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Application of Incremental Dynamic Analysis to a Moment-Frame Reinforced Concrete building in Albania designed in 1982.

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Keywords

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Abstract

This study covers the seismic performance evaluation of an old template reinforced concrete building in Albania designed in 1982. This building category is constructed as residential moment-frame with no shear walls. For the demand calculation, Incremental Dynamic Analysis (IDA), is selected as a method which provides the response behavior of the structure under a set of ground motion records from the elastic range until total collapse. More than one thousand dynamic analyses are performed in the environment of ZeusNL software, developed particularly for earthquake applications. A set of 18 ground motion records with magnitude ranging from 6.5 until 7.1 is used to perform the analyses. Furthermore, IDA curves are generated based on the values gathered from the intensity measure (IM) and damage measure (DM) defined as 5% damped first mode spectral acceleration, Sa(T1,5%) and maximum global drift ratio, θmax respectively. In addition, limit states are selected as Immediate Occupancy (IO), Collapse Prevention (CP) and Global Instability (GI) based on FEMA guidelines. Finally, the interpretation of the building performance is presented in terms of IDA fractiles summarized as 16%, 50% and 84%.

1.Introduction

In this paper the seismic performance assessment of a reinforced concrete (RC) template building in Albania is conducted using nonlinear dynamic analysis. These template buildings were designed in 1982 and constructed in different cities in our country according to old building code [1]. Moreover, Albania has been evaluated as a region with relatively high seismic vulnerability [2]. Recently, On November 26, 2019, western part of Albania was hit by a 6.4 Mw earthquake with epicenter in Durrës, causing major loss in human and buildings [3, 4]. From site investigation it has been observed that most common failures were objected to improper reinforcement and poor material quality due to aging. Therefore, the seismic response evaluation of these buildings must be done as early as possible. On the other hand, one of the main targets of Performance-Based Earthquake Engineering (PBEE) is to evaluate the seismic response of the structure as accurate as possible [5]. Hence, Incremental Dynamic Analysis (IDA) is used for the estimation of the building vulnerability due to the earthquake motion under a set of records. To model the structure, ZeusNL, a finite element software established especially for the earthquake engineering applications [6, 7] is used. Selecting the appropriate ground motion records and an applicable software is crucial while running Incremental Dynamic Analysis. Nevertheless, performing IDA involves several other important steps as presented below:

I. Prepare a suitable building model in the environment of a software capable of running IDA.
II. Select an applicable set of more than ten ground motion records for midrise buildings.
III. Chose an incrementing method which is compatible with selected software until non-convergence is encountered (e.g, hunt and fill or stepping method).
IV. Define a suitable intensity measure (IM e.g, 5% damped first mode spectral acceleration, Sa(T1,5%)) for the ground motion and a damage measure (DM e.g, maximum global drift ratio, θmax) [5, 8]
    a. Generate the IDA curve by interpolation for each of the ground motion record once the IM and DM results are ready.
    b. Define the limit states.
    c. Summarize IDA curves into 16%, 50% and 84% fractiles.
V. Interpret the seismic structural performance by using the generated information.

In addition, we will provide a methodology on the application of the Incremental Dynamic Analysis as well as interpretation of the results for this old template building.

2. Building model and ground motion selection

We have selected “Banesa TIP 82/2” as a representative of old reinforced concrete buildings in Albania constructed in the communism era. This building template was used in different cities of our country, and they are classified as the first reinforced concrete structures which were built using early building code [1]. It was designed in 1982 and is serving as residential building which is still in use as yet. In plan, the building is symmetrical in both longitudinal directions, 17.3m long and 10.0m wide composed of 6 bays and 3 frames. First four stories have an elevation of 2.8m while the top story is 3.22m, reaching a total building height of 14.42m. The structural system is reinforced concrete moment resisting frames without shear walls. The mathematical model of this building is conducted in the environment of Zeus-NL software using a cubic elasto-plastic type 3D element 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 [7]. We have chosen to model the middle frames of the building, representative of x and y directions as shown in figure 1. The concrete class given in the blueprint belongs to class C16/20.

