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Assessment of seismic damage of multistory structures using fragility curves

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Abstract
Performance-based design, PBD, is gaining popularity and its concept hasbeen applied in many international seismic building codes. In this research, five real structures designed according to the Egyptian Building Code, which does not consider PBD, are considered and modeled in a three dimensional way using the software SeismoStruct in order to assess their performance under expected earthquakes. The structures are 2-story, 4-story, 6-story, 8-story and 10-story reinforced concrete framed structures. The structural system of these structures is of the moment-resisting frame type, with and without shear walls. The structures weredesigned under dead, live and seismic forces of "Zone 3" with a design acceleration of 0.15g.The models were analyzed using incremental dynamic analysis, IDA, considering 12 real records of historical earthquakes. IDA curves were developed for all analyzed models, considering four damage states. Fragility curves were subsequently developed to provide an overview of the expected seismic performance of a typical low or mid-rise multistory reinforced concrete framed structure in Egypt as designed in accordance with thecurrent Egyptian Building Code.
Keywords: Performance-based, seismic, fragility, Building code, Damage state

I. Introduction

Most building codes provide minimum provisions for design and construction of structures to resist potential ground motions. However, no clear definition of the expected performance orpossible damage is provided, which hampers accurate estimation of potential life and economic losses under possible earthquakes. An international trend is presently emergingtowardsdeveloping performance-based design codes to provide a comprehensible and quantitative definition for structural damage resultingfrom probable earthquakes. The emerging performance-based earthquake engineering considers the elements of design, evaluation and construction of structures with a seismic performance that must satisfy the owners and users of these structures (SEAOC 1995; FEMA356 2000). The performance level is an expression of the maximum desired extent of damage to a structure under specific earthquake.SEAOCdefined four performance levels as follows:

Fully Operational: Continuous service of the structure with negligible structural and nonstructural damage.

Operational: Most operations and functions of the structure can resume immediately after the seismic event. Damage is light.

Life Safe: Damage of the structure is moderate. Repair is possible, but may be economically impractical.

Near Collapse: Damage of the structure is severe, but structural collapse is prevented.
A performance-based design mainly depends on the fact that the structural performance can be well predicted with sufficient confidence so that the engineer and client can select the desired performance level of the structure under possible earthquakes;such level of performancewould definitely affect the design and construction of the structure.

There are many ways to assess the seismic performance of structures. Incremental dynamic analysis, IDA, is considered one of the important methods in this regard. Incremental dynamic analysis (IDA) is applied in context of the performance-based earthquake engineering in order to investigate expected structural response, damage, and financial loss under earthquakes with different intensities. IDA gives a clear vision about the performance of a certain type of structures under seismic excitations with wide range of intensities (Vamvatsikos and Cornell 2002). The IDA curves give a relationship between the maximum interstory drift ratio and the intensity of the ground motion. Many researchers have developed and used IDA curves in their research for multistory structures (Kircil and Polat 2006; Kinali and Ellingwood 2007).

IDA is considered the first step towards developing the fragility curves, which are used in the assessment of the seismic performance of structures. The fragility curves are considered useful tools for predicting the extent of probable damage under potential earthquakes. Moreover, the fragility curves can be used in decisions associated with retrofitting options, estimationof casualties and economic losses, and finally in the disaster response planning.

Fragility curves were developed by many researchers for different types of structures, includingbridges (Siqueira et al. 2014; Yang et al. 2015) and multistory buildings (Celik et al. 2010; Ji et al. 2007; Erberik 2008; Ibrahim and El-Shami 2011; Ibrahim et al. 2014).Also, fragility curves were used to assess the effectiveness of retrofitting techniques (Özel and Güneyisi 2011) and in decision-making (Williams et al. 2009).

In this research, fragility curves for typical multistory structures, designed according to the Egyptian Building Code (2008), are developed based on IDA results conducted on 3-D structural models of fivereal existing structures using SeismoStruct (2010). Twelve historic ground motions were used in the analysis and four performance levels are considered; fully operational, operational, life safe and near collapse.These fragility curves are used to assess the expected seismic performance and quantify damage of such structures under potential earthquakes. This assessment and damage quantification is not presented or well defined in current Egyptian Building Code.

