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Seismic Fragility Evaluation of a Moment Resisting Reinforced Concrete Frame

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ABSTRACT
This study examines the seismic behavior of a seven-storey moment resisting reinforced concrete frame under 9 different ground motion (GM) records through incremental dynamic analysis (IDA). The IDA results allowed a thorough understanding of changes in the structural response as the intensity of the GM increases. The selected earthquake hazard is based on maximum considered earthquake ground motions. The seismic performance is quantified through nonlinear collapse simulation on a set of archetype models developed in SeismoStruct. The drift behavior, record-to-record variability of the response and height-wise distribution of drift demand were reported. On the other hand, for collapse evaluation, ground motions are systematically scaled to increasing earthquake intensities until median collapse is established and analyzed the model as a form of IDA. Using collapse data obtained from IDA results, the collapse fragility curve defined through a cumulative distribution function, which related the ground motion intensity to the probability of collapse.

Keywords: Incremental dynamic analysis, seismic capacity, inter-storey drift, reinforced concrete structure.

1. Introduction

Reinforced concrete (RC) is concrete that contains embedded steel bars, plates, or fibers having higher tensile strength and/or ductility that strengthen the concrete's relatively low tensile strength and ductility [1-5]. Reinforced materials are embedded in the concrete in such a way that the two materials resist the applied forces together. In reinforced concrete, the tensile strength of steel and the compressive strength of concrete work together to allow the member to sustain tensile, shear and compressive stresses over considerable spans [4]. Such a material can be used for making any size and shape, for utilization in the construction. The worldwide use of reinforced concrete construction stems from the wide availability of reinforcing steel as well as the concrete ingredients [2]. With the rapid growth of urban population in both the developing and the industrialized countries, reinforced concrete has become a material of choice for residential construction [5].

In the consequence, RC frames consist of horizontal elements (beams) and vertical elements (columns) connected by rigid joints. These structures are cast monolithically- that is, beams and columns are cast in a single operation in order to act in unison. RC frames provide resistance to both gravity and lateral loads through bending in beams and columns. On the other hand, moment-resisting frames are rectilinear assemblages of beams and columns that resist forces by bending. In moment resisting frames, the joints, or connections, between columns and beams are designed to be rigid [2,,5]. The bending rigidity and strength of the frame members is the primary source of lateral stiffness and strength for the entire frame. Resistance to lateral forces is provided primarily by rigid frame action-that is, by the development of bending moment and shear force in the frame members and joints [1]. At a rigid joint, the ends of the columns and beams cannot rotate. This means that the angle between the ends of the columns and beams always remain the same. This causes the columns and beams to bend during earthquakes depending on the geometry of the connection [4]. Therefore, these structural members are designed to be strong in bending. Frequently, reinforced concrete construction is used in regions of high seismic risk. By virtue of moment resistance frames, rigid joints should be designed carefully to make sure they do not distort [2,4]. However, the 1994 Northridge earthquake revealed a common flaw in the construction, and building codes [2].

There is a lack of information about the dynamic performance of RC moment resistance frames. Thus, the progress and adoption of moment resistance frames, particularly in practice, has been hindered by the lack of performance-based criteria and design methodology for this type of structural system. To address this issue and examine the seismic response of this system under different earthquake records, incremental dynamic analyses (IDAs) were performed on seven-storey RC frame. The IDA results allowed a thorough understanding of changes in the structural response as the intensity of the Ground Motion (GM) increases. For collapse evaluation, ground motions are systematically scaled to increasing earthquake intensities until median collapse is established and analysed the model as a form of IDA. Using collapse data obtained from IDA results, the collapse fragility curve defined through a cumulative distribution function, which related the ground motion intensity to the probability of collapse.

2. Methodology

2.1 Description of the structure

In order to investigate the seismic performance of a RC moment resisting frame, a case study building was

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adopted which has 7-story, 166 m2 residential building located in Dhaka, Bangladesh (Figure 1). This structure is made of reinforced concrete frame building, is located on stiff soil and in an area in which near-fault ground motions are not prevalent (Zone 2 in [3]). In layout plan, the building has 19 m x 8.5 m and 4 bays x 2 bays (Figure 1). The long direction is oriented East-West. The building is approximately 21 m tall. The slabs are 115 mm deep. Columns in the south frame are 305 mm wide by 508 mm deep, i.e., oriented to bend in their weak direction when resisting lateral forces in the plane of the frame. Beams are generally 254 mm wide by 508 mm. The concrete has a nominal strength of 25 MPa and the reinforcement steel is scheduled as Grade 60 (400 MPa) (Table 1).

