Seismic Evaluation of the RC Moment Frame Structure using the Shake Table

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Abstract-This paper presents the findings of an experimental investigation on a reinforced concrete frame structure (ordinary moment resistant frame). The test model was subjected to lateral excitation employing the 1994 Northridge earthquake accelerogram. The reinforced concrete test model was fabricated in 1:3 reduced scale acquiring dimensional similarities. The utilized ingredient mix ratio was 1:1.65:1.75 and the water to binder ratio was 0.47. The dynamic characteristics (natural frequency and elastic viscous damping) were calculated using the free vibration record. Story shear, drift, and displacement profiles were drawn using multiple excitation records along with damage patterns and capacity curves. The natural frequency of 2.47Hz was calculated for the test specimen, which is equivalent to 1.41Hz for the prototype. Structural damping (elastic viscous) of 12.36% was calculated for the prototype.

Keywords-shake table testing; inter-story drift; story displacement; story shear; damage mechanism

I. INTRODUCTION

The construction growth rate of Reinforced Concrete (RC) buildings is globally increasing. RC construction is primarily used in high raised and multi-story buildings such as hospitals, schools, and residential projects [1]. Shake table testing is used to investigate the performance of both full and reduced scale test models. Seismic response parameters, dynamic characteristics, and damage behavior can be examined for the test model if subjecting it to lateral loads on a shake table [2, 3]. The evaluation of dynamic characteristics and response parameters is important in seismic analysis and design of structures [4-6]. Dynamic characteristics and response parameters of a 3D panel system were explored in [7], where the test specimen was scaled down as per the available payload capacity of the shake table. This work fabricated a reduced scale model of a typical prototype in Pakistan for evaluating its response under lateral loads. In general, construction/design flaws comprise of poorer quality of concrete (low compressive strength), joints lacking ties, reduced flexural reinforcements in beam and column members, spacing of shear reinforcement larger than those specified in code, and avoiding seismic hooks [3, 8]. Structures built with those deficiencies in high seismic zones are adversely affected by seismicity, leading to disastrous failures and consequent human and economic losses [9-11]. During model construction, concrete cylinders were also fabricated for evaluating compressive strength. This study was carried on a reduced scale reinforced concrete frame structure, subjected to lateral loads using a shake table. The model was first subjected to free vibration on the shake table (jerks) for the assessment of its dynamic characteristics (fundamental vibration period and structural damping), as in previous research studies [12]. The free vibration test was followed by dynamic testing using multiple runs of low to moderate and then sever excitations, i.e. from 5% to 100% of the 1994 Northridge earthquake accelerogram. The time history of the 1994 Northridge earthquake and some of its features were produced in detail [13]. The seismic assessment of RC frame structures using shake table reveals the viability of model configuration and material selection and checks the responses of other under-designed and code incompliant specimens [14-16].

II. FABRICATION OF THE TEST SPECIMEN

The test model is a representation of the typical prototype (two storys, one bay in the x- and two in the y-direction) in Pakistan. The plan view of the prototype is shown in Figure 1. The middle frame was considered to have one bay and two storys as shown in Figure 2. High-grade reinforcement steel (ASTM, A615, Grade 60) was used. In the superstructure, the deformed bars i.e., Ø4mm (#1) and Ø7mm (#2) were used as required by the dimensional analysis, as the model was fabricated on a reduced scale [17]. The fabricated RC test specimen was identical to the typical frame (prototype) structure [18]. The beams were 304.8×457.2mm (12×18in),

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reinforced with 2Ø20mm (2#6) top/bottom main/longitudinal bars, and Ø10mm (#3) stirrups provided at 229mm center-to-center distance. Columns of the frame had dimensions of 304.8×304.8mm, were reinforced with 8Ø20mm (8#6) main/longitudinal reinforcement and provisioned with Ø10mm (#3) stirrups provided at 229mm center-to-center distance. The fabricated test specimen was lacking lateral ties in the beam-column joint [19]. The reinforcement and geometric detailing of the frame under consideration were identical to those of Model-5 previously evaluated in [18, 20, 21]. The corresponding structural detailing for the test specimen is shown in Figures 2 and 3. It is worth mentioning that during the construction of each story, three standard concrete cylinders were also fabricated for compressive strength evaluation as shown in Figure 4.