II. Analyzed Structures and their Modeling

Five existing reinforced concrete structures in Egypt were selected for analysis in this research. The structures are residential buildings with a story height of 3.0 m each. The structural system of the floors is flat plates, witha slab thickness of 20cm with an upper and lower reinforcement mesh of 6 ϕ 12/m. Details of the selected structures in terms of location, number of stories and floor area are summarized in Table 1, along with the dimensions and reinforcement of their structural elements.The structures were designed according to the Egyptian Building Code with a design ground acceleration of 0.15g.

The structures were modeled using SeismoStruct. The reinforced concrete was modeled using the uniaxial constant confinement concrete model initially presented by Madas (1993). The confinement effects provided by the lateral transverse reinforcement are included through the model introduced by Mander et al. (1988), which assumesa constant confining pressure throughout the entire stress-strain range of the concrete element. The reinforcing bars were modeled using a uniaxial bilinear stress-strain model with kinematic strain hardening. In this model, the elastic range remains constant throughout the various loading stages, and the kinematic hardening rule for the yield surface is assumed as a linear function of the increment of the ensuing plastic strain. The parameters usedto model the concrete and steel materials of the analyzed structures are tabulated in Table 2 and 3, respectively. The structuralmodels are shown in Figure 1. According to the structural dynamic analysis using SeismoStruct, the first mode shape of these structures is shown in Figure 2. The natural time periods of these structures are 0.155s, 0.63s, 0.79s, 0.93s and 1.263s, respectively.

Table 1: Characteristics of the modeled structures

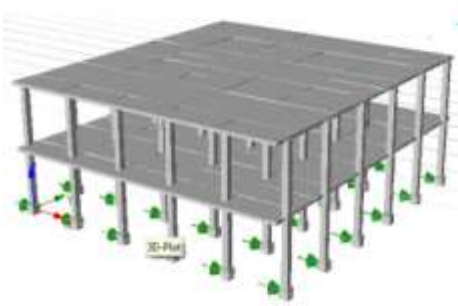
Structure No.	No. of stories	Floor Area (m^2) Location	Columns (Dimensions, reinforcement)	Shear walls (Dimensions, reinforcement)
1	2	400 Hehia Sharkia	Corner: 30 cm x 30cm, 8 ϕ 12 Edge: 30 cm x 30cm, 8 ϕ 12 Center: 30 cm x 30cm, 8 ϕ 12	None
2	4	144 Zagazig Sharkia	Corner: 30 cm x 30cm, 8 ϕ 12 Edge: 30 cm x 30cm, 8 ϕ 12 Center: 35 cm x 35cm, 8 ϕ 16 + 4 ϕ 12	None
3	6	240 Zagazig Sharkia	Corner: 30 cm x 40cm, 6 ϕ 16 Edge: 30 cm x 50cm, 8 ϕ 16 Center: 30 cm x 60cm, 10 ϕ 16	30 cm x 200cm 16 ϕ 16 at corners 6 ϕ 12/m both sides
4	8	96 Zagazig Sharkia	Corner: 30 cm x 60cm, 12 ϕ 16 Edge: 30 cm x 80cm, 16 ϕ 16	30 cm x 200cm 10 ϕ 16 at corners 6 ϕ 12/m both sides
5	10	240 10th of Ramadan Sharkia	Corner: 30 cm x 60cm, 12 ϕ 16 Edge: 30 cm x 80cm, 16 ϕ 16 Center: 30 cm x 100cm, 20 ϕ 16	30 cm x 200cm 16 ϕ 16 at corners 6 ϕ 12/m both sides

Table 2: Concrete Properties

Property	Value
Compressive strength	25 MPa
Tensile strength	0
Strain at peak stress	0.002
Confinement factor	1.1
Unitweight	25 (kN/m³)

Table 3: Reinforcing Steel Properties

Property	Value
Modulus of elasticity	2.1E+5 (MPa)
Yield strength	350 (MPa)
Strain hardening parameter	0.005
Unitweight	78 (kN/m³)



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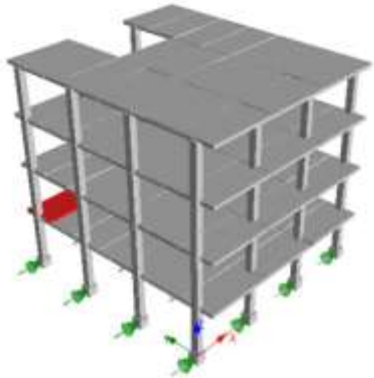

