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ORIGINAL ARTICLE **OPEN ACCESS**

Evaluation of Seismic Behavior of Progressive Collapse of the Steel Structures Equipped With Coaxial Bracing Using Fragility Curve

Peyman Sabbahfar
Msc in Structural Engineering University of Bologna - Italy
Email:: Peyman.sabbahfar@studio.unibo.it

ABSTRACT
One of the key instruments in evaluation of seismic risk that is being widely used at the current age is fragility curve. Fragility curve expresses the exceeding probability of structural damage from a certain damage level for several risk levels of seismic motions. The curve has abundant uses before and after earthquake, so that in addition to evaluate seismic vulnerability, it could be used in other cases such as determination of priorities in retrofitting structures and crisis management planning. Progressive collapse is consecutive destruction (domino), which connects positional damage to large scale in a structure. Hence, in this study, the seismic behavior of progressive collapse of moment steel frames is evaluated using fragility curves under fault far and near earthquakes. In this study, models are developed in 2-D mode for a 5-storey in OpenSees software with 4 spans. 4 earthquake records from different regions of the world on soil type II were selected and the earthquake records were analyzed under nonlinear time history. Then, maximum drift values for each model were obtained using MATLAB software under each earthquake record. Then, using the equations to calculate failure probability and extraction of required coefficients from the ASCE40-06, the probability of occurrence of each failure mod was obtained in each Sa value for each model and finally, the fragility curve was traced using statistical relations among data. The obtained results show high sensitivity of moment frames behavior, whether in linear or nonlinear section for wrong implementation of clamped joints in floors 2 and 3.
***Key words**: seismic behavior, progressive collapse, fragility curves, steel frames, fault near and far earthquakes*

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INTRODUCTION

Iran is located in active region of the world in terms of seismic status and is considered among the most hazardous regions of the world as a result of powerful earthquakes according to information caused by academic documents and evidences of 20th century. Over the years, in average, an earthquake happens every 5 years with high life and financial losses in a region of country and Iran is current in top of list of countries with earthquakes with high life losses. Although it is hard and even impossible to prevent damages of hard earthquakes completely, with the increase in information about seismicity of Iran and careful study of buildings, infrastructural facilities and vital arteries and correct and basic retrofitting of buildings, the losses caused by earthquake could be decreased to desirable level. According to various progressive collapses while earthquake, it is important to take designations against this event, along with seismic designations. Moreover, effect of details of seismic designs in reduction of progressive collapse could be evaluated through case studies of this event in buildings. Progressive collapse is a phenomenon, in which positional collapse of an element of structure is extended to adjacent elements and this can lead to total collapse or vast collapse of the structure, which is not comparable with the initial positional collapse (figure 1 and 2). To prevent progressive collapse, the structure should have enough continuity to provide alternative path and structural sustainability when a member of vertical loading system is omitted. A structure designed based on seismic resistance capacity in seismic regions has close designation properties to regulations of progressive collapse. The relevant studies have shown that appropriate details and retrofitting processes to improve seismic resistance of a structure could provide high safety system against progressive collapse [1, 2]. Seismic design regulations have been fundamentally revised after the recent earthquakes and the evaluations have revealed some defects in previous engineered buildings. In general, safer seismic buildings are those buildings designed based on current seismic regulations. Seismic designs are basically concentrated on lateral loadings; although designation for progressive collapse considers gravity loads. Innate resistance of designed seismic structures against progressive collapse could be evaluated using alternative path analysis of case loading. For progressive collapse evaluations, an analytical process should be considered, which has the ability to consider effects of lateral seismic loadings at the same time with gravity loads. Common methods of progressive collapse considering just gravity loads have not the ability to calculate and model all effects of progressive collapse while earthquake. Moreover, falling rubbles of collapsed members could lead to considerable impact loading on other elements, which should be considered in analysis and their effects on structure should be evaluated.

figure 2: progressive collapse as a result of Taiwan Earthquake, 1999

figure 1: progressive collapse of middle class of building as a result of Kobe Earthquake, 1995