Fig.1 The studied structure: a) Full scale building, b) building layout, c) finite element model

2.2 Finite element modeling and model validation

The building was modeled in a simulation environment, SeismoStruct 5.2.2 [6] for analysis considering a 2D interior frame in the East-West direction. The concrete and steel materials were modeled using the built-in models in SeismoStruct. For instance, Menegotto-Pinto steel model and Mander et al. nonlinear concrete model were implemented [6]. On the other hand, RC rectangular sections were used to model the beam and column sections. The beams were divided longitudinally into 5 elements and each beam and column element was divided transversely into 300 by 300 fiber elements. The model was validated against the time period of the structure as calculated according to BNBC code. In the current study, the time period was 0.47 second which is about 2% lower than the code value.

Table 1 Material properties.

Materials	Properties	Values
Concrete	Compressive strength (MPa)	25
	Tensile strength (MPa)	2.5
	Ultimate strain (%)	0.35
Steel	Modulus of elasticity (MPa)	200000
	Yield strength (MPa)	400
	Strain hardening parameter (α)	0.5

3. Incremental dynamic analysis

This study examines the seismic behavior of seven-storey RC moment resisting frame under 9 different ground motion (GM) records through incremental dynamic analysis (IDA). The IDA results allowed a thorough understanding of changes in the structural response as the intensity of the GM increases. The drift behavior, record-to-record variability of the response and height-wise distribution of drift demand were reported.

3.1 Selected ground motion records

A set of 9 GM records were used to conduct nonlinear incremental dynamic time history analyses on the moment resisting reinforced concrete frame model. The GM records were selected in a bin of relatively large magnitudes of 5.5– 7.6. Soil type C was considered for all the records. The selected ground motions were scaled with the Dhaka response spectrum. The ground motions are matched with Dhaka spectrum using SeismoMatch software [6]. A typical time history records for the unscaled and scalded records are shown in Figure 2. The spectrums of the unscaled and scaled records are shown in Figure 3. These GMs are presumed to be representative of events that have the potential to cause severe GMs at the considered location [7,8].

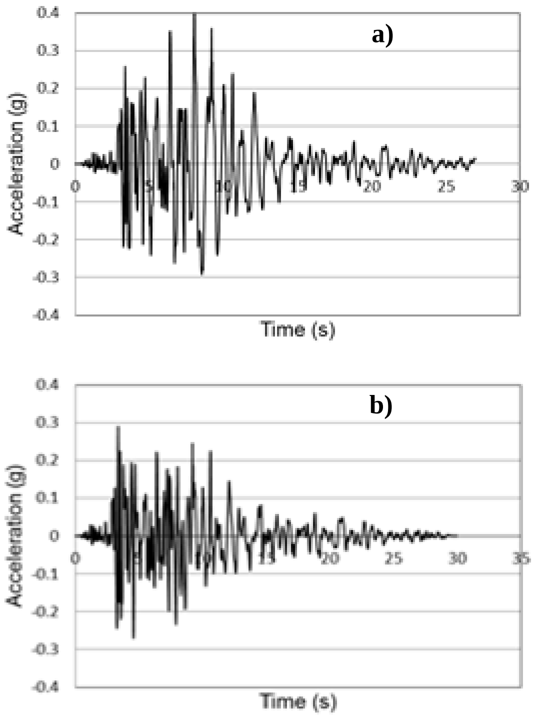


Fig.2 A typical earthquake record: a) unscaled, b) scaled

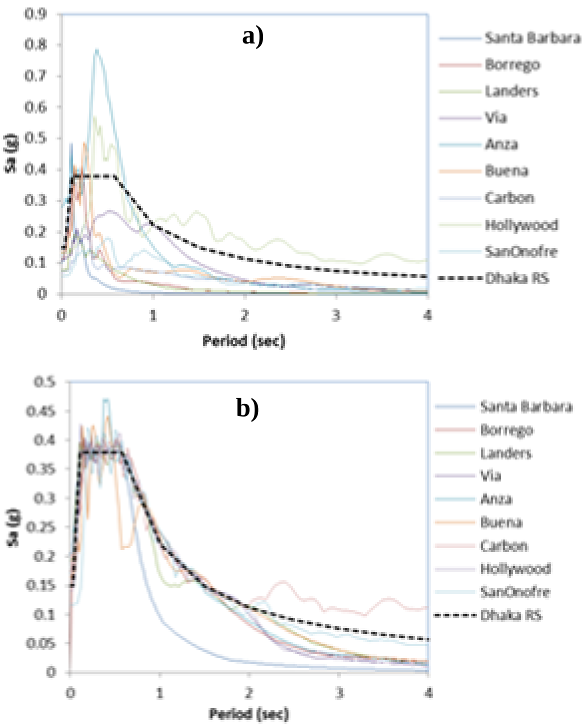


Fig.3 The ground motion records with Dhaka response spectrum: a) unscaled, b) scaled

