and the ratios are 1:1.5:3 and 1:2:4 (cement: fine aggregate: coarse aggregate). And the water to cement ratio is set to 0.45 in order to prepare all of the specimens. For evaluating the performances, both the static and seismic loads are employed. In order to perform dynamical tests, the shake-table is used by employing the scaled El Centro 1940 earthquake data which is scaled for 15, 20, and 25 sec respectively due to the current facility of the lab. The prototype models are scaled down by a factor 10 assuming a slab span of 610 mm × 610 mm standing on 63.5 mm × 63.5 mm column. In the first phase, the slabs are tested for three different durations and some cracks are formed in the slabs, especially, for the flat-plate system. Afterward, the partially damaged slabs are retrofitted by using ferrocement and then the dynamic tests are carried out for all three different test periods (see Fig. 1). The dynamic response of un-retrofitted (UR) and retrofitted (RF) models are made with concrete mix ratio of 1:1.5:3 and 1:2:4 and tested for 15, 20, and 25 sec, accordingly. And same configurations (in terms of material properties and structural dimensions) are used for numerical simulations by using SAP2000. Finally, the post-processing of all results has done via MATLAB®.

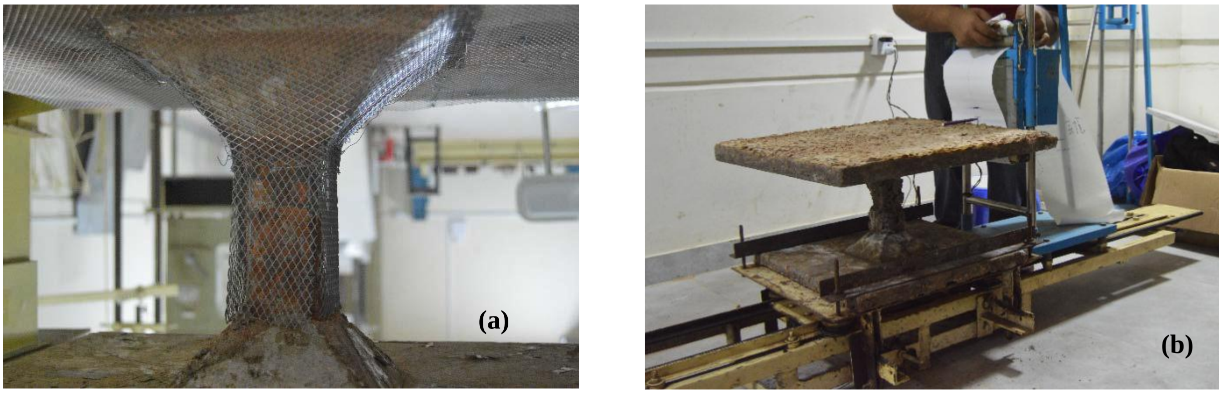

Figure 1. Experimental setup: (a) retrofitting detailing, and (b) data collection from shake table test.

TABLE I. Overview of the Experimental Model.

Mix Ratio	Case	Model Name	Drop Panel	Drop Panel with Column Capital
1:1.5:3 and 1:2:4	Un-retrofitted	M1-UR	×	×
		M2-UR	✓	×
		M3-UR	✓	✓
	Retrofitted	M1-RF	×	×
		M2-RF	✓	×
		M3-RF	✓	✓

III. Results and Discussion

Herein static and dynamic responses of three models of flat-slabs made with unconventional concrete (compressive strength at 28 days, $fc_{28days} \approx 10$ MPa for mix ratio of 1:2:4 and $fc_{28days} \approx 15$ MPa for mix ratio of 1:1.5:3) are examined. In order to evaluate the load-deflection behavior of all slab models, static incremental load is applied vertically at about the center of the models. The deflection of the models are monitored at the beneath of the plate/slab via four digital dial gauges placed at four corners of the models and the results are presented in Fig. 2. As expected, significantly higher deflections are observed for flat-plate i.e., M1 than other two slab models (M2 and M3). This behavior could be due to the lower stiffness of flat-plate than other two slab models. Since the flat-slab systems have the additional load carrying path (e.g., drop panel/drop panel and column capital) connected with slab-column joint which makes the slabs stiffer than the simple flat-plate system. Almost similar load-deflection behavior is observed for the slab made of concrete with mix ratio of 1:1.5:3. From the static load-deflection behavior, it implies that the flat-plate system (i.e., M1) could be more vulnerable than other two slab systems (M2 and M3).