Through analyzing existing references, it could be mentioned that seismic behavior of moment frame system and bracing systems has been evaluated in numerous studies over the 3 decades. However, the behavior of these systems in facing progressive collapse while collapse of important elements has not been investigated completely. Paul has used various analysis methods and has found that impact factor 2 used in linear static analyses could provide same desired result [7]. Ruth et al found that coefficient of 1.5 show dynamic effect better than other coefficients, especially for steel moment frames [1]. Kim et al studied capacity of resistance against progressive collapse of steel moment frames using secondary path analyses offered in DoD and GSA guidelines and observed that nonlinear dynamic analysis could result in larger responses for the structure. However, linear method is more conservative decision for probability of progressive collapse of model structures [3]. Lourdes A. Mieses, Ricardo R. López, Ali Saffar (2007) [4] have conducted a study and provided fragility curve for structures with shear walls in Puerto Rico. The study was done on middle story structures and for this purpose, 26 models with 3-10 stories were selected. 2 artificial earthquakes were applied based on geological conditions and also, 3 previously occurred earthquakes were used including Imperial Valley, Northridge and San Salvador earthquakes. The models were analyzed based on LARZ instruction numerically [5].

MATERIALS AND METHODS

In this study, seismic vulnerability of one common structural type in Iran as steel structures with medium moment frame system is studied. The studied model in this research is a 2-D and 4-span 5-storey frame with uniaxial bracing frame. The fragility curve of this system has been traced using IO LS CP service index and drift failure index inserted in ASCE41-6. To this end, models have been provided in 3-D mode in OpenSees software, under the near and far seismic records and the records are scaled from 0.1 to 3.5g, and were analyzed using nonlinear time history analysis. Then, through applying required statistical techniques on the data, fragility curves were provided for each model. Moreover, the studied structure was analyzed with no loss and then, the joints with 15% failure were omitted and other sections were remained unchanged (figure 3).

figure 3: model with 10% failure

table 1: information of the columns used in the model

floor 1	**648x330x38x21**
floor 2	**648x330x38x21**
floor 3	**648x330x38x21**
floor 4	**544x312x20x13**
floor 5	**544x312x20x13**

Table 2: information of the beams used in the model

floor 1	**693x252x24x13**
floor 2	**693x252x24x13**
floor 3	**693x252x24x13**
floor 4	**549x214x24x13**
floor 5	**549x214x24x13**

information of beam and column materials

E_s	***200 Gpa***
F_y	**260 Mpa beam** **Mpa 320 column**
μ	**0.015**
R_0	**20**
a_1	**15**
a_2	**0.15**
a_3	**0**
a_4	**1**
ε_{ult}	**0.1**
γ	**0**

Earthquake records

Selecting earthquake records near the origin of the found near the earthquake could be the most important parameter affecting the collapse caused by earthquakes. Phenomena such as directional earthquake could be effects of such nearness. Direction caused by an impact at the beginning of time history of earthquake is very important. The investigations have shown that big cities of Iran like Tehran, Tabriz and many other residential regions like cities of Kerman Province have been constructed near the active faults and extension of these cities over the years has caused faults pass over the cities [5]. In this study, the behavior of steel structures under the far and near earthquakes to fault has been analyzed. For this purpose, for dynamic analysis, two earthquakes near the fault and two earthquakes far from the fault are applied. The information of applied records are presented in table 4.

Table 4: applied records

Earthquake	Station	Year	Max acceleration (g)	Area
Imperia1 valley	E1 Centro Array	1979	0/4273	Near to fault
Northridge	Sylmar Convertsr Sta	1994	0/3848	Near to fault
Chi Chi	HWA 053	1999	0/02732	Far from fault
Codling	Parkfield Chohame 3 E	1983	0/4432	Far from fault

Incremental nonlinear dynamic analysis

The first step in an IDA analysis is to have right understanding of inputs and outputs of this type of analysis. In fact, the main issue in conducting a seismic evaluation of existing structures is a purpose based on applying a series of sequential operations on the data and outputs. Recently, a seismic research institute in Berkeley, California has proposed a logical procedure for analysis of this issue. The process is defined in this form that firstly, through conducting a seismic risk analysis in the studied area, a parameter is applied on the structure called IM as input. In next step, through conducting analysis, the structural response to the seismic stimulation is obtained and the incremental nonlinear dynamic parameter (EDP) is obtained per IM. In next step, through introducing a structural damage index, the probability of damage or exceed of authorized input vibration value from a special value could be obtained and in next step, the amount of the cost for repairs caused by losses could be measured. Therefore, IDA curves refer to a series of IM curves against EDP, on which probable lateral investigations could be conducted. The graph in following figure could illustrate the process in better way [6].