4. Results and discussion

The IDA method was studied to examine the response of the RC moment resisting frame subjected to varied earthquake excitations. The IDA technique was developed in detail by [9]. IDA involves performing a series of nonlinear time history analyses on the modeled structure subjected to one or more GM records [8]. Each record is scaled to several intensity levels so as to cover the entire range of structural response, from elastic behavior through yielding to collapse (or until a defined 'failure' limit state occurs) [9]. In this study, the 5% damped spectral acceleration at the fundamental mode period of the structure, Sa(T1, 5%), was used as an intensity measure. In order to examine the structural response of the frame under earthquake excitations, the maximum inter-storey drift (MID) ratio were selected as damage measures. It should be noted that the inter-storey drift ratio was defined as the relative displacement of each storey divided by the storey height. Moreover, the analysis was continued until Sa =2.4g or until numerical non-convergence occurred which indicated the global dynamic instability.

4.1 Inter-storey drift ratio

The nonlinear time history analyses were conducted on the modeled frame, from which the IDA curves shown in Figure 4 are generated. The inter-storey drift ratio was computed as the difference in the displacements of two immediate floor levels divided by the height of that floor [7]. The IDA curves display the full range of behavior, showing quite large record-to-record variability. On the basis of the plot of Sa(T1, 5%) versus inter-storey drift ratio, the frame experienced a wider range of response measured as inter-storey drift. The IDA curves start as a straight line signaling the linear elastic range which stays straight up to 1.5% inter-storey drift ratio (Figure 4). Then the tangent slope changes as a result of nonlinearity. It is worth mentioning that the larger dispersion of the demand measure implies the necessity for considering a sufficient number of Ground motion records.

By increasing the intensity of earthquakes, the inter-storey drift ratio is also increasing from a linear to nonlinear range. The analysis was performed upto a Sa=2.4 g. However, all the GMs did not reach to Sa=4.5g, while some of the records reached to dynamic instability around Sa= 3g. From the IDA curves, it is observed that the inter-storey drift demand varied in a wide range. For instance, at Sa=2.0 the inter-storey drift ratio for the 9 GMs varied from 2.2%-8.0%.

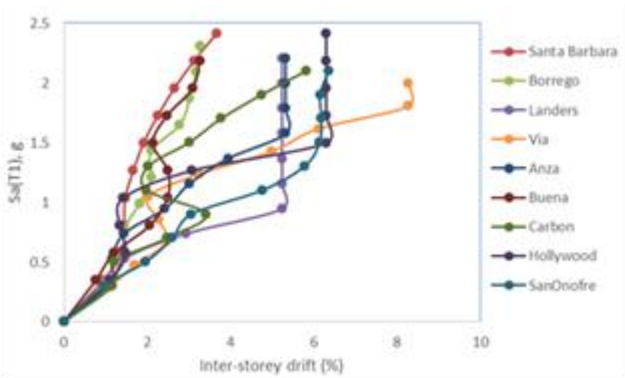


Fig.4 IDA curves for 9 ground motions

4.2 Nonlinear response along the height of the frame

In order to explore the effect of earthquake intensity on the distribution of inelasticity over the height of the building, the responses of each storey in terms of MID are provided through the use of IDA curves. Figure 5 illustrates a record-to-record specific picture of each storey subjected to earthquake records. At first storey the MID is varied linearly up to Sa= 1.5g. On the other hand, all the storey from 2nd to top floor the MID become inelastic after the design Sa (T1) = 0.7g.

In order to explore inelastic demand over the height of the building, the median values of MIDs were generated. Moreover, for each storey under the 9 GM records at three different intensity levels, i.e. Sa(T1) = 0.7g, 1.5g, and 2.1g were reported. Figure 6 show the inter-storey drift distribution along the height of the frame.

