Use of Incremental Dynamic Analysis for the seismic performance assessment of RC framed structures

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ABSTRACT

In this study seismic performance assessment of existing low and mid-rise reinforced concrete buildings is presented by using Incremental Dynamic Analysis. Incremental dynamic analysis (IDA) is known as an accurate method and it can provide the whole range of structural responses from elastic range to collapse. The method performs a series of nonlinear dynamic analyses in which the intensity is incrementally increased for the ground motion selected to investigate the behavior until the global collapse capacity of the structure is reached. The mathematical models are prepared in the environment of Zeus-NL software, a finite element program developed especially for earthquake engineering applications. IDA curves are developed considering spectral acceleration (Sa (T1,5%)) as intensity measure (IM) parameter. The nonlinear dynamic analyses were conducted using a set of twenty natural ground motion records selected with a range from 0.042g-3.5g peak ground acceleration and without directivity influence. In addition, the immediate occupancy (IO), collapse prevention (CP) and global instability (GI) limit states are defined based on FEMA guidelines. Moreover, the IDA curves are summarized based on 16%, 50% and 84% fractiles. Finally, conclusions are summarized based on the findings done from the analysis results, while recommendations for the future research are presented.

Keywords: *Low and Mid-Rise Buildings; Nonlinear Analysis; Seismic Performance; Incremental Dynamic Analysis; Zeus-NL*

INTRODUCTION

The proper design of the structures to resist the severe ground motions, causing as few as possible losses, whether they are human or material, has been the main attention of both researchers and professional engineers. Consequently, the Performance-Based Earthquake Engineering (PBEE) was born as a new but innovative and fast-growing idea. Recently a new method has been developed in association with PBEE principles, known as Incremental Dynamic Analysis to help the engineers in assessing the performance of structures [1]. This procedure is able to replicate time history analyses, while scaling the ground motion records in order to evaluate the structural performance from elasticity until the total collapse of the building occurs. Considering multiple records, this tool aims to plot the capacity curve for the structure modelled. By appropriately summarizing the IDA curves, defining limit states and combining the results with Probabilistic Seismic Hazard Analyses (PSHA), will easily reach the goals for a better structural design [2]. In this paper the seismic performance of a low and mid-rise reinforced concrete building is conducted under nonlinear analysis procedures. For the estimation of the structures vulnerability due to the earthquake motion, the Incremental Dynamic Analysis (IDA) was applied under a set of records. The numerical model of the buildings selected is prepared in the environments of Zeus-NL software, a finite element program developed specifically for earthquake engineering applications [3] [4]. For the development of IDA curves, a set of twenty ground motion records have been selected with peak ground acceleration from 0.042 to 3.50g. The maximum response parameters, intensity measure (IM) and damage measure (DM), are plotted on a two-dimensional graph for every scaling factor. According to previous studies [1] [2], it is selected 5% damped first mode spectral acceleration Sa(T1,5%) for the intensity measure and maximum global drift Θ_{max} for the damage measure while plotting the IDA curves. Additionally, the immediate occupancy (IO) and the life safety (LS) limit states are defined for every IDA curve. The structural performance under seismic loadings is done by interpretation of the IDA fractiles categorized as 16%, 50% and 84%.

METHODOLOGY FOR SEISMIC VULNERABILITY ASSESSMENT

In this study two RC buildings are selected without any geometrical irregularities and modelled as framed structures in the environments of Zeus-NL software for both x and y directions. A new nonlinear dynamic analysis proposed in literature, known as Incremental Dynamic Analysis, is utilized to achieve the objectives of this paper. Incremental Dynamic Analysis (IDA) was initially proposed by Bertero in 1977 and was adopted by the Federal Emergency Management Agency [5]. The first computer algorithms for the implementation of this method were introduced and presented by Vamvatsikos and Cornell [6]. Unlike from static pushover analyses, this method incorporates the use of time history analyses as an increasing intensity measure. Also called as dynamic pushover analyses (DPO) [7], this method uses the ground motion records to perform the analyses. Hence, IDA can be expressed as a repetition of the time history analyses, while the intensity of the record increases step by step to plot the two-dimensional graph same as static pushover procedure. Figure 1 illustrates the dynamic pushover curve as an increasing scale of time history analyses.