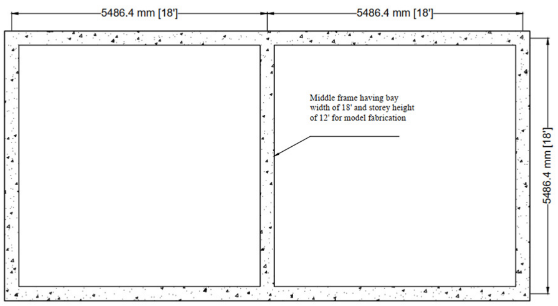

Fig. 1. Prototype plan configuration.

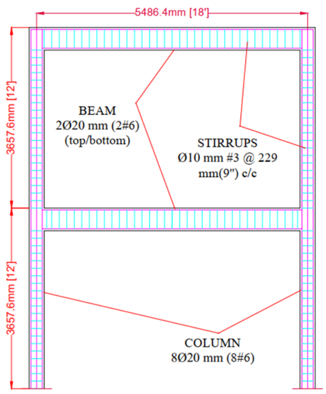

Fig. 2. Prototype elevation and structural detailing.

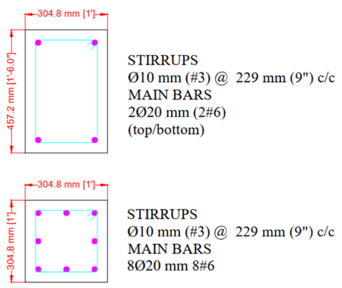

Fig. 3. Beam and column section detailing (prototype).

Five displacement transducers and five accelerometers were installed at appropriate locations on the model to record the displacement and acceleration response. Similitude scale factors were used in data analysis for converting the parameters in respect of the prototype [22]. Story shear, drift, and displacement profiles were plotted for each story in each run, as in [23]. The displacement versus base shear curve was also plotted to reveal the deformation capacity of the test specimen. The fabricated cylinders were tested using a Universal Testing Machine. The average compressive strength for the concrete was calculated as 29.27MPa.

Fig. 4. Standard concrete cylinders.

TABLE I. TEST RUNS

Load tons (kip)	Area mm^2 (in^2)	Strength MPa (ksi)	Average MPa (ksi)
58.4 (128.48)	18248.99 (28.29)	31.37 (4.55)	29.27 (4.25)
60.2 (132.44)	18248.99 (28.29)	32.34 (4.69)	
52.4 (115.28)	18248.99 (28.29)	28.15 (4.08)	
57 (125.40)	18248.99 (28.29)	30.62 (4.44)	
47.5 (104.50)	18248.99 (28.29)	25.52 (3.70)	
51.4 (113.08)	18248.99 (28.29)	27.61 (4.01)	

III. EXPERIMENTAL SCHEME

A. Shake Table

The test specimen was subjected to lateral loads on the shake table test available at the Earthquake Engineering Centre, University of Engineering and Technology, Peshawar, Pakistan as shown in Figure 5. Some recent studies on the response of an RC model subjected to lateral loads were also used [19, 24].

B. Instrumentation

After anchoring the model on the shake table, transducers and accelerometers were installed at various locations. One accelerometer was installed at the center of the pad of the model and one at the right/left corner through the centerline of each slab. Similarly, displacement transducers were installed on the reference frame at an appropriate location. Details of instrumentation are shown in Figure 5.

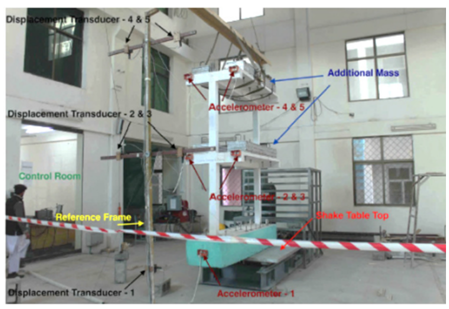

Fig. 5. Instrumentation plan of the test specimen.

C. Time History and Testing Protocol

The accelerogram of the 1994 Northridge earthquake (Figure 6), was utilized for dynamic simulation of the test model having a PGA of 0.57g.

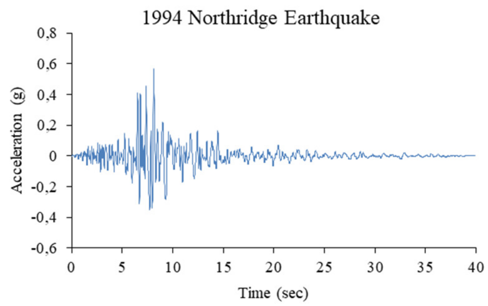

Fig. 6. Acceleration time history (Northridge 1994)

The testing protocol, shown in Table II, comprised of free vibration and multiple excitations (dynamic runs). The purpose of multiple excitations was to simulate the specimen from low to moderate and then severe (disastrous) shaking. In each run, damages were also examined to notice the adequacy of the Ordinary Moment Resistant Frame (OMRF) structure under the lateral loads on the shake table.