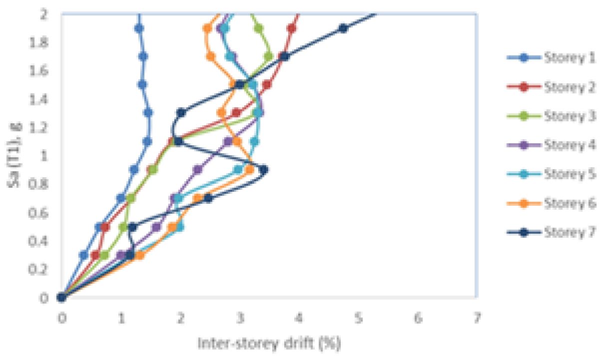
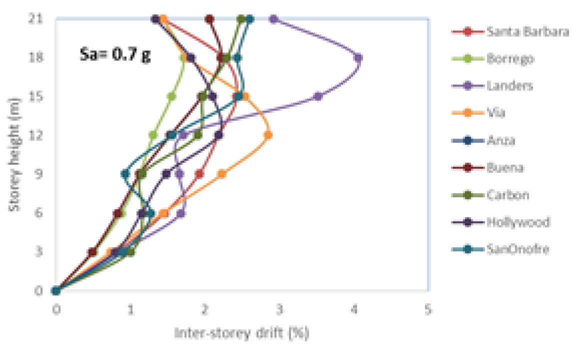


Fig.5 IDA curves for all stories

At Sa (T1)= 0.7g, the inter-storey drift at top floor varies up to 3.9% with a standard deviation of 17%. Similarly, at 1.5g and 2.1g level, the top floor inter-storey drift ratio goes up to 6% and 6.6%, respectively with a standard deviation of 23%, 42%, respectively (Figure 6). Therefore, it is observed that the variation of inter-storey drift ratio spread along the height of the frame. This is because as the intensity increases, the top storey reached to it nonlinear range.



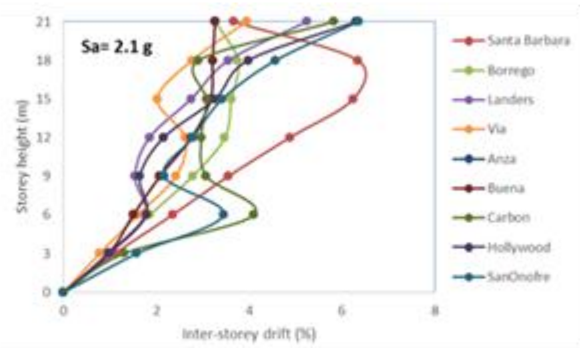


Fig.6 Inter-storey drift ratios for all stories at different Sa (T1) levels

The median inter-storey drift ratio is also plotted in Figure 7 along the height of the frame with a variation of Sa (T1). Comparing the NBCC [2] inter-storey drift limit of 2.5%, it can be concluded that the RC frame can be withstood up to Sa of 0.7g. Therefore, a strengthening scheme is necessary for the structure under severe GM excitations.

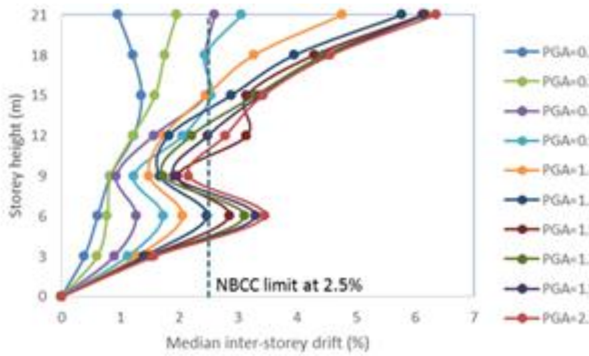


Fig.7 Median inter-storey drift ratios at different Sa(T1)

5. Seismic performance

The seismic performance of the RC moment resisting frame building was evaluated according to methodology describe in FEMA P695 [7]. The key notes to get the performance are stated below:

- Performance is quantified through nonlinear collapse simulation on a set of archetype model developed in SeismoStruct [6].
- The selected earthquake hazard is based on Maximum Considered Earthquake ground motions.
- Safety is expressed in terms of a collapse margin ratio (CMR).

5.1 Collapse margin ratio (CMR)

Safety of the studied building was expressed in terms of Collapse Margin Ratio (CMR). In order to quantify the safety, the collapse level ground motions are considered as the intensity that would result in median collapse of the seismic-force-resisting system, whereas, median collapse occurs when one-half of the structures exposed to this intensity of ground motion would have some form of life-threatening collapse.