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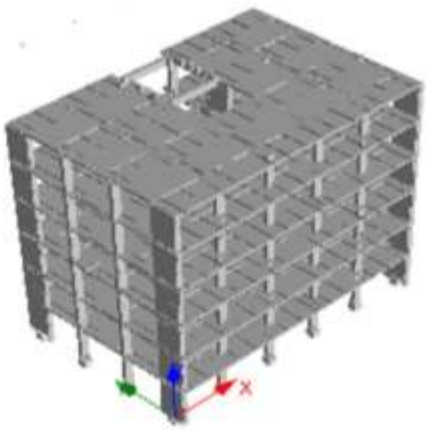

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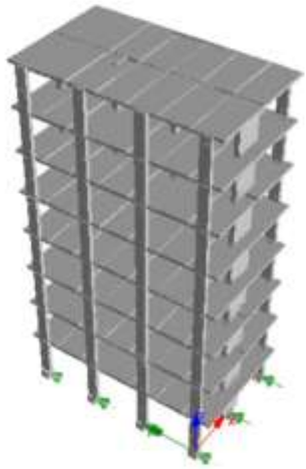

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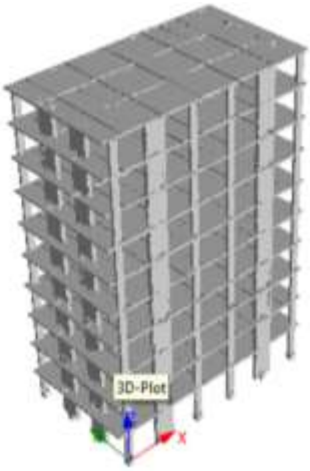

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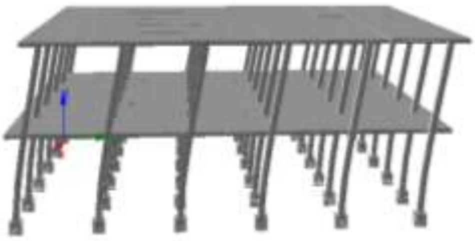
Figure 1: Structural models used in the analysis



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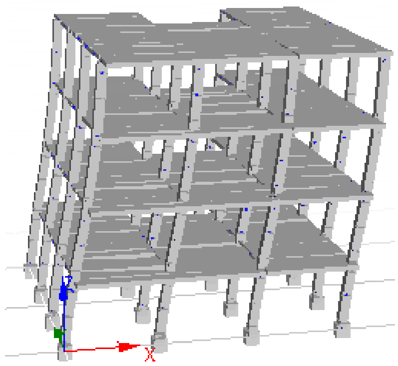

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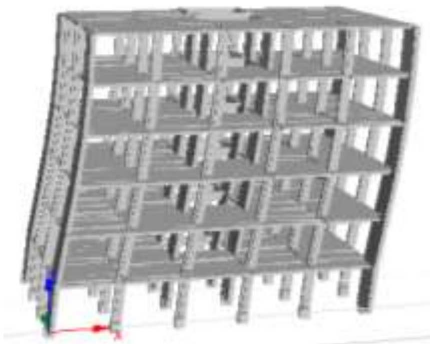

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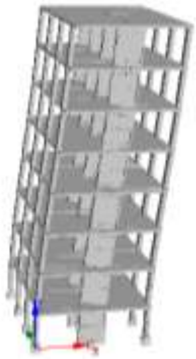

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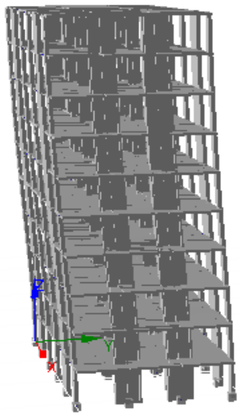


Structure No. 5

Figure 2: Mode Shapes

III. Ground Motions used in the Dynamic Analysis

An appropriate set of ground motions is required to perform the incremental dynamic analysis. As suggested by several seismic codes (UBC 1997; Eurocode 8 2005)and by researchers (Bommer et al. 2003), a minimum of seven ground motions should be used to describe the behavior of a building. However, for mid-rise buildings, ten to twelve ground motions are required to obtain a reliable estimation of the seismic demand (Shome and Cornell 1999). Kircil and Polat (2006) used twelve ground motions to perform IDA and develop fragility curves for 3-story, 5-story and 7-story structures in Turkey. Rota et al. (2010)used seven ground motions to perform the IDA and develop associated fragility curves for a 3-story masonry building located in Benevento, Italy.The ground motions required can be either selected fromreal records of earthquakes or generated artificially. In fact, real records are more realistic, since they include all ground motions characteristics such as amplitude, frequency, duration, energy content, number of cycles and phase (Rota et al. 2010). Unfortunately, no ground motions were recorded forthe past earthquakes in Egypt. Accordingly, 12 earthquake records from other regions were used to perform the nonlinear time history analysis performed in this paper. Details of The 12 records of ground motions that were selected are tabulated in Table 4.