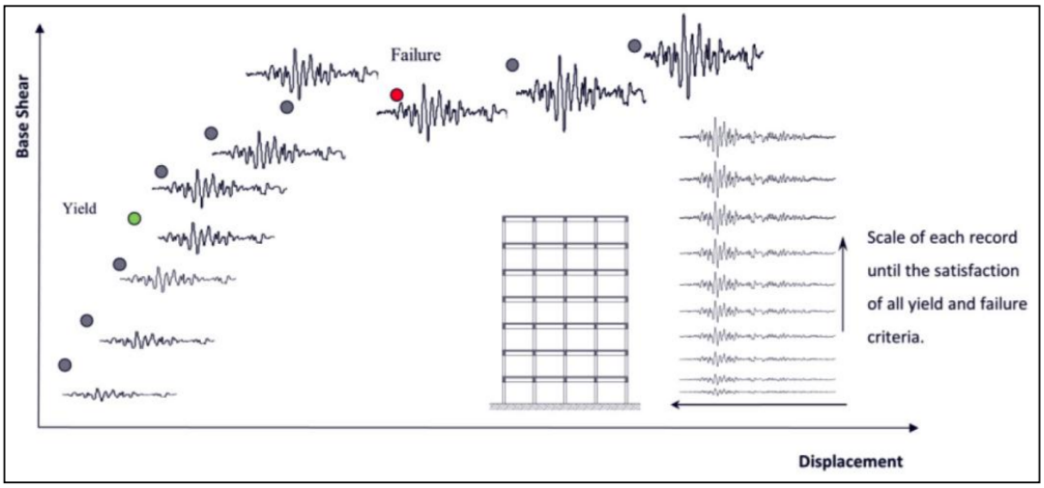


Figure 1. Incremental dynamic capacity curve [8]

IDA curves are developed under a set of ground motion records showing no directivity, so they do not influence the intensity measure parameter. In literature, researchers have suggested to use ten to twenty records for midrise buildings [9]. For this study a suite of twenty earthquake records with peak ground acceleration from 0.042g up to 3.50g are selected as shown in table 1. Ground motion records are taken from the Pacific Earthquake Engineering Research Centre (PEER) [10] and from the U.S Geological Survey (USGS) [11].

The IDA calculation parameters involve the scale factor, measure intensity of the earthquake and the measure of structural response. The scale factor produces a scaled accelerogram applied to the natural acceleration time history. The earthquake intensity measure has been selected as 5% damped of first mode spectral acceleration Sa(T_1,5%). The damage measure is considered the maximum global drift $\Theta_{max.}$ In addition, the interpolation of the results to generate the IDA curves without needing to generate massive analysis, is done using super spline function as presented by [12].

Table 1: The suite of twenty ground motion records used for this study

No	Event	Year	Station	Ø°	Soil	M	R (km)	PGA (g)
1	Erzincan	1992	Turkey, Erzincan	90	C	6.7	8.9	0.488
2	Imperial Valley	1979	Westmoreland Fire Station	90	C,D	6.5	15.1	0.074
3	Loma Prieta	1989	Agnews State Hospital	90	C,D	6.9	28.2	0.159
4	Loma Prieta	1989	Coyote Lake Dam Downstr.	285	B,D	6.9	22.3	0.179
5	Loma Prieta	1989	Hollister South & Pine	0	D	6.9	28.8	0.371
6	Loma Prieta	1989	Sunnyvale Colton Ave	270	C,D	6.9	28.8	0.207
7	Imperial Valley	1979	Chihuahua	282	C,D	6.5	28.7	0.254
8	Imperial Valley	1979	Plaster City	45	C,D	6.5	31.7	0.042
9	San Fernando	1971	LA, Hollywood Stor. Lot	180	C,D	6.6	21.2	0.174
10	Northridge	1994	LA, Hollywood Storage FF	360	C,D	6.7	25.5	0.358
11	San Fernando	1971	LA, Hollywood Stor. Lot	90	C,D	6.6	21.2	0.210
12	Spitak	1988	Armenia, Gukasian	90	C	6.8	36.1	0.207
13	Sup.erstition Hill	1987	Wildlife Liquefaction Array	360	C,D	6.7	24.4	0.200
14	Tabas	1978	Iran, Dayhook	280	B	7.4	20.6	3.500
15	Loma Prieta	1989	WAHO	0	D	6.9	16.9	0.370
16	Loma Prieta	1989	WAHO	90	D	6.9	16.9	0.638
17	Northridge	1994	LA, Baldwin Hills	90	B	6.7	31.3	0.239
18	Friuli	1976	Italy, Tolmezo	270	B	6.5	20.2	0.345
19	Corinth	1981	Greece, Corinth	0	C	6.6	19.9	0.264
20	Kocaeli	1999	Turkey, Duzce	180	C	7.1	1.6	0.427