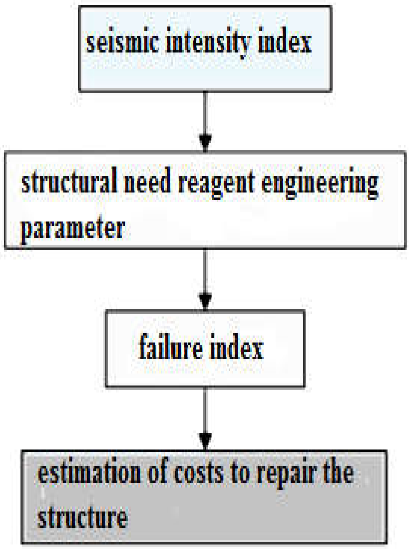


Figure 4: the procedure of designation method based on function introduced in PEER California [6]

RESULTS

Incremental nonlinear dynamic analysis

At the present study, for purpose of incremental nonlinear dynamic analysis, IDA graphs are traced in two forms: to trace the first graph, two inputs of maximum base shear (y axis) and roof drift (axis x) are used for each earthquake and in another graph, Scale Factor is used in y axis and maximum roof drift in x axis and in each graph, the transition point is illustrated from 3 service levels including CP, LS and IO.

Incremental nonlinear dynamic analysis for areas near to fault

In this study, for the areas near to fault, two earthquake records are used. In figures 5-8, the IDA graph is illustrated for Imperial Valley Earthquake and in figures 9-12 have illustrated these areas for Northridge Earthquake.

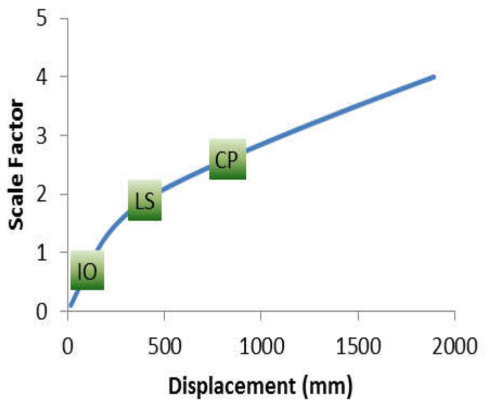


figure 6: IDA curve for Imperial Valley Earthquake with scale factor with no damage

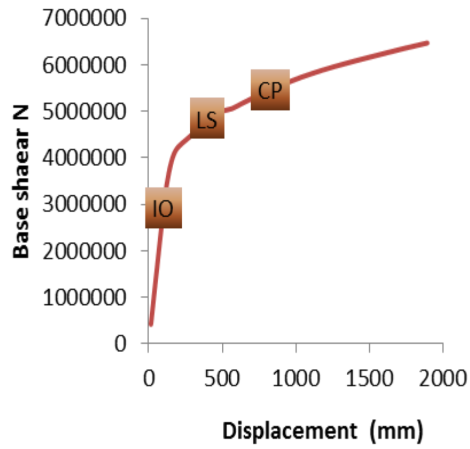


figure 5: IDA curve for Imperial Valley Earthquake with base shear with no damage

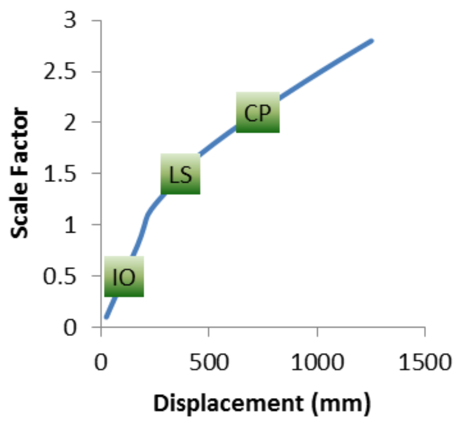


figure 7: IDA curve for Imperial Valley Earthquake with scale factor and 10% damage

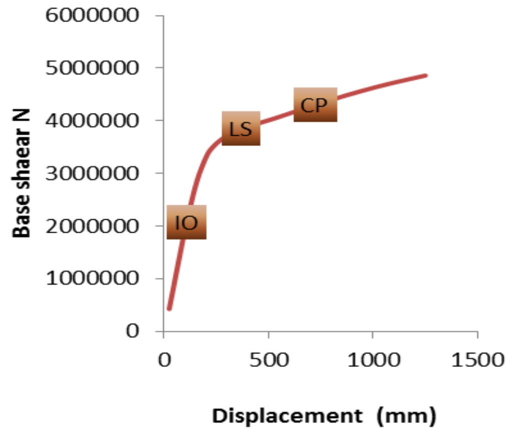


figure 7: IDA curve for Imperial Valley Earthquake with base shear with 10% damage