IV. IDA and Fragility Curves

The analysis presented in this section covered the four performance levels described earlier, namely fully operational, operational, life safe and near collapse states. In order to quantify the level of damage that correspond to each of these four states, the inter-story drift ratio was chosen as a non-cumulative damage index, as mentioned by SEAOC[1]. The values of the maximum inter-story drift ratio used to assess the damage are 0.2%, 0.5%, 1.5% and 2% for the states of fully operational, operational, life safe and near collapse damage, respectively.

Table 4: Details of ground motions

No.	Earthquake	Duration	Location	Year	PGA
1	El Centro	50 sec	San Diego	1940	0.35g
2	Northridge	60 sec	Arleta and Nordhoff Fire Station, USA	1994	0.60g
3	Parkfield	30 sec	Cholame, Shandon, USA	1966	0.24g
4	49 OLY	40 sec	USA	1965	0.28g
5	Kern	55 sec	Taft Lincoln School Tunnel, USA	1952	0.16g
6	Loma Prieta	40 sec	Corralitos recording station, USA	1989	0.28g
7	San Fernando	60 sec	8244 Orion Blvd., USA	1971	0.28g
8	Kobe	50 sec	Takatori, Japan	1995	0.35g
9	Chi-Chi	37 sec	Unknown, Taiwan	1999	0.36g
10	Friulli	20 sec	Unknown, Italy	1976	0.48g
11	Hollister	15 sec	City Hall, USA	1974	0.12g
12	Sakaria	20 sec	Sakaria, Turkey	1999	0.63g

Using SeismoStruct software, the nonlinear time history analysis was conducted on each structure using a certain ground motion with the peak ground acceleration, PGA scaled incrementally up to 1.0g using a step of 0.1g. The maximum interstory drift ratio was calculated for each PGA, and thisrepresents a point on the IDA curve. The points of this drift ratio resulting from the various GPA values form the full IDA curve for a specific ground motion. The procedure was repeated for all 12ground motions used in this paper. The full set of the IDA curves from these 12 ground motionscharacterize the seismic response of a specific structural model. The IDA curves for the structural models are presentedin Figure3. Distribution of the peak story drift ratio on each floor for structures No. 3 and No. 5 under 49OLY earthquake are presented in Figure 4. The IDA curves resulting from application of the Friulli and Parkfield earthquakes are shown in Figure 5for all structural models.

To describe the state of damage in relation to the four performance levels postulated above,a cumulative damage state occurrence wasconsidered. It wascalculated as the number of occurrence among the ground motions that exceeded certain performance level at each PGA value. Then the probability of exceeding this damage state wascalculated. Mean and standard deviation, μ and σ, of the natural logarithm of PGA at which each structure reaches the threshold of a specific damage state or performance level werecalculated. These values are tabulated in Table 5, and were used in developing the fragility curves presented below.

The conditional probability of a structure to reach or exceed a specific damage state, D, for a given PGA, is defined by:

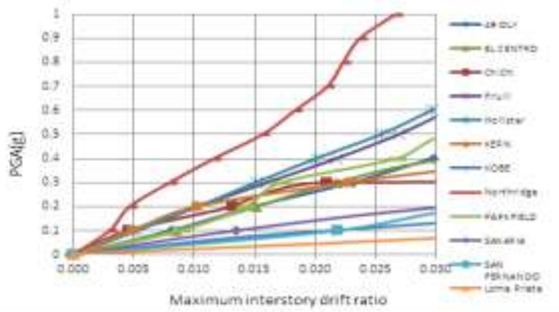
$$P[D/PGA] = \Phi\,[(\ln(PGA)-\mu)/\sigma] \qquad (1)$$

where:

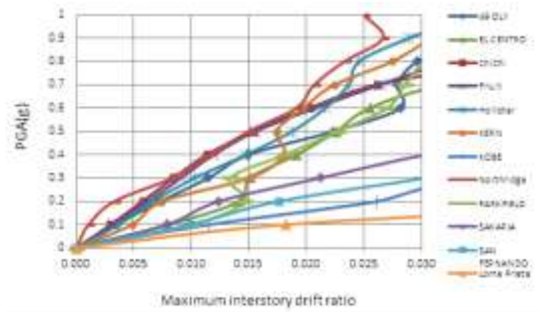
Φ is the standard normal cumulative distribution function. Using Easy Fit software (2010), log-normal functions with two parameters (μ and σ) were fitted for the four performance levels for different structures which create fragility curves. The resulting fragility curves of the structural models are shown in Figure 6.

Table 5: Fragility curves parameters for each structure

Model	Damage state	μ	σ
Structure No.01	Fully operational	-3.341	1.339
	Operational	-2.524	0.857
	Life safe	-1.591	0.747
	Near collapse	-1.092	0.760
Structure No.02	Fully operational	-2.986	1.142
	Operational	-2.143	0.754
	Life safe	-1.141	0.573
	Near collapse	-0.628	0.596
Structure No.03	Fully operational	-3.167	0.635
	Operational	-2.223	0.657
	Life safe	-1.133	0.589
	Near collapse	-0.608	0.610
Structure No.04	Fully operational	-3.021	0.588
	Operational	-2.046	0.603
	Life safe	-1.032	0.601
	Near collapse	-0.370	0.515
Structure No.05	Fully operational	-2.948	0.648
	Operational	-2.112	0.576
	Life safe	-0.947	0.638
	Near collapse	-0.522	0.595



Structure No. 1



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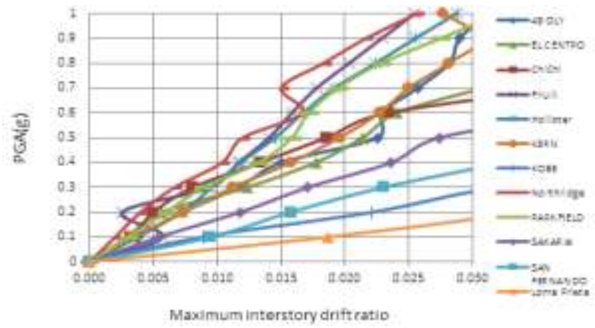

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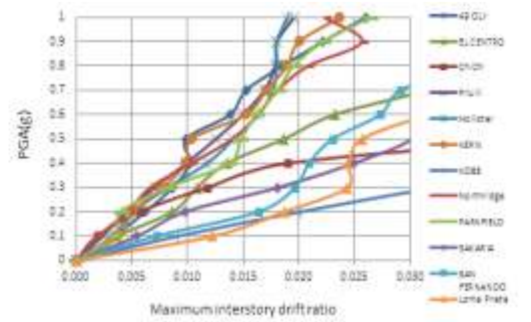

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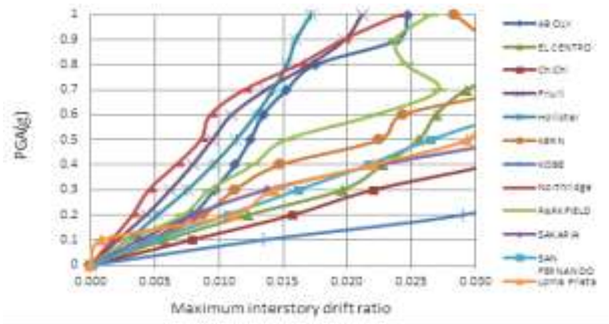