TABLE II. TEST RUNS

Time History	Intensity
1994 Northridge	Free vibration
	Self-check (jerks)
	5%
	10%
	20%
	30%
	40%
	50%
	60%
	70%
	80%
	90%
	100%

IV. RESULTS

A. Data Analysis

SeismoSignal was used for the filtering and base-line correction of the data recorded in each run, as employed in [18, 25, 26]. After base-line correction and noise removal the corrected data were analyzed using Microsoft Excel for the calculation of dynamic characteristics, story shear, inter-story drift, displacement profile, etc. Deformation versus base shear curve was also plotted using multiple run records.

B. Dynamic Characteristics

Recorded data were used to evaluate the dynamic characteristics, story shear, drift, and displacement profile. The fundamental frequency was calculated as 2.47Hz (0.41s) for the test specimen, as shown in Figure 7. This indicates the prototype fundamental duration of vibration calculated using a similitude factor of: $\sqrt{3} \times 0.41 = 0.71s$

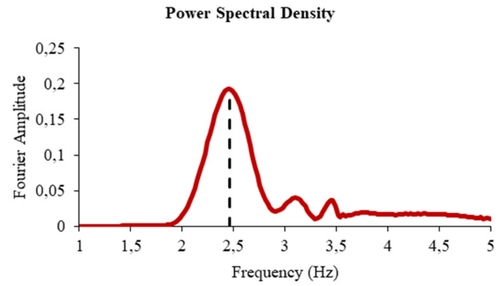

Fig. 7. Fundamental frequency of the test specimen.

Elastic viscous damping was calculated using the decay function proposed used in [27]:

$$\zeta = \frac{1}{2n\pi} \times \mathrm{Ln}(A_1/A_n)$$

where ζ is the coefficient of elastic-viscous structural damping, A_1 is the peak amplitude of displacement at the reference point 1, A_n is the peak amplitude after n cycles at the reference point, and n the number of cycles between the considered peaks. The measured damping based on the last two cycles of displacement response is shown in Figure 8. The structural damping measured was 12.36% for the frame.

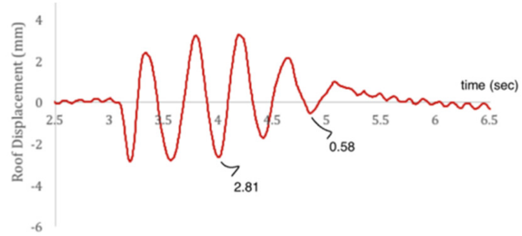

Fig. 8. Free vibration test for calculation of damping.

C. Inter-story Shear

The inter-story and base shear was measured using the records from multiple runs. The stiffer the structural system, the higher is the amount of shear and moment it absorbs. The base shear increased while subjecting the model to moderate and then sever intensity excitations in comparison to low intensity runs. This means that the base shear demand is high in case of sever shaking. The observed base and story shear are shown in Figures 9, 10, 11, and 12 for some selected runs.

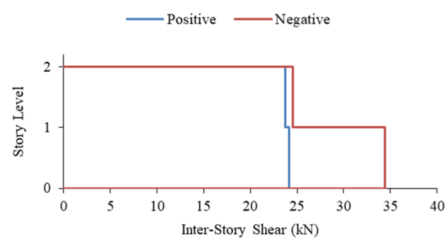

Fig. 9. 20% excitation of the 1994 Northridge earthquake.

D. Inter-story Drift Profile

Inter-story drift was calculated while normalizing the story displacement at story levels. Drift increased from low to moderate and then high as shaking intensity increased from 5% to 100%. Both positive and negative drifts were calculated for all runs. The profiles are shown in Figures 13-16 for some selected runs. A drift value greater than 2.5% indicates increased danger, while drift greater than 10% means the overall collapse of the structure.

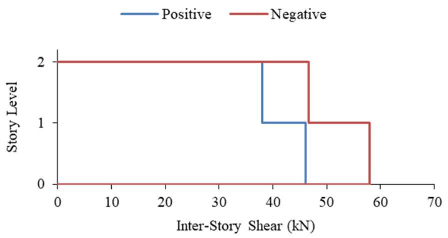

Fig. 10. 30% excitation of the 1994 Northridge earthquake.