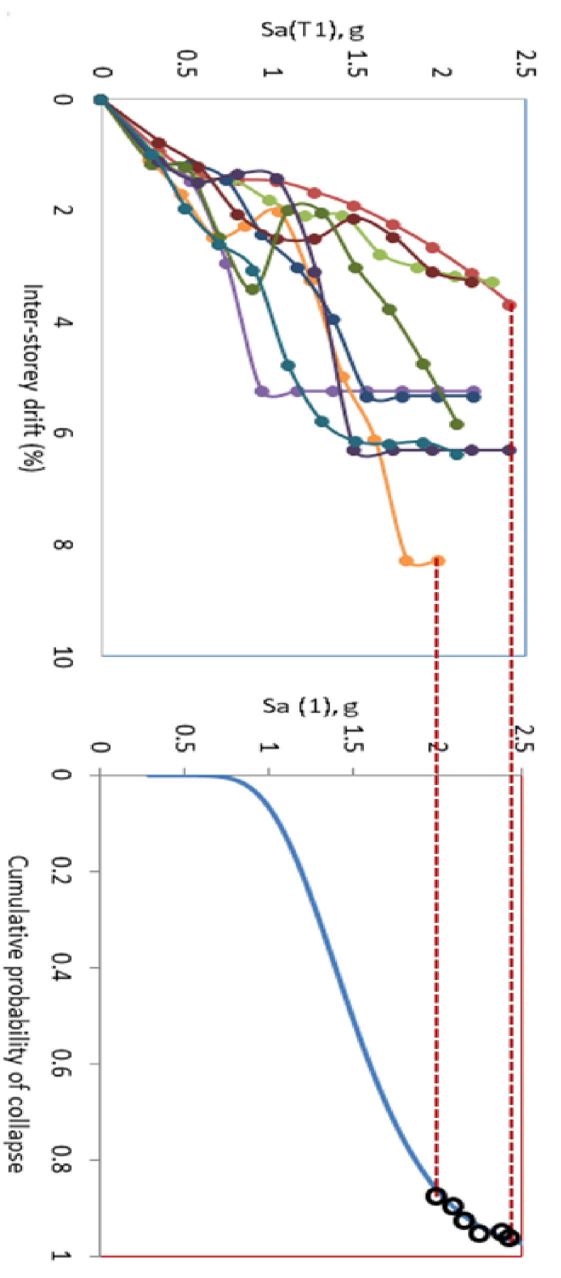


Fig.8 Incremental dynamic analysis response with the collapse fragility curve

The collapse margin ratio, CMR, is the ratio of the median 5%-damped spectral acceleration of the collapse level ground motions to the 5%-damped spectral acceleration of the MCE ground motions at the fundamental period of the seismic-force-resisting system.

For collapse evaluation, ground motions are systematically scaled to increasing earthquake intensities until median collapse is established and analyzed the model as a form of IDA. Using collapse data obtained from IDA results, the collapse fragility curve defined through a cumulative distribution function (CDF), which related the ground motion intensity to the probability of collapse. Figure 8 shows an example of a cumulative distribution plot obtained by fitting a 3 parameter lognormal distribution to the collapse data. Figure 9 shows the probability of collapse of the given structure under a given ground motion. Besides, the CMR value for the given RC moment resisting frame building is obtained as of 4.72. The value indicates the structure is safe under the design earthquake load.

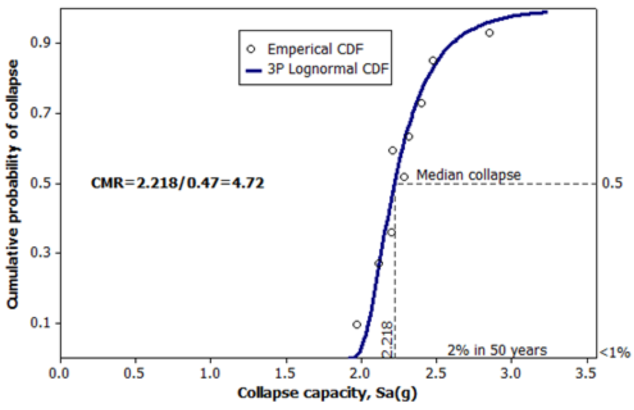


Fig.9 Collapse fragility curve

6. Conclusions

The present study provided a better understanding for the seismic performance of a RC moment resisting frame. A nonlinear incremental dynamic analysis procedure was developed in a finite element program, SeimoStruct. The results obtained discussed in the previous sections can be summarized as follows:

- From the IDA curves, it is observed that the inter-storey drift demand varied in a wide range. For instance, at Sa=2.0 the inter-storey drift ratio for the 9 GMs varied from 2.2%-8.0%.
- Comparing the NBCC inter-storey drift limit of 2.5%, it can be concluded that the RC frame can be withstood up to Sa of 0.7g.
- Structural safety is expressed in terms of a collapse margin ratio.
- The obtained CMR indicates the safe condition of the given structure.

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