The dynamic response of the un-retrofitted (UR) and retrofitted (RF) models made with unconventional concrete mix ratio of 1:1.5:3 and 1:2:4 are tested for the duration of 15, 20 and 25 sec, presented in Fig. 3. In general, the un-retrofitted tests show that the flat-plate

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has exhibited a bit higher displacement than the other two slab models. This is more pronounced when the duration of the test is decreased (e.g., 15 sec). This is happening for the lower stiffness of flat-plate (M1) than M2 and M3. During the dynamic tests, the flat-plate system suffered with crack for concrete mix ratio of 1:2:4 (see Fig. 4 (left)). Similar, behavior is also observed for M2 model with the concrete mix ratio of 1:1.5:3 (see Fig. 4 (right)). Meanwhile, no similar cracking or damage is observed for M3. The behavior is in good agreement with the static test since higher deflection is observed for M1 than other models (M1 and M2).

As regards retrofitted tests, it can be noticed that the dynamic responses of retrofitted models are better than the un-retrofitted models. In all retrofitted slab models, even if higher displacement is observed, none of the retrofitted models have damaged or collapsed. While the un-retrofitted models M1 and M2 are partially damaged (see Fig. 4) and few have collapsed (see Table 2). From this observation, it can be said that the retrofitted models are more ductile than the un-retrofitted models. This behavior could be explained by the additional tensile strength provided by the steel wire mesh of ferrocement. Indeed, the ductility of the structure is one of the main key parameters which could provide more deflection and can give warning to the peoples inside the building to escape during earthquake.

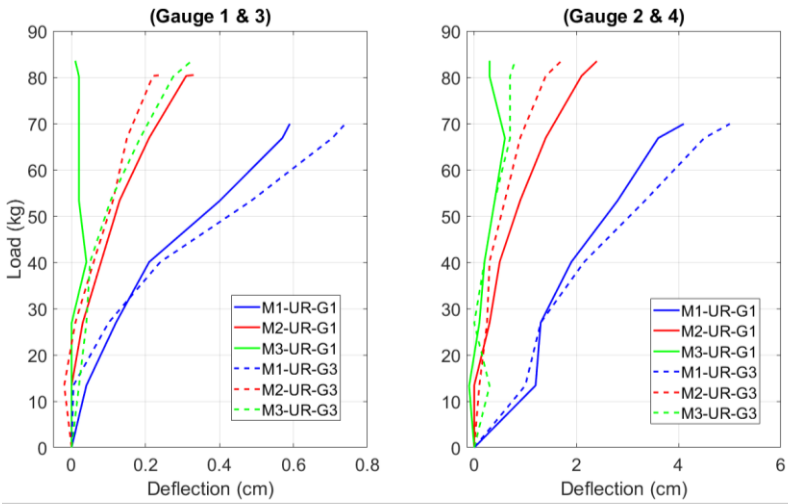

Figure 2. Static load-deflection behavior of slab models made with an unconventional concrete mix ratio of 1:2:4.