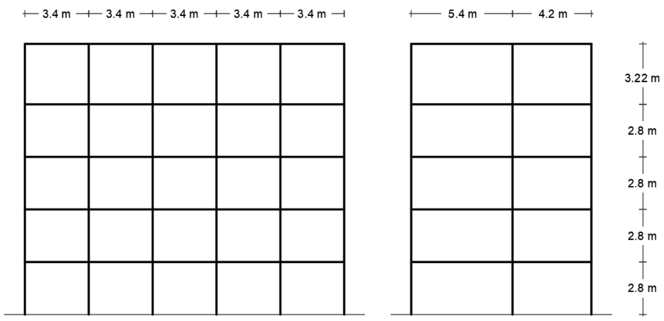

Figure 1. Structural model used in ZeusNL.
(X-direction left and Y-direction right)

However due to aging of these structures we chose to use C10 and C16 which represent better the actual concrete condition. Therefore, in overall there will be 4 models to be analyzed using Incremental Dynamic Analysis. To implement this procedure, we will need a suite of ground motion records. In literature it is proposed to use ten to twenty earthquake records for midrise buildings to get sufficient results while targeting the estimation of the seismic demand [9].

Table 1. The suite of eighteen ground motion records used for this study.

N	Event	Year	Station	Ø°	Soi	M	R(km	PGA(g
1	Corinth	1981	Greece, Corinth	0	C	6.6	19.9	0.264
2	Kocaeli	1999	Turkey, Duzce	18	C	7.1	1.6	0.427
3	Erzincan	1992	Turkey, Erzincan	90	C	6.7	8.9	0.488
4	Friuli	1976	Italy, Tolmezo	27	B	6.5	20.2	0.345
5	Imperial	1979	Chihuahua	28	C,D	6.5	28.7	0.254
6	Imperial	1979	Plaster City	45	C,D	6.5	31.7	0.042
7	Imperial	1979	Westmoreland Fire	90	C,D	6.5	15.1	0.074
8	Loma Prieta	1989	Agnews State	90	C,D	6.9	28.2	0.159
9	Loma Prieta	1989	Coyote Lake Dam	28	B,D	6.9	22.3	0.179
10	Loma Prieta	1989	Hollister South &	0	D	6.9	28.8	0.371
11	Loma Prieta	1989	Sunnyvale Colton	27	C,D	6.9	28.8	0.207
12	Loma Prieta	1989	WAHO	0	D	6.9	16.9	0.370
13	Loma Prieta	1989	WAHO	90	D	6.9	16.9	0.638
14	Northridge	1994	LA, Hollywood	36	C,D	6.7	25.5	0.358
15	San	1971	LA, Hollywood Stor.	90	C,D	6.6	21.2	0.210
16	San	1971	LA, Hollywood Stor.	18	C,D	6.6	21.2	0.174
17	Spitak	1988	Armenia, Gukasian	90	C	6.8	36.1	0.207
18	Superst.	1987	Wildlife Liq. Array	36	C,D	6.7	24.4	0.200

Consequently, we have selected a set of 18 ground motions from a range of 6.5 – 7.1 magnitude as shown in table 1. All records are selected with no marks of directivity so they can represent a real earthquake scenario. Ground motion records are taken from the Pacific Earthquake Engineering Research Centre (PEER) [10] and from the U.S Geological Survey (USGS) [11].