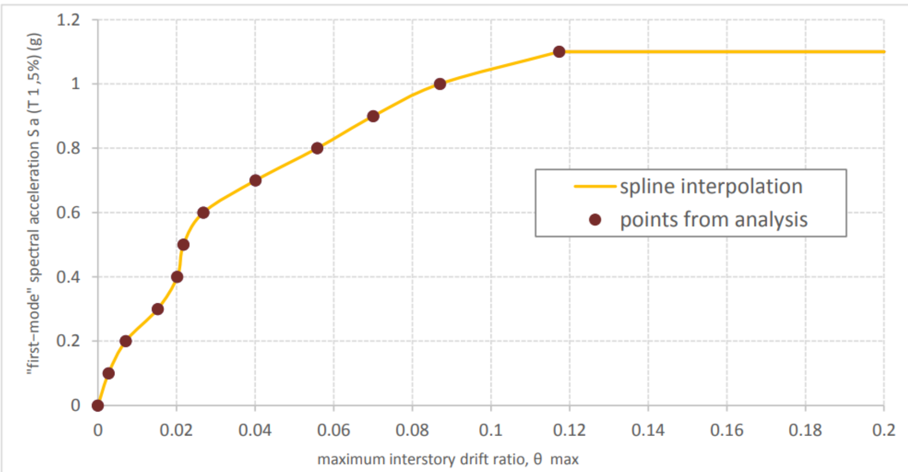
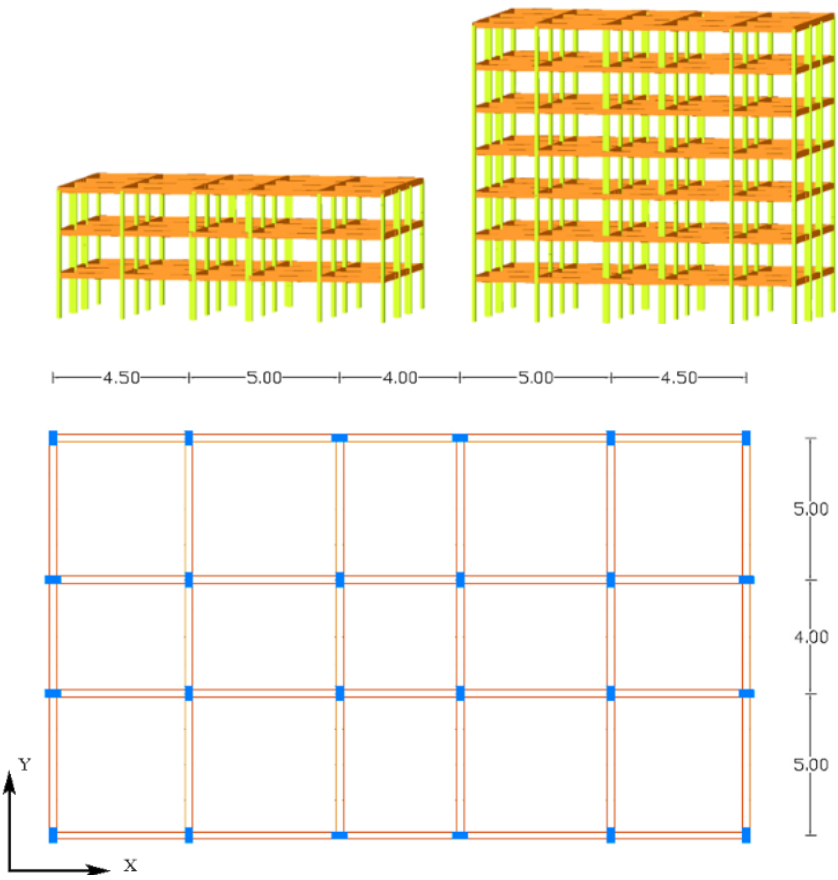


Figure 2. The interpolation of dynamic analyses points for Loma Prieta Sunn. Colton.