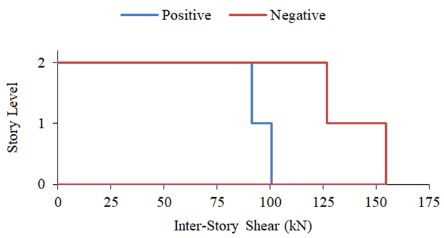

Fig. 11. 80% excitation of the 1994 Northridge earthquake.

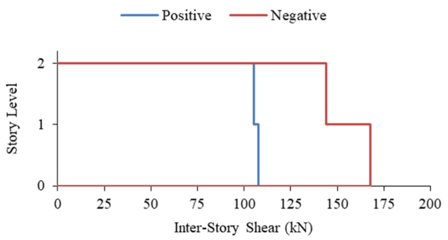

Fig. 12. 100% excitation of the 1994 Northridge earthquake.

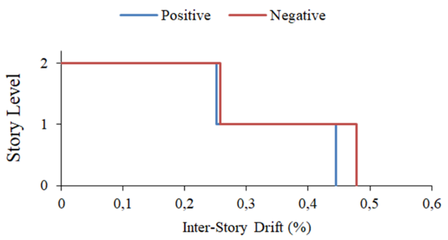

Fig. 13. 20% excitation of the 1994 Northridge Earthquake.

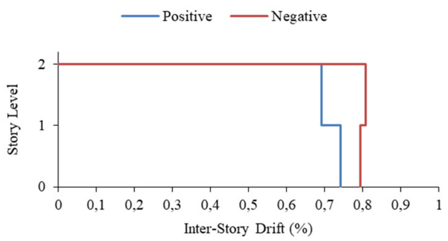

Fig. 14. 30% excitation of the 1994 Northridge Earthquake.

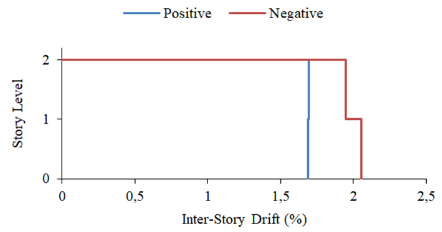

Fig. 15. 80% excitation of the 1994 Northridge earthquake.

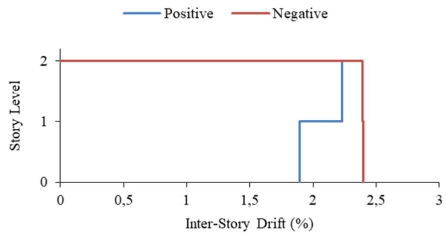

Fig. 16. 100% excitation of the 1994 Northridge earthquake.

E. Inter-story Displacement Profile

Multiple records of dynamic excitations were analyzed and processed for story displacement profiles. Both in negative and positive direction, the displacement profiles were plotted as shown in Figures 17-20 for some selected runs. It can be observed that high-intensity shaking caused large lateral displacement on the model.

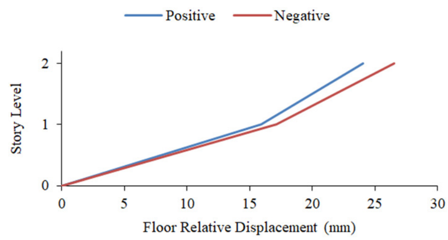

Fig. 17. 20% excitation of the 1994 Northridge earthquake.

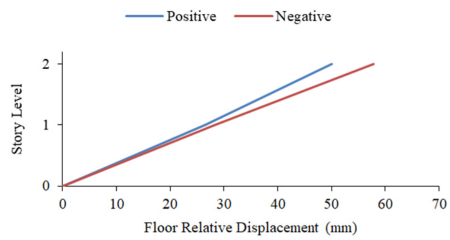

Fig. 18. 30% excitation of the 1994 Northridge earthquake.

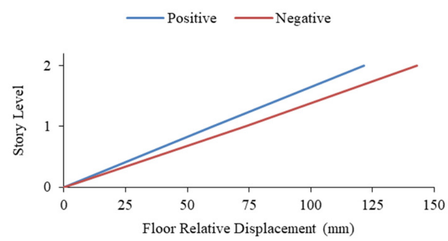

Fig. 19. 80% excitation of the 1994 Northridge Earthquake.

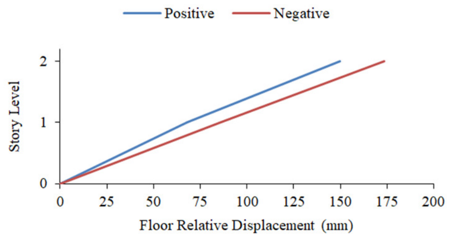

Fig. 20. 100% excitation of the 1994 Northridge earthquake.