3. Methodology for seismic performance assessment

3.1. Performing Incremental Dynamic Analysis

Once the template building model is prepared and ground motion records are selected, then we will need to conduct the nonlinear dynamic analysis. Incremental Dynamic Analysis (IDA) [5], also known as Dynamic Pushover Analysis (DPO) [12], was initially proposed in 1977 by Bertero and adopted by the Federal Emergency Management Agency [13]. Later, Vamvatsikos and Cornell introduced the first computer algorithm for the implementation of this analysis method [14]. IDA uses the earthquake record to replicate time history analysis by increasing step by step the intensity measure. In this way, by scaling each of the records, the target is to force the entire structural from elastic region, to yielding and finally total collapse. One of the most advanced algorithms to predict minimum steps required per record is presented by Vamvatsikos and Cornell as the hunt and fill algorithm [15]. However, in this study we will use stepping method employed in ZeusNL software due to its simplicity to understand and implement [16]. In this case we will need to specify the starting IM, maximum number of dynamic analysis and the preferable IM-step. The IDA calculation parameters involve the scale factor, intensity measure of the earthquake and the damage measure of structural response. The earthquake intensity measure is selected as 5% damped of first mode spectral acceleration Sa(T1,5%)(g) and the damage measure is considered the maximum global drift ratio θmax(%) as proposed by previous studies [15]. In the table 2, there are shown all steps needed for the analysis together with the structural drift values. The last step ends in the global instability and is denoted by "+∞". Global instability happens when any small increase in the IM produces huge DM values, essentially ending of the IDA. In total, 17 runs were needed for record #1.

Table 2. IM and DM values from C16-building in x-direction for record No.1

No.	Sa(T1,5%)	θmax
1	0.05	0.14
2	0.11	0.28
3	0.16	0.34
4	0.21	0.47
5	0.26	0.60
6	0.32	0.76
7	0.37	0.97
8	0.42	1.28
9	0.48	1.60
10	0.53	1.96
11	0.58	2.14
12	0.63	2.28
13	0.69	2.40
14	0.74	2.72
15	0.79	3.33
16	0.84	4.69
17	0.90	+∞

3.2. Producing IDA Curves by Interpolation

As soon as all analysis are ready then we will need to generate the IDA curves. The proper selection of the intensity measure plays an important role in the evaluation of the building performance and interpretation of IDA outcomes [17]. For this study, we have selected 5% damped of first mode spectral acceleration Sa(T1,5%) as intensity measure parameter since our set of ground motions have no signs of directivity and building is a midrise one. On the other hand, we are interested to monitor the rooftop displacement of the building, hence the global drift ratio θmax is chosen as damage measure parameter. Once the IM and DM values are gathered from the analysis, then we will need to select a procedure to interpolate the results for the IDA curves. The interpolation of the results to generate the IDA curves without needing to conduct massive analysis, is done using super spline function and prepared as an algorithm in python programing language. In figure 2, it is presented the IDA curve which is generated after the interpolation. The dots represent each scale factor of the incremented dynamic analysis plotted in terms of IM and DM selected parameters and the line shows the interpolation from the data collected. Initially it is observed the linear region of the IDA curve which is followed by the first damages occurring. The curve start softening at about 0.37 g and then reaching the "flatline" after intensity measure of 0.85 g, indicating the global instability where the structure will response with "infinite" θmax.

3.3. Defining IDA Limit States and Fractiles

Performance-Based Earthquake Engineering requires to define the limit states on the IDA curve to perform the estimation of the building performance [18]. To achieve this target, we will select three limit states: Immediate Occupancy (IO), Collapse Prevention (CP) which are both defined in FEMA guidelines [13] and the Global Instability (GI) as have been previously suggested [5]. Following these guidelines, we set immediate occupancy limit state to occur at 1% or 0.01 of the global drift ratio. Moreover, collapse prevention point will be located on the IDA curve when it reaches to 20% of the elastic slope or when DM goes to 10%.

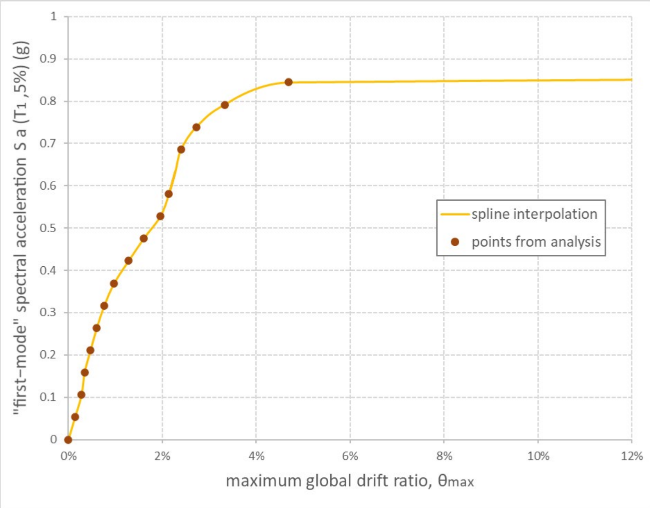

Figure 2. The interpolation of dynamic analyses points for record No.1.