For each of the IDA curves the Immediate Occupancy (IO), Collapse Prevention (CP) both defined in [FEMA-350, 2000; FEMA (2000a), 2000], and Global Instability are determined. Defining especially the collapse prevention limit state is not an easy task and required an accurate procedure to get the most appropriate 20% of elastic slope in the IDA tangent. To achieve this step, the study involves the usage of a parametric curve used in computer graphics known as "Bezier curve" function. Finally, IDA curves are summarized as 16%, 50% and 84% fractiles as suggested by authors [1].

DESCRIPTION OF THE BUILDING AND MATHEMATICAL MODELLING

For this study two reinforced concrete buildings are selected, a three story and a seven story as shown in the figure 3. Both buildings have the same plan dimensions, 23 m long and 14 m wide. The plan is composed of 5 bays and 4 frames and is symmetrical in x and y directions therefore there will develop no torsional effect due to structural irregularities. The story height is 3 meters in each story elevation. Both buildings are modeled in the environment of Zeus-NL software as reinforced concrete structures with a concrete strength of fck = 30 MPa and steel class fy = 355 MPa. From the available library of the selected software, a cubic elasto-plastic type 3D element was used to model beams and columns. The bilinear elasto-plastic material model with kinematic strain hardening (stl1) was used for the steel reinforcement and rigid links modeling, while the uniaxial constant confinement concrete material model (conc2) was used for the concrete [4].



(a)

(b)

Figure 3. a) Structural plan (units in m); b) Elevation view of the frames

Each of the buildings has different element details. The low-rise model is composed of two types of columns and two types of beams, while the mid-rise building is composed of four types of columns and two types of beams as presented also in the Table 2. The element types change from each other according to their cross-sectional size and reinforcement. The infill walls have a thickness of 20 cm and slab thickness of 15 cm according to plan details.

Table 2. Column and Beam details

Column Type	Column size	Longitudinal reinforcement (No. of bars / bar size)	Beam Type	Beam size	Longitudinal reinforcement (No. of bars / bar size)	Structure
Type 1	40 * 70 cm	12 Ø18	Type 1	30 * 50 cm	8 Ø14	7-Story
Type 2	40 * 70 cm	8 Ø18	Type 2	30 * 50 cm	8 Ø12	7-Story
Type 3	30 * 70 cm	12 Ø16	---	---	---	7-Story
Type 4	30 * 70 cm	8 Ø16	---	---	---	7-Story
Type 5	25 * 50 cm	8 Ø16	Type 3	25 * 40 cm	8 Ø12	3-Story
Type 6	25 * 50 cm	6 Ø16	Type 4	25 * 40 cm	6 Ø12	3-Story

Both buildings are modeled in Zeus-NL program, a platform which uses finite element analyses facility developed especially for earthquake engineering applications [3] as moment resisting frames. Zeus-NL uses a fiber approach for the nonlinear analyses, monitoring the cross section into several fibers such as reinforcement fiber, confined concrete fibers and unconfined concrete cover. The structural elements (Beams and Columns) are modeled according to project details to increase the accuracy of the results. The self-weight of the structural members is calculated and assigned as distributed load in beams and as concentrated loads in columns. Since there is no slab or infill wall member type in the Zeus-NL library, the self-weight, dead loads and live loads are calculated and assigned over the beams as distributed load. At the base nodes all the degrees of freedom are restrained.

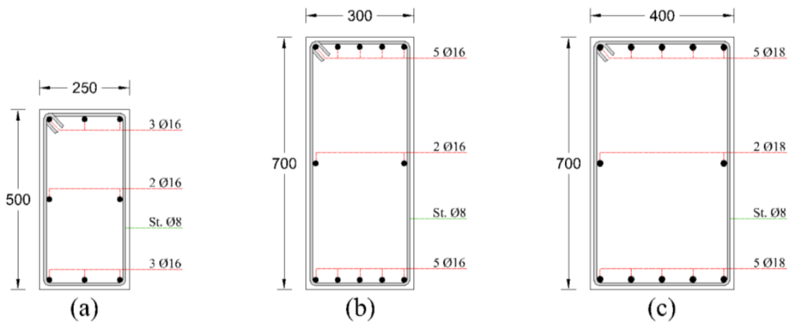


Figure 4. Lower story columns: a) 3-story column, b) 7-story column, c) 7-story column (units in mm)