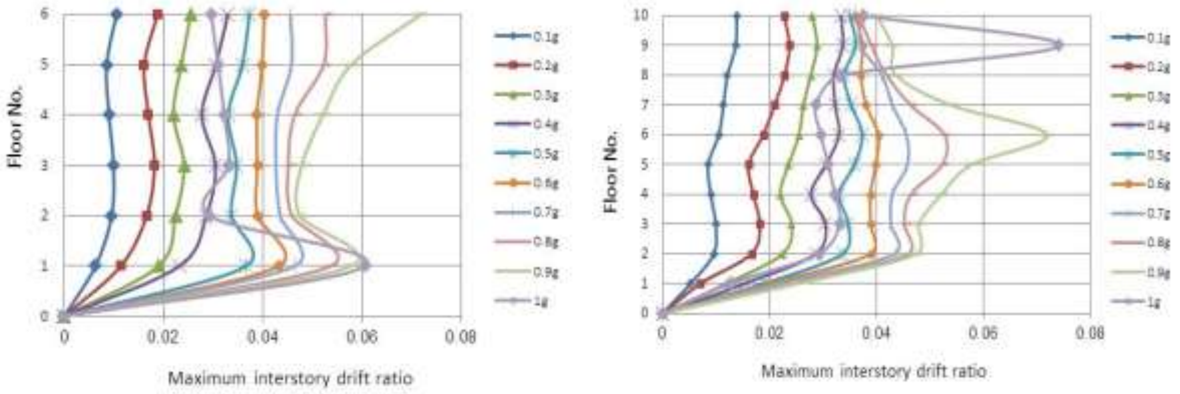
Structure No. 5

Figure 3: IDA curves

V. Results and Discussion

According to the developed fragility curves, the following observations were obtained:

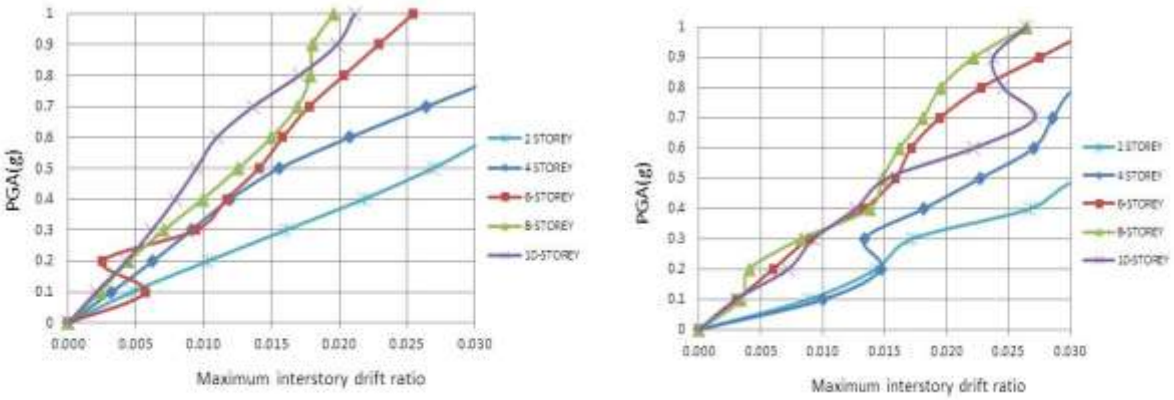
- For structure No. 1 with PGA equals to 0.4g, life safe damage state was reached or exceeded under 11 out of the 12 ground motions, while a near collapse damage state was reached or exceeded under 9 out of 12 ground motions. For PGA of 0.2g, there is 100% chance of reaching or exceeding the fully operational performance level, 92% of reaching or exceeding operational performance level, 42% probability of reaching or exceeding life safe performance level and 33% probability of reaching the near collapse performance level.



Structure No.3 Structure No.5

Figure 4: Peak story drift ratio under 49OLY earthquake

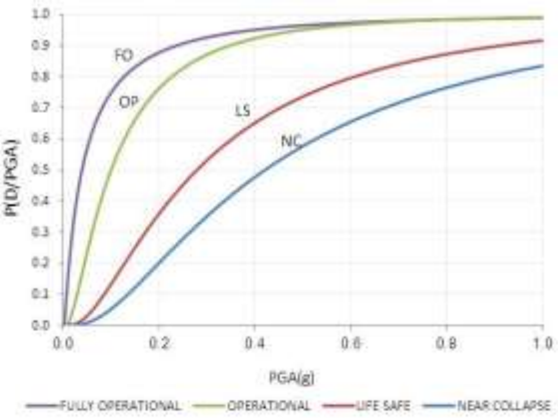
- For structure No. 2, for PGA of 0.4g, out of the 12 analyses using different ground motions, a total of 7 cases reached the life safe performance level and 4 reached the near collapse limit state. There is 100% chance of reaching or exceeding the fully operational performance level, 92% chance of reaching or exceeding the operational performance level, 25% probability of reaching or exceeding life safe performance level and 17% probability of reaching the near collapse performance level.