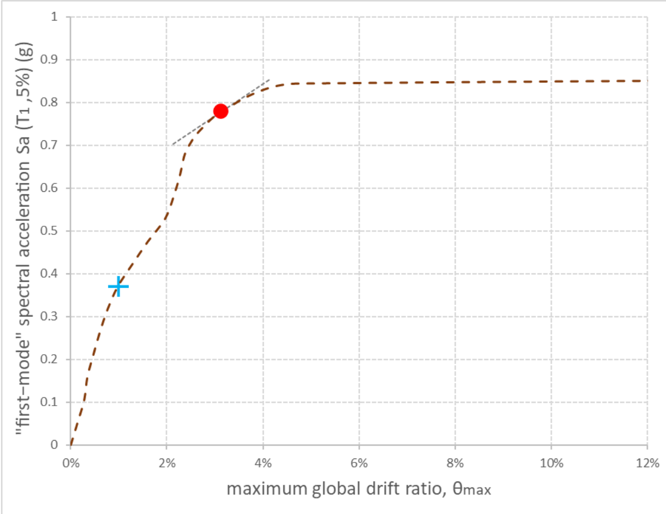

Figure 3. Defining IO and CP limit states in IDA curve for record No.1

The one occurring first in terms of intensity measure will be selected as CP point. With great significance here is to properly locate the CP point when the curve starts softening, still without exceeding 10% of the DM parameter, so the structural model can be trusted. In some cases, it happens that IDA curve softens and hardens more than one time showing multiple CP points. According to previous studies, the latest CP point should be accepted before reaching the 10% of DM value [15, 16]. As a final point, global instability occurs when the flatline is reached. This corresponds to huge values of DM, theoretically infinite, caused by any small increase of the IM values. Figure 3 demonstrates the IDA curve and limit states for the first record in X-direction of the C16 Building. The limit states for each record and building are calculated using an algorithm written especially for this purpose in python version 3.7 [19].

Table 3. Limit States generated for record No.1

Sa(T1,5%)			θmax		
IO	CP	GI	IO	CP	GI
0.37 g	0.78 g	0.85 g	1%	3.12%	+∞

Furthermore, summarizing IDA curves into different percentiles will provide large amount of data for the structural response behavior under the suite of ground motions selected. We have chosen to calculate the 16%, 50% and 84% percentile values using one of the methods proposed in previous studies [16]. In addition, fractile values of IM and DM are interpolated to generate finally the IDA fractile curves from 18 earthquake records usen in this study.

By properly reading the fractiles, it is much easier to get sufficient information from the demand calculation. As shown in the Figure 4, when Sa(T1,5%)=0.2g, 16% of the records produce θmax=0.5%, 50% of records produce θmax <0.7% and 84% of the records produce θmax <1.1%. Alternatively, the fractiles can be used in the inverse way to get more practical information. Therefore, in order to get demand θmax =3.0%, 16% of the records have to be scaled to Sa(T1,5%)≥0.96g, 50% of records to Sa(T1,5%)≥0.54g and 84% of the records should be scaled to Sa(T1,5%)≥0.40g.