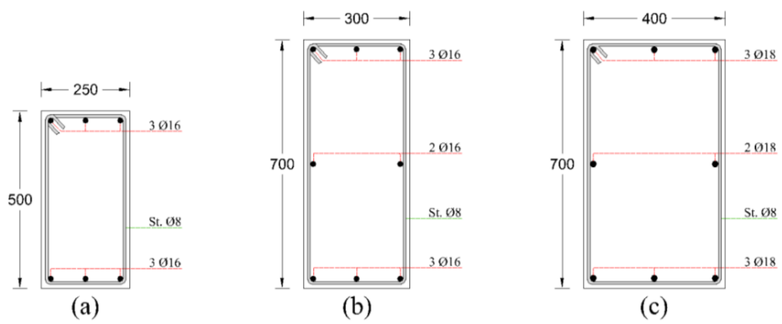


Figure 5. Upper story columns: a) 3-story column, b) 7-story column, c) 7-story column (units in mm)

Zeus-NL does not provide a very user-friendly method to model structural elements, especially for the reinforcement. To accelerate the modeling stage for this study a new methodology is followed while modeling the structural elements. Since the software allows easily to modify the element library, a new library has been prepared using Microsoft excel 2013 and the allocation of the steel bars in each member is calculated in common with reinforcement area aiming to minimize the calculation mistakes.

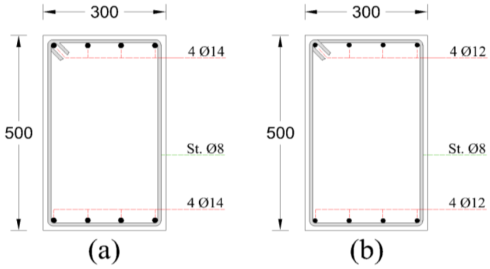
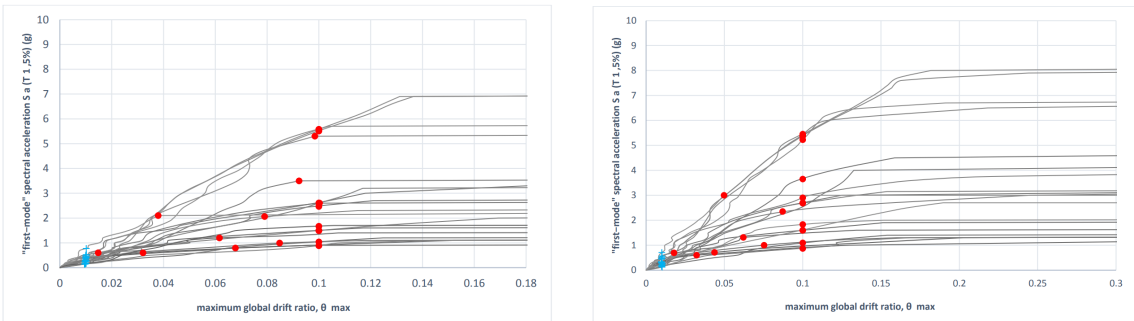


Figure 6. Mid-rise model beams: a) lower story beams, b) upper story beams (units in mm)