F. Capacity Curve

The capacity curve [28-30] is plotted in Figure 21. The idealized elastic-plastic curve using the energy balance equation was also drawn to pinpoint the equivalent value for ultimate displacement and the corresponding base shear, as used in [30].

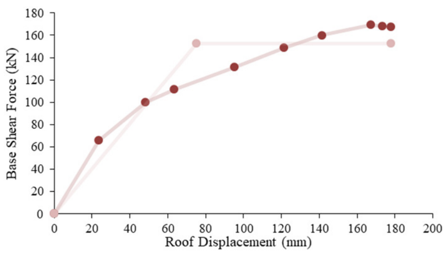

Fig. 21. Capacity curve of the tested specimen under shake table testing.

The details of the top floor displacement and the corresponding base shear are given in Table III for various intensity excitations of the 1994 Northridge earthquake.

TABLE III. DISPLACEMENT AND BASE SHEAR

Run Level	Displacement mm (in)	Base shear kN (kip)
Self-check-1o	23.47 (0.92)	66.06 (14.85)
Self-check-1a	48.35 (1.90)	100 (22.48)
Self-check-1b	63.35 (2.94)	111.7 (25.11)
Self-check 1	95.16 (3.75)	131.14 (29.48)
50%	121.59 (4.79)	148.72 (33.44)
60%	141.46 (5.57)	159.95 (35.96)
90%	167.18 (6.58)	169.34 (38.07)
100-1%	173.26 (6.82)	167.68 (37.70)
100-2%	177.94 (7.00)	167.61 (37.68)

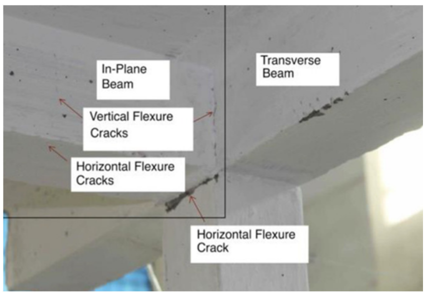

Fig. 22. Vertical and horizontal flexural cracks in in-plane beam.

G. Damage Mechanism

No damages and cracks were noticed during low-intensity runs. Upon moderate-intensity runs, cracks were produced in the beams at the ground and first floor. During the sever excitation, the existing cracks were further aggravated. Figures 22-24 show a few cracks and damages marked. Figure 25 shows the spalling of concrete from the peripheral beam-column joint along with minor damages.

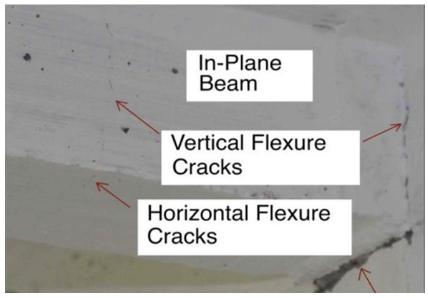

Fig. 23. Distribution of cracks beam (in-plane).

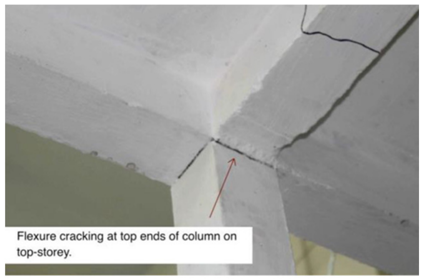

Fig. 24. Flexural cracks at the top end of a column.

Fig. 25. Spalling of concrete.

V. CONCLUSION

This work presented the seismic response evaluation of RC moment resisting frame structures on 1/3 scale reduced model via shake table testing. The response of the test model under uni-directional lateral excitations was obtained in terms of dynamic characteristics profiles for inter-story shear, and displacement drift. Damage mechanism and prototype model capacity curves were also obtained. The following findings were noticed:

- The calculated natural period of vibration and elastic-viscous damping for the prototype were 0.71s and 12.36% respectively.
- The base and inter-story shear were higher in the high-intensity excitation runs in contrast to low-intensity excitations.
- It was also evident that the calculated story displacement and drift were within limits. The highest drift noted was

less than 2.5%. Moreover, in high intensity runs, displacement and drift were higher than moderate and low-intensity runs.

- The ultimate floor displacement of 177.94mm and the base shear of 152.406kN for the prototype were calculated as predicted in the idealized elastic-plastic curve.
- Cracks and damages at low-intensity excitations were absent, however, the cracks produced at moderate excitation runs were further widened along with spalling of concrete at sever excitations.

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