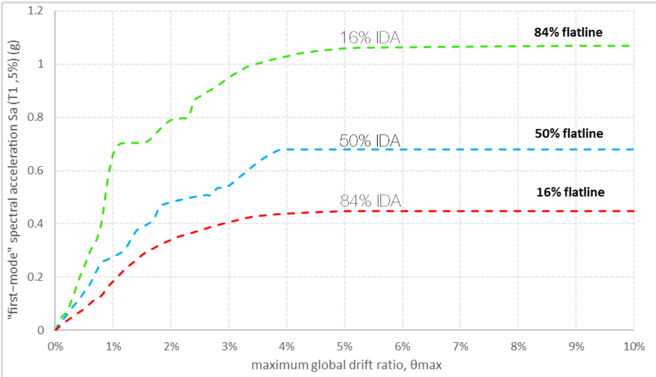

Figure 4. 16%, 50% and 84% IDA fractiles

4. Results

More than one thousand dynamic analyses are performed for the case study building in both directions modeled with concrete C16 and C10. Values for each earthquake record are used to generate 18 IDA curves for each of the four models. Moreover, limit states are defined for each of the IDA curve for the Immediate Occupancy, Collapse Prevention and Global Instability as shown in the figures below.

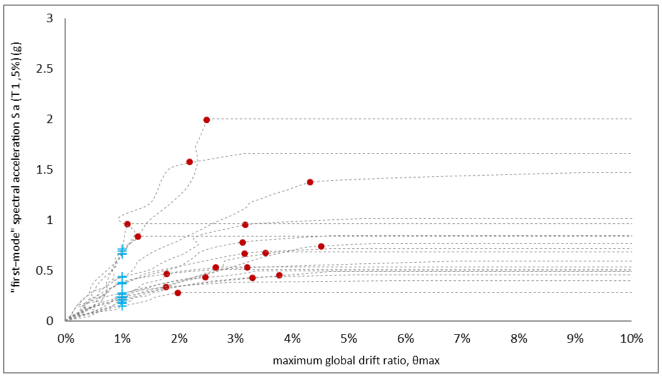

Figure 5. IDA Curves and Limit States for C16 - X direction

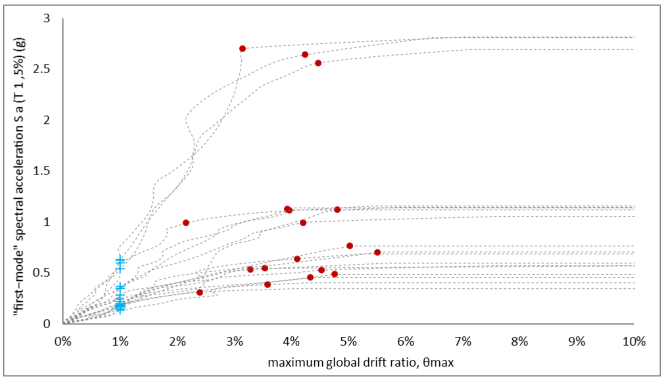

Figure 6. IDA Curves and Limit States for C16 - Y direction

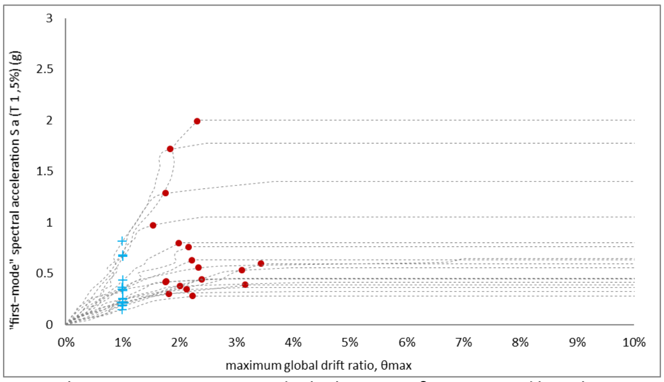

Figure 7. IDA Curves and Limit States for C10 - X direction

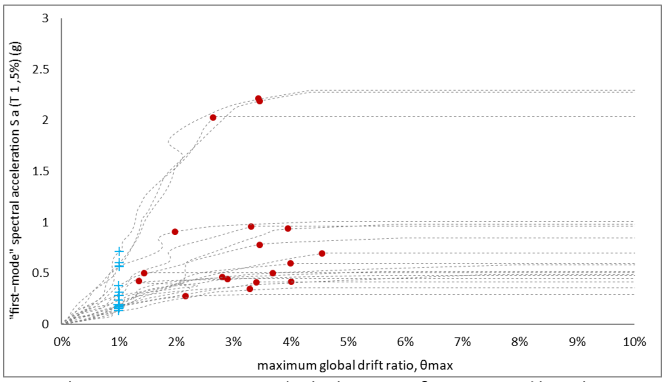

Figure 8. IDA Curves and Limit States for C10 - Y direction

From the graphs, it is clearly observed the softening and hardening of the IDA curves until the global instability (GI) is reached. GI is represented with flatlines on each of the curves indicating the total collapse of the building. Together with IDA curves, the limit states are plotted. With "+" sign is shown the immediate occupancy which corresponds to 1% of the damage measure. Furthermore, values from the collapse prevention limit states are calculated considering 20% of the elastic slope or 10% of the damage measure and plotted with dots in the graphs. Once the IDA curves and limit states are ready, it is more practical to observe the effect of each earthquake record on our building. As can be seen from the graphs, it is obvious that all models will fail in a range from about 0.3g to 0.9g from most of the earthquakes. However, earthquakes such as: Friuli (PGA = 0.345), Loma Prieta WAHO 000 (PGA = 0.370), Loma Prieta WAHO 090 (PGA = 0.638) will force the structure to fail later, thus at a higher intensity measure. This phenomenon is better observed especially in the y-direction of the models.

On the other hand, the information provided by the summarization of the IDA curves into 16%, 50% and 84% fractiles is remarkable especially in terms of seismic performance calculation. Consequently, it is possible to observe the response of the structure in any intensity measure increment, from the initial condition until total collapse of the building takes place.