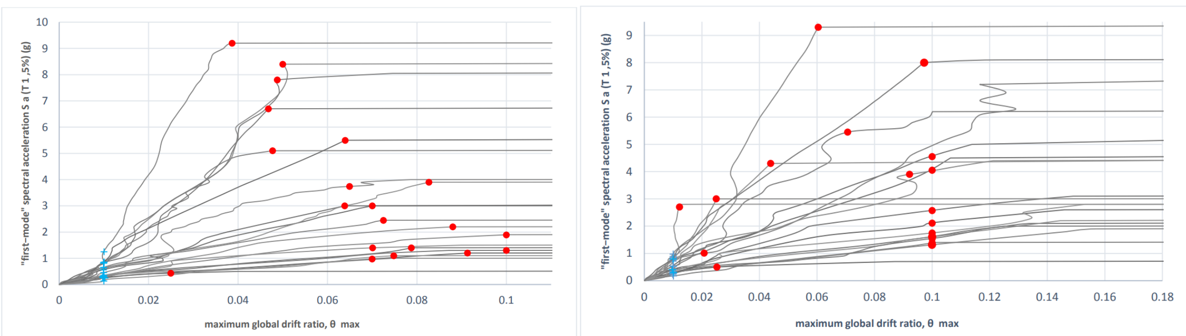
RESULTS

Four moment frames, representing the low-rise and mid-rise building cases, are subjected to more than thousand nonlinear dynamic analyses. These values are used to plot the IDA curves. The fragility curves developed from incremental dynamic analysis will be considered as a suitable tool to conduct an earthquake assessment as well as structural damage under a suite of twenty ground motion records. 80 IDA curves are ploted and illustrated as simple IDA curves, with dots to represent each increment scale, together with limit states. In addition, these curves are summarized as 16%, 50% and 84% fractiles as presented below.



(a) (b)

Figure 7. Twenty IDA curves and associated limit-state capacities for 3-Story Building in x-direction (left) and y-direction (right). The IO limit is represented by plus sign, collapse prevention limit is represented by dots and global instability with flatlines.



(a) (b)

Figure 8. Twenty IDA curves and associated limit-state capacities for 7-Story Building in x-direction (left) and y-direction (right). The IO limit is represented by plus sign, collapse prevention limit is represented by dots and global instability with flatlines.

As can be seen from the presented IDA curves, it is very practical to observe the hardening and softening on each of the curve until the global instability (GI) is reached. This limit state is represented by the flatline segment on the curves. The constant line of the IDA curve shown in the graph indicated that the building reached the maximum load bearing capacity and total collapse with take place. The immediate occupancy limit state is shown with a "+" sign in the IDA curves which corresponds to 1% of the damage measure parameter. Similarly, the collapse prevention is demonstrated by dots on each of the curves plotted in the graph.

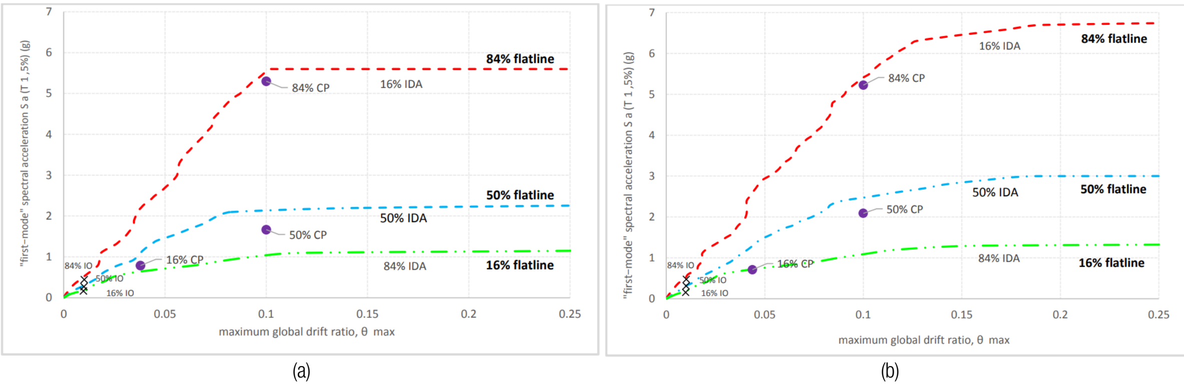


Figure 9. 16%, 50%, 84% IDA fractile for the 3-Story, X-direction Frame on the left and Y-direction Frame on the right