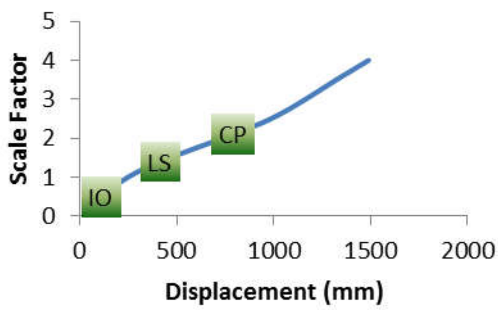


figure 10: IDA curve for Northridge Earthquake with scale factor with no damage

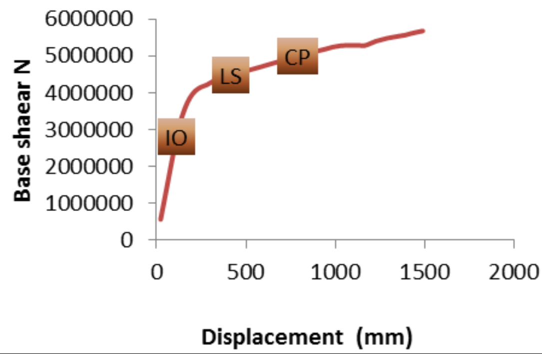


figure 9: IDA curve for Northridge Earthquake with base shear with no damage

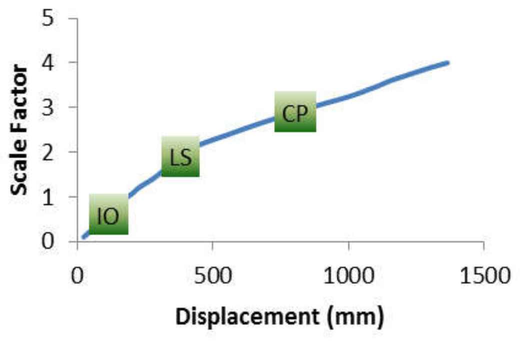


figure 12: IDA curve for Northridge Earthquake with scale factor with 10% damage

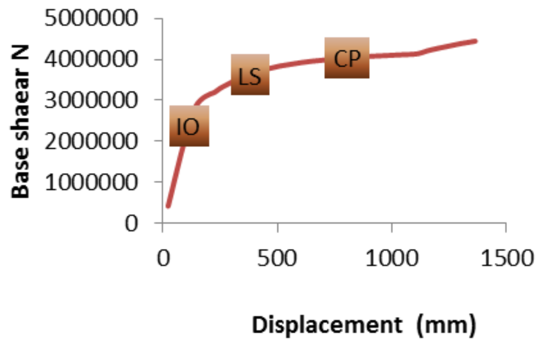


figure 11: IDA curve for Northridge Earthquake with base shear with 10% damage

Incremental nonlinear dynamic analysis for areas far from fault

In this study, for the areas far from the fault, two earthquake records of Chi Chi and Codling are used. In figures 13-16, the IDA graph for Chi Chi square and figures 17-20 have illustrated the graphs for Codling Earthquake.