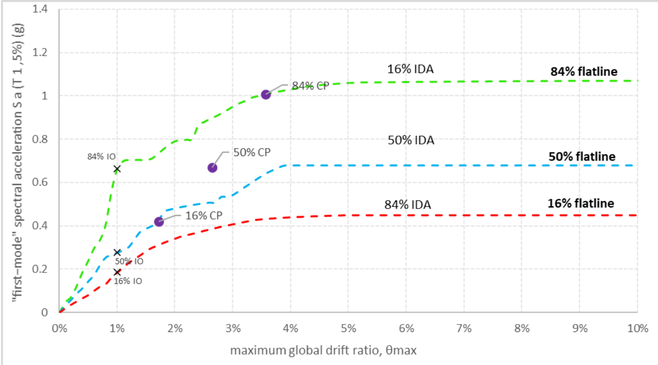

Figure 9. IDA Fractiles and Limit States for C16 - X direction

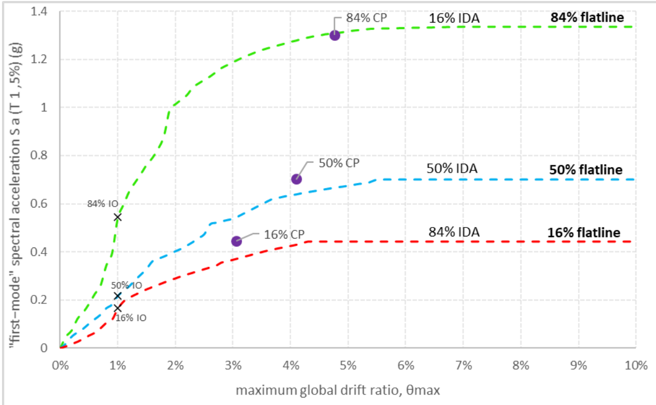

Figure 10. IDA Fractiles and Limit States for C16 - Y direction

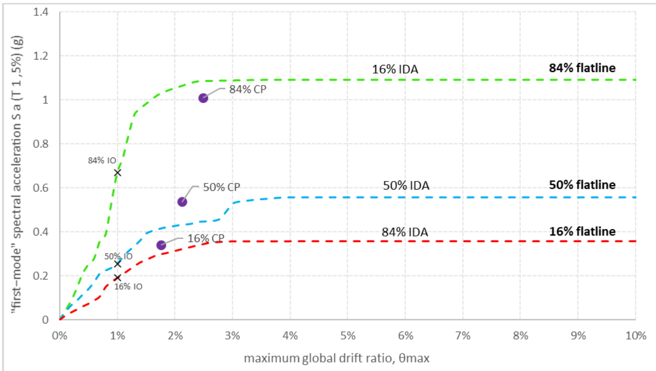

Figure 11. IDA Fractiles and Limit States for C10 - X direction

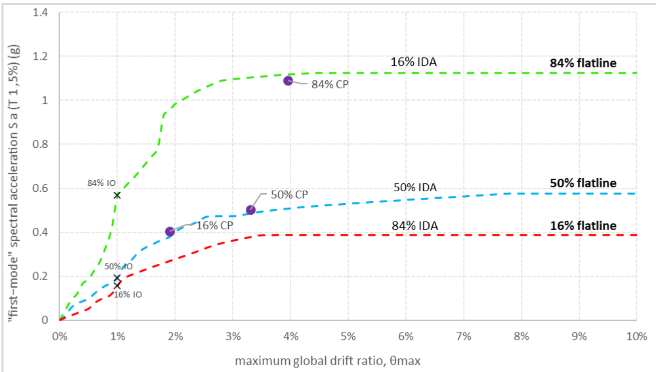

Figure 12. IDA Fractiles and Limit States for C10 - Y direction

For instance, when the intensity measure is equal to 0.4 g, it is observed that 16% of the records produce θmax ≤ 0.8%, 50% of the records produce θmax ≤ 1.6% and 84% of the records produce θmax ≤ 2.9% for the C-16 x direction model. Similarly, fractiles can be used to gather more information on the intensity measure for a target displacement. Thus, C16 y-direction model will reach θmax = 2.0%, when 16% of the records are scaled to 0.98g, 50% of the records when Sa(T1,5%) = 0.38g and 84% of the records when Sa(T1,5%) = 0.28g. Moreover, the limit states are very helpful for performance levels of the structure. As shown graphically, a rapid comparison can be done based on different concrete classes. Hence, in x-direction of the C16 model, 16% of the IDA records reached IO at Sa(T1,5%) = 0.19, 50% at Sa(T1,5%) = 0.28 and 84% at Sa(T1,5%) = 0.66. While in the same direction of C10 model, IO limit state is reached at Sa(T1,5%) = 0.19g by 16% of the records, 50% of the records at Sa(T1,5%) = 0.25g and 84% of the records at Sa(T1,5%) = 0.67g. From the collapse prevention limit state can be easily demonstrated the ductility difference between two concrete classes. For example, C16 – y-direction will reach CP limit state at $\theta max \leq 4.1\%$ by 50% of the records. On the other hand, we can observe an early CP point for the same direction