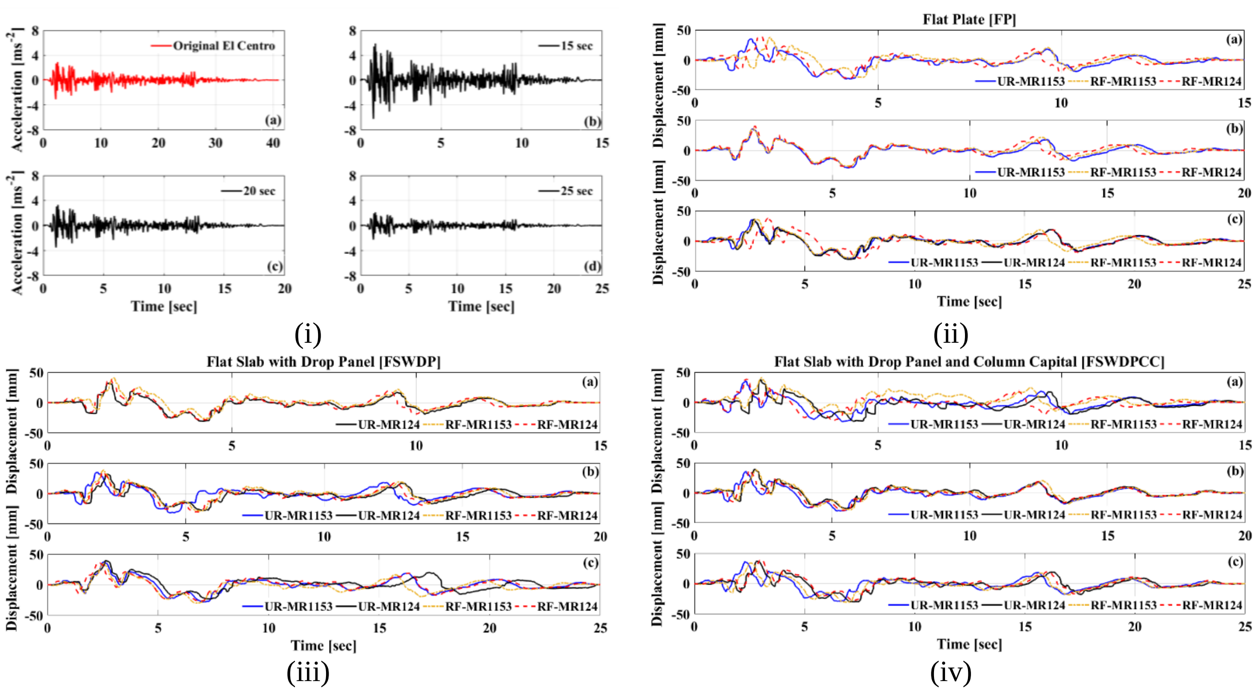

Figure 3. (i) Input excitations; (ii-iv) displacement of un-retrofitted (UR) and retrofitted (RF) slabs made with mix ratios of 1:1.5:3 (MR1153) and 1:2:4 (MR124) for 15, 20 and 25 sec, respectively.

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TABLE II. COMPARISON OF MAXIMUM AND MINIMUM PEAK VALUES. (*STRUCTURE HAS FAILED).

		Un-retrofitted				Retrofitted			
		Experimental $^{(+)}$ (mm)		Experimental $^{(-)}$ (mm)		Experimental $^{(+)}$ (mm)		Experimental $^{(-)}$ (mm)	
Models	Time (sec)	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
M1	15	*	35.9	*	-30.3	38.5	38	-30.1	-28.5
	20	*	34.2	*	-28.8	40.2	35.5	-28.2	-25.9
	25	35.4	35.4	-30.2	-27.2	39.5	35.8	-28.4	-27.6
M2	15	31.6	*	-23.7	*	38.1	40.6	-28.9	-26
	20	32.4	35	-27.8	-30.8	35.4	38.8	-30.3	-28.7
	25	39.4	35.6	-23.1	-28.5	35.9	35.3	-26.3	-29.9
M3	15	37.3	35	-31.3	-31.1	38.1	41.3	-30.1	-18.9
	20	39.3	34	-25.9	-29.7	36.8	38.1	-28.7	-27.2
	25	36.7	35.4	-29.7	-28.7	39.2	34.1	-26.8	-30.5

Figure 4. Damage behavior of M1-UR of concrete mix ratio of 1:2:4 after 25 sec dynamic test (left) and M2-UR of concrete mix ratio of 1:1.5:3 after 20 sec dynamic test (right).