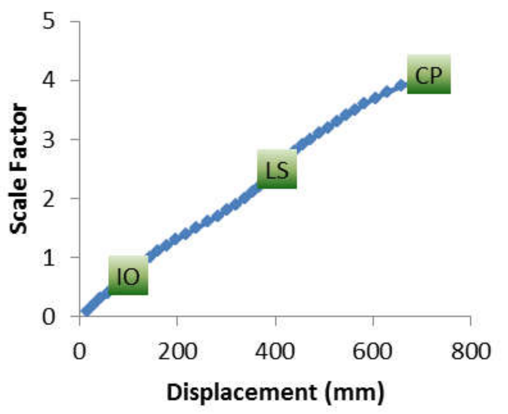


figure 14: IDA curve for Chi Chi Earthquake with scale factor with no damage

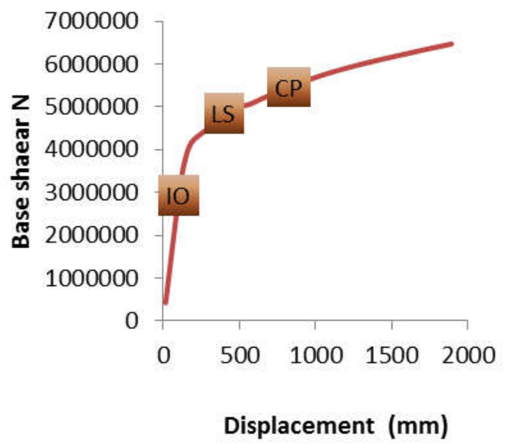


figure 13: IDA curve for Chi Chi Earthquake with base shear with no damage

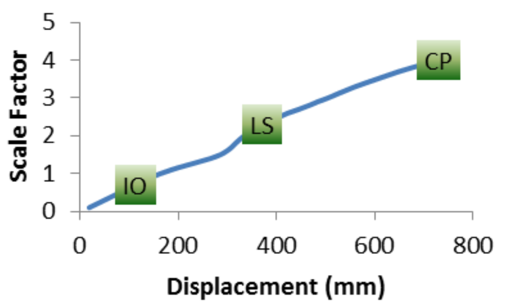


figure 15: IDA curve for Chi Chi Earthquake with scale factor with 10% damage

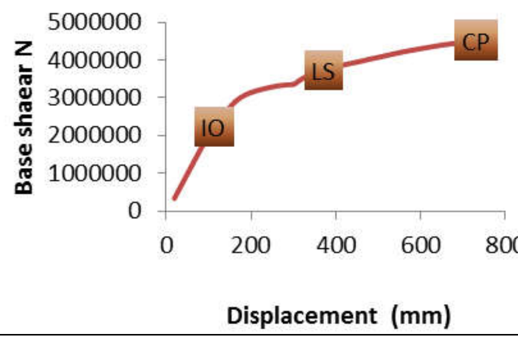


figure 15: IDA curve for Chi Chi Earthquake with base shear with 10% damage

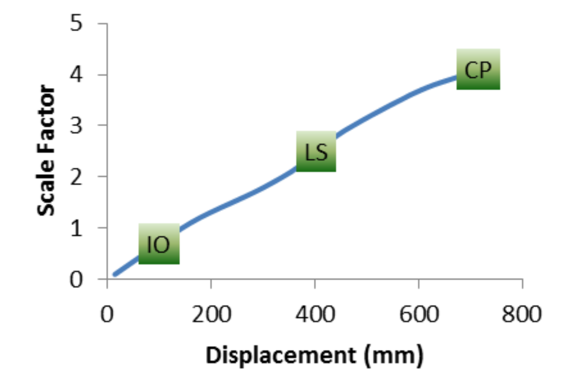


figure 18: IDA curve for Codling Earthquake with scale factor with no damage

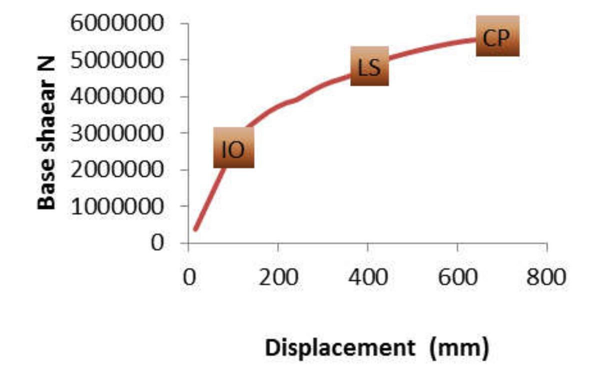


figure 17: IDA curve for Codling Earthquake with base shear with no damage

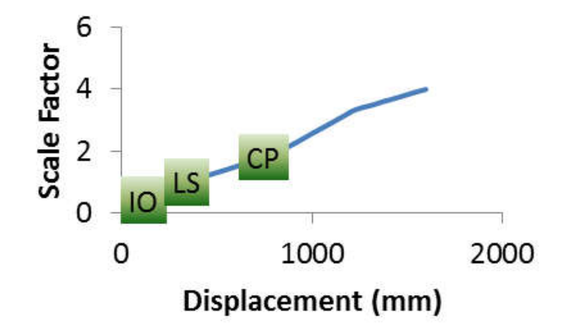


figure 20: IDA curve for Codling Earthquake with scale factor with 10% damage

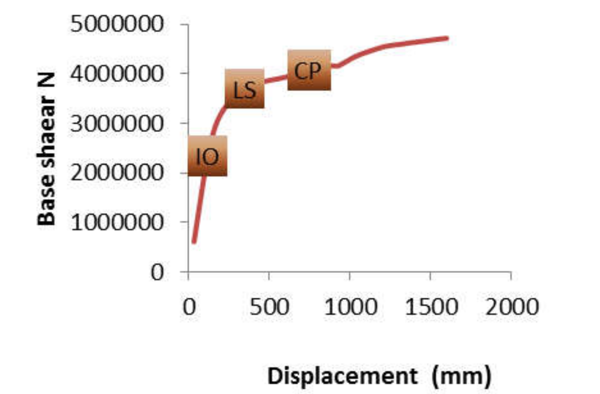
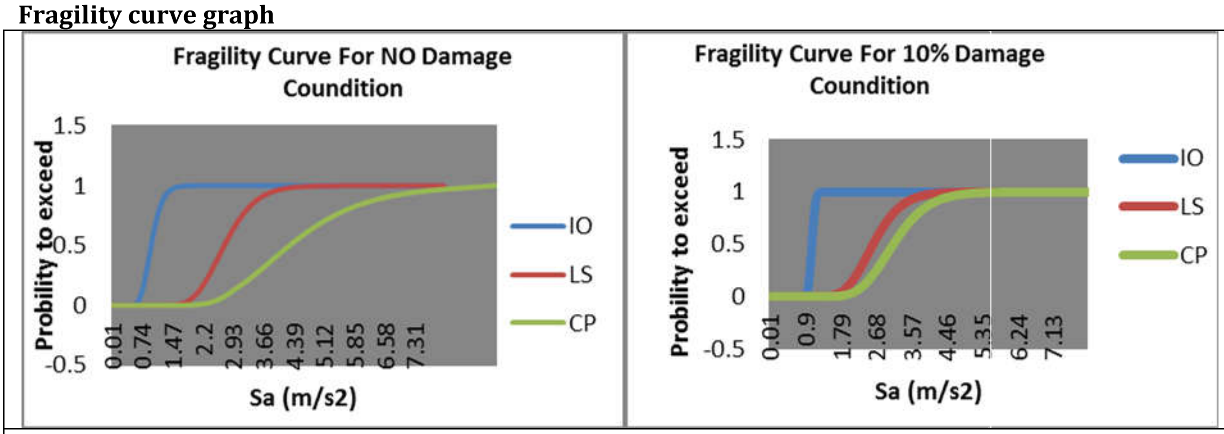


figure 19: IDA curve for Codling Earthquake with base shear with 10% damage

Fragility curve graph



A **B**

figure 21: a) fragility curve with 10% damage b) structural fragility curve without failure**B**

Analysis of collapse after earthquake caused by omission of one column

In this study, because of further analysis of structural seismic behavior caused by earthquake and omission of one column because of accidents after earthquake like fire that is more common than terrorist attacks in Iran, a seismic comparison has been given based on service level in two modes of failure and checking DCR of columns according to loading in the UFC-97 Act in linear static way in third step of modeling, which is more powerful comparison than DCR comparison of two structures in a special scale factor.

To this end, DCR of columns and the increasing percent of columns in collapsed mode of 10% compared to no collapse mode in service levels of CP and LS related to two studied structures is obtained for all 10 earthquakes.