of C10 model at $\theta max \leq 3.3\%$. In the same trend we could interpret the response of the building for the total collapse. For instance, 50% of the records force the C16-X-direction model to fail at Sa(T1,5%) = 0.68g and C10-X-direction model at Sa(T1,5%) = 0.56g.

5. Conclusions

Seismic performance estimation is presented for a five-story reinforced concrete building designed in 1982 according to old Albanian building code. The building is a moment resisting frame template residential building without shear walls. Both of its transverse frames are modeled in the environment of ZeusNL software, which uses fiber approach modelling technique for the nonlinear analysis. Due to concrete aging, the building is modeled using C16 and C10 concrete classes. Demand calculations are performed using one of the most recent methods used in the Performance-Based Earthquake Engineering (PBEE) such as Incremental Dynamic Analysis (IDA). For nonlinear dynamic analysis, a set of 18 ground motion records is selected, bearing no signs of directivity. Moreover, a methodology is presented for the development of the IDA curves by properly selecting a suitable intensity measure (IM-5% damped first mode spectral acceleration) and damage measure (DM- maximum global drift ratio). In addition, the limit states are selected as Immediate Occupancy (IO), Collapse Prevention (CP) both defined in FEMA guidelines and Global Instability (GI). Furthermore, IDA curves are summarized in 16%, 50% and 84% fractiles together this their limit states. Finally, is introduced a detailed interpretation of the structural response in terms of IM as well as DM for the seismic evaluation.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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