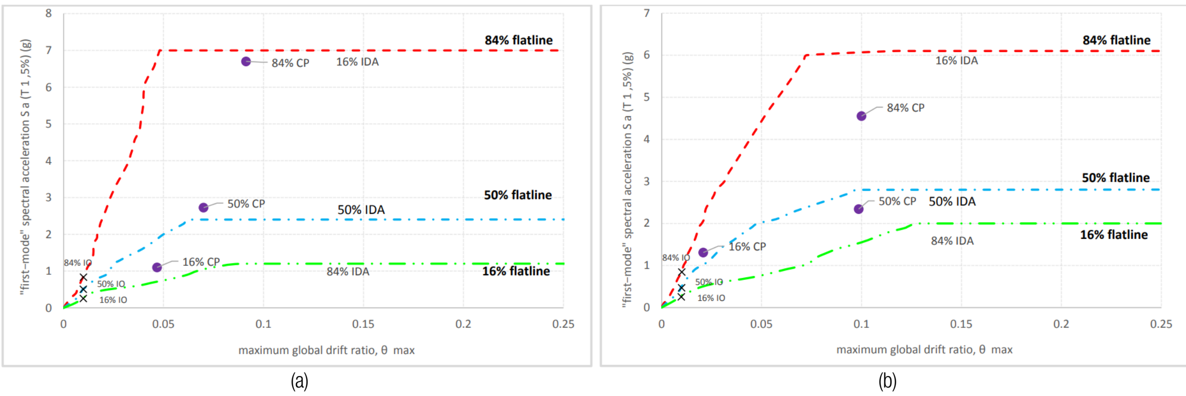


Figure 10. 16%, 50%, 84% IDA fractile for the 7-Story, X-direction Frame on the left and Y-direction Frame on the right

IDA curves can represent very detailed information by plotting the fractiles into 16%, 50% and 84% according to the methodology provided in previous studies. From the generated IDA fractiles, it is possible to observe the structural response for any increase of intensity measure until the global collapse limit state is reached. Reading from the IDA graphs, it can be summarized that for an IM equal to 1.0g, 16% of the samples produce approximately $\theta_{max} \leq 1.77\%$, 50% of the samples produce $\theta_{max} \leq 3.62\%$ and 84% produce $\theta_{max} \leq 9.31\%$ for the 3-Story X-direction frame. For the same IM value (1.0 g), the 3- Story, Y-direction frame at the 16% of samples produce $\theta_{max} \leq 1.84\%$, for the 50% $\theta_{max} \leq 3.51\%$ and for the 84% produces $\theta_{max} \leq 8.72\%$. 7-Story, X-direction frame produces at the 16% IDA curves, $\theta_{max} \leq 1.13\%$, at 50%, $\theta_{max} \leq 2.28\%$, and at the 84% IDA curves produces $\theta_{max} \leq 6.67\%$. Lastly, 7-Story, Y-direction frame produces $\theta_{max} \leq 1.10\%$ for 16% of fractiles, $\theta_{max} \leq 1.98\%$ for 50% of the curves and $\theta_{max} \leq 7.07\%$ for the 84% of the IDA curves. In an alternate way, the summarized fractiles can be used inversely to gather more information. For a specific damage measure, the respective value of the intensity measure depending on the 16%, 50% or 84% fractiles can be observed. Simultaneously, as graphically illustrated in Figure 9 it is observed that for $Sa(T_1,5\%) = 1.667g$ and $2.090g$ or equivalently at $\theta_{max} = 0.10$, 50% of the ground motion records have forces the three-story structure to violate the Collapse Prevention performance level in x- and y-direction respectively. In the same way it can be interpreted that for the seven-story building for the $Sa(T_1,5\%) = 2.723g$ and $2.340g$ or equivalent at $\theta_{max} = 0.070$ and 0.099, 50% of the records are violating the CP limit state in x- and y-direction respectively as shown in the Figure 10. Finally, it is observed that due to inherent characteristics of the accelerograms some records (I.Valley - Westmoreland Fire Station; S.Fernando - LA, Hollywood Stor. Lot; Friuli –Italy, Tolmezo; Tabas - Iran, Dayhook; L.P – WAHO 090; Northridge - LA, Baldwin Hills; Corinth – Greece and Kocaeli - Turkey, Duzce) forced the low-rise building to fail before the mid-rise one.

CONCLUSION

In this study, Incremental Dynamic Analysis is used for the seismic performance assessment of reinforced concrete buildings. A three story and seven story buildings have been used as representative of low and midrise constructions. Mathematical model is prepared using Zeus-NL software. For the nonlinear analysis, a set of twenty ground motion records is selected showing no directivity. In addition, a methodology is presented for the development of IDA curves as well as Immediate Occupancy, Collapse Prevention and Global Instability limit states based on FEMA guidelines. From the results, it is observed that due to inherent characteristics of the accelerograms some records forced the low-rise building to fail before the mid-rise one. The limit states can be very useful to interpret the structural performance for each earthquake. Finally, IDA curves and IDA fractiles provide detailed information for the demand calculation due to any intensity measure increase. More information can be gathered from IDA fractiles for the structural performance due to ground motion forces, nevertheless this requires a deep research which can be a beneficial recommendation for the further studies.

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