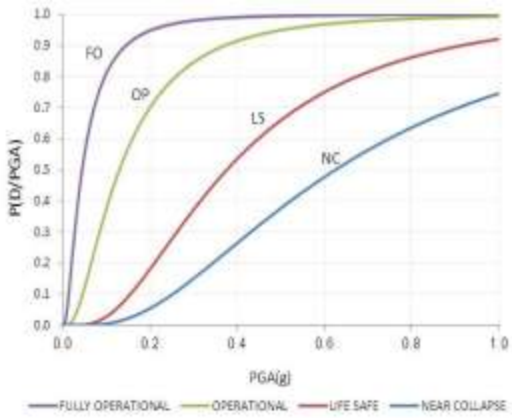
Friulli Earthquake Parkfield earthquake

Figure 5: IDA curves for all structural models under a specific earthquake

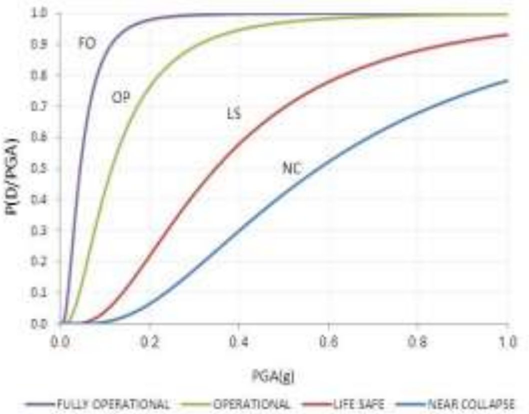
- For structure No.3, for PGA of 0.4g, , life safe damage state was reached or exceeded under 7 out of 12 ground motions, while near collapse damage state reached or exceeded under 3 out of 12 ground motions. For PGA of 0.2g, there is 92% chance of reaching or exceeding fully operational performance level, 75% of reaching or exceeding operational performance level, 25% probability of reaching or exceeding life safe performance level and 8% probability of reaching the near collapse performance level.
- For structure No. 4, for PGA of 0.4g, out of 12 runs using different ground motions, a total of 5 runs reached life safe performance level and only one reached near collapse limit state. For PGA of 0.2g, there is 100% chance of reaching or exceeding fully operational performance level, 75% of reaching or exceeding operational performance level, 25% probability of reaching or exceeding life safe performance level and 0% probability of reaching the near collapse performance level.



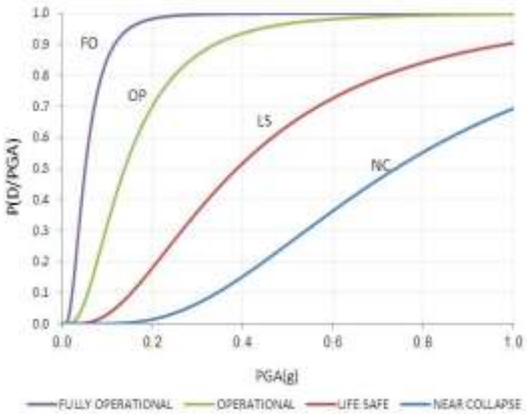
Structure No. 1



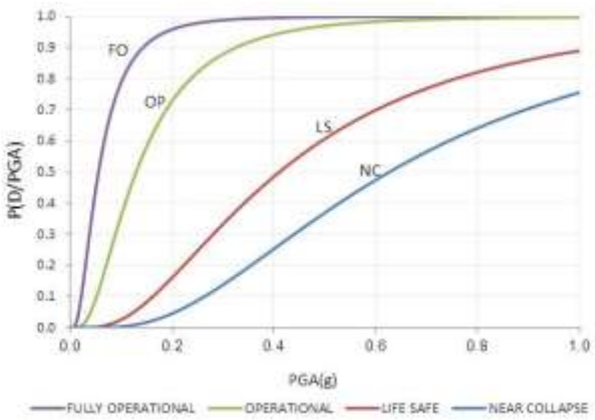
Structure No. 2



Structure No. 3



Structure No. 4



Structure No. 5

Figure 6: Analytical fragility curves

For structure 5, for PGA of 0.4g, , life safe damage state was reached or exceeded under 6 out of 12 ground motions, while near collapse damage state reached or exceeded under 2 out of 12 ground motions. For PGA of 0.2g, there is 92% chance of reaching or exceeding fully operational performance level, 83% of reaching or exceeding operational performance level, 17% probability of reaching or exceeding life safe performance level and 8% probability of reaching the near collapse performance level.