The overall results of DCR in 10 earthquake records are presented as follows:

Table 5: overall results of DCR, 4 earthquake records for LS

Codling	0.96310299	1.073039069
Chi Chi	1.233057987	1.236593499
Imperia1 vally	0.963312126	1.076508667
Northridge	0.962946132	1.073607063
Tabas	0.934922372	1.084846448

table 6: overall results of DCR, 4 earthquake records for CP

Codling	0.960451209	1.069931418
Chi Chi	1.233057987	1.236593499
Imperia1 vally	0.961998089	1.072965009
Northridge	0.966318281	1.070622893
Tabas	0.938386135	1.085363864

CONCLUSION

According to the results obtained from the graphs for each area, it could be found that falling has happened from the IO service level before the slope failure point (linear curved area that base shear is increased linearly with the increase in scale factor) and this shows that the defined index drift=0.7% by the ASCE40-06 in studied structure for this service level has been conservative and in fact, the structure has passed from this service level in higher scale factor. This shows that real time slope of IO graph in failure curves is lower than the slope illustrated in figure traced based on collapse index of ASCE-40-06. In fact, the desired structure has better linear performance than 4 studied earthquake records. The functional levels of CP and LS of the structure with 10% damage are closer to each other compared to non-manipulated structure. This issue is illustrated in fragility curve graphs of the two service levels in two mentioned modes. More nearness of LS to CP in the graph of 10% damage shows that passing from the two levels happens in two responses of spectral acceleration closer to each other and shows that in damages higher than 10%, two mentioned curves become closer to each other and in worst mode; the curves would be overlapped. In other words, it could be mentioned