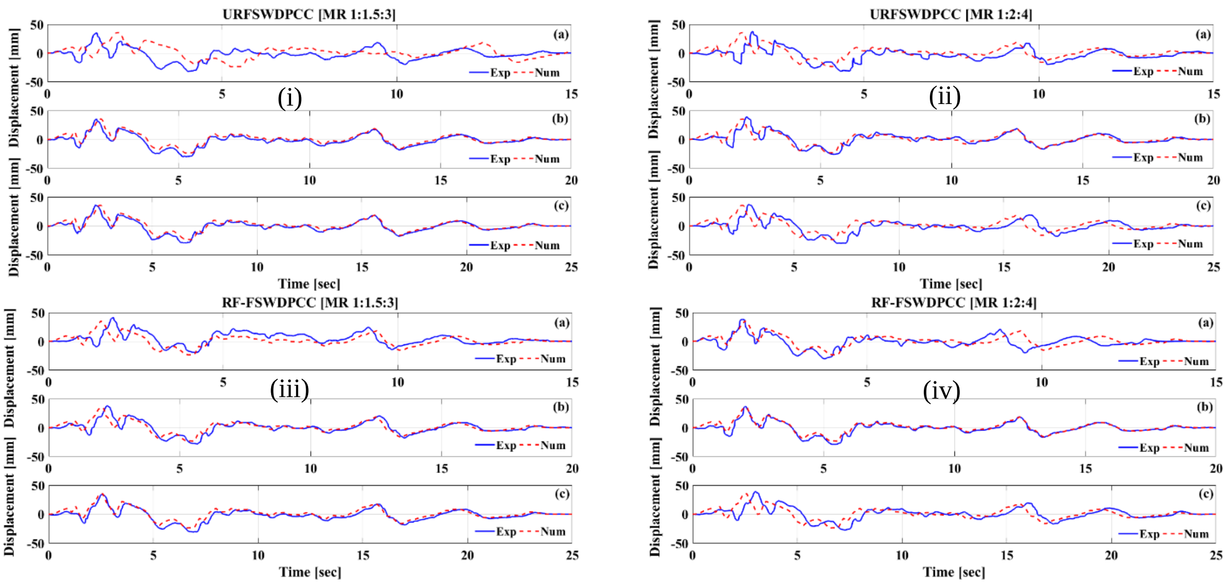

Figure 5. Comparison between experimental and numerical response of un-retrofitted flat-slab with drop panel and column capital (URFSWDPCC) made with concrete mix ratio of 1:1.5:3 and 1:2:4 in (i)-(ii) and retrofitted in (iii)-(iv) tested for 15, 20 and 25 sec respectively.

As expected, the concrete slabs made with mix ratio of 1:2:4 exhibits higher displacement than the mix ratio of 1:1.5:3. As an example, the maximum positive response determined during the dynamic tests of retrofitted flat-plate, flat-slab with drop panel, and flat-slab with drop panel and column capital are, respectively, 39.5 mm, 35.9 mm and 39.2 mm for mixing ratio of 1:2:4, while 35.8 mm, 35.3 mm and 34.1 mm for mixing ratio of 1:1.5:3 accordingly (see Table 2). This behavior can be explained by the compressive strength of two different concrete ($fc_{28days} \approx 10$ MPa for mix ratio of 1:2:4 and $fc_{28days} \approx 15$ MPa for mix ratio of 1:1.5:3 respectively). Further, this behavior also could be due to dense microstructure and strong interfacial transition zone between the cement paste and aggregates of concrete made with mixing ratio of 1:1.5:3 than the concrete made with the mixing ratio of 1:2:4. However, among three different test duration, the response of 15 sec seems to be more vulnerable rather

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than the responses for 20 sec and 25 sec because of its higher displacement, see Table II.

In order to validate the experimental results obtained for M1, M2 and M3 models, the linear time history analysis is performed via SAP2000 where the same input force as experimental tests are used. The numerical simulations are performed for both un-retrofitted and retrofitted slab models. The comparison of numerical and experimental results for un-retrofitted and retrofitted flat-slab with drop panel and column capital made with two different mix ratios (i.e., 1:1.5:3 and 1:2:4) are compared in Fig. 5 respectively.

Almost all of the cases, numerically obtained results show quite good agreement with the experimentally measured results for tests duration of 15, 20 and 25 sec accordingly. Since most of the numerical results are in good agreement with the experimental results, hence only the results of M3 is presented herein. It can be noticed that for some cases, when the intensity of the tests are increased (i.e., decrease the test duration), the peak of the displacement obtained from numerical analysis is delayed then the experimental one. Also, the peak displacement is a bit lower than the experimental results. Despite the aforementioned discrepancies, similar behavior is observed in un-retrofitted and retrofitted results.

IV. Conclusion

This study examines the static and dynamic performances of retrofitted and un-retrofitted flat-plate and flat-slabs made with unconventional concrete (≈ 10 and ≈15 MPa at 28 days) both experimentally and numerically. The dynamic tests are conducted via shake-table by employing the El Centro 1940 earthquake data. Later, the simulations are performed by using SAP2000 considering same input loads. In a nutshell, quite good agreement between experimental and numerical results are observed. It can be concluded that the early mentioned model M3 showed superior performances under both static and dynamic tests as compared to the other two models (i.e., M1 and M2). It is also observed that M1 and M2 models are more vulnerable in punching shear type failure than flexural failure. Additionally, it is noticed that the retrofitted models are more ductile than the un-retrofitted models probably due to additional tensile strength provided by the steel wire mesh of ferrocement. Indeed, the ductility of the structure is one of the key parameters that can play an important role during earthquake which can be improved by using ferrocement. Among those two mix ratios, the specimens with mix ratio of 1:1.5:3 performed better than the mix ratio of 1:2:4 due to inherent mechanical properties of concretes. Ferrocement technique has several advantages such as cost-effectiveness, locally available materials, available workmanship (i.e., unskilled workers), light in weight and efficient construction time and so on. Therefore, it could be recommended to use ferrocement technique for strengthening the structures to mitigate the sudden collapse due to earthquake.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, methodology and writing—original draft by M. S. Miah; and reviewing and results preparation is contributed by M. J. Miah.

Acknowledgement

The authors would like to acknowledge the financial support of the IEERD (Ref: IEERD/AC/17) at UAP.

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