From the previous results, it was observed that the fragility curves obtained for all structures are very close, when considering the same performance level. This can lead to an important conclusion of obtaining very similar seismic performance of low to mid-rise structures of a certain category in terms of structural system, use and type if designed according to the Egyptian Building Code with the same design ground acceleration. Accordingly, developing an overall set of fragility curves for such structures considering different performance levels is of great importance.

These fragility curves represent the average of all fragility curves obtained for all structures considering fully operational, operational, life safe and near collapse performance levels (Figure 7). According to these curves, for similar structures exposed to an earthquake with a PGA equals the design acceleration of 0.15g, there is 97% chance of reaching or exceeding fully operational performance level, 83% of reaching or exceeding operational performance level, 32% probability of reaching or exceeding life safe performance level and 13% probability of reaching the near collapse performance level. Until the Egyptian Building Code undergoes a new development to quantify the expected damage under potential earthquakes, these results can give good seismic performance estimation in terms of structural and nonstructural damage to the designers and owners of similar structures if designed according to the current code provisions and to allow them to seek better performance, if needed, by considering modifying the structural system and increasing the structural ductility.

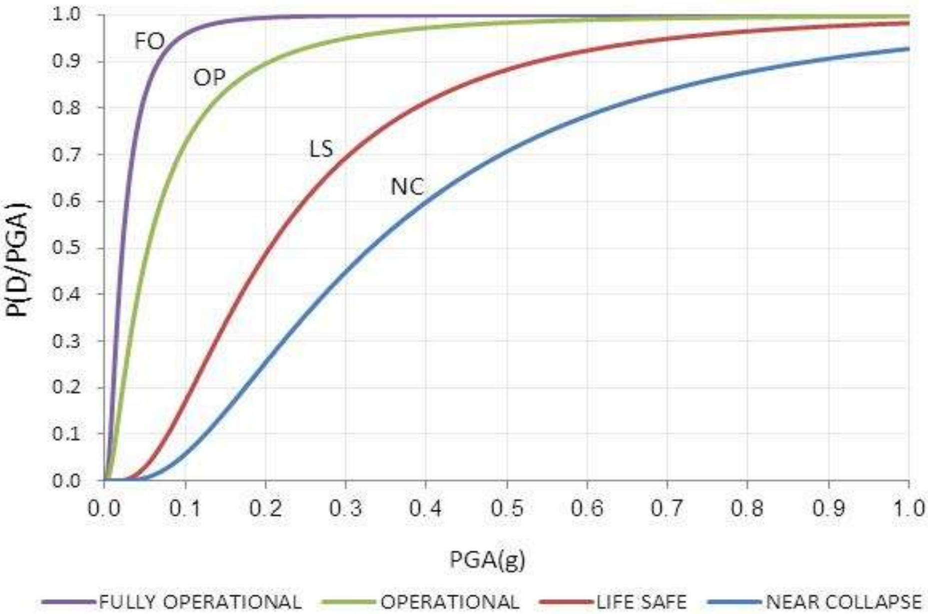


Figure 7: Overall fragility curves for all structures

VI. Conclusions

1. Current Egyptian building code (2008) does not provide a clear definition of the expected damage of structures designed according to its provisions under expected earthquakes. This research was performed in order to assess the damage of existing multistory residential structures, which were designed according to the Egyptian building code.
2. To accomplish the goal above, incremental dynamic analysis, IDA, was conducted on 3-D structural models using SeismoStruct softwarefor five existing multistory residential structures designed according to Egyptian Building Code under dead, live and seismic forces of "Zone 3" with a design acceleration of 0.15g. These structures are 2-story, 4-story 6-story, 8-story and 10-story reinforced concrete structures. Twelve historic real ground motions were used in the analysis. Analytical fragility curves were developed considering 4 different performance levels; fully operational, operational, life safe and near collapse.
3. According to the obtained IDA curves and developed fragility curves, the structural performance of the different structural models was not very dissimilar. For PGA of 0.15g, the average probability of reaching or exceeding the fully operational, operational, life safe and near collapse performance levels are 97%, 83%, 32% and 13%, respectively..
4. It may be intuitive to expect that the owner may request the structural engineer toseek better performance under certain intensity of ground motion. This can be readily obtained byenhancing the overall ductility of the structure and altering itslateral stiffness
5. Expected seismic performance of structures designed according to current code provisions, which is assessed herein through developed analytical fragility curves, can be considered in future development of local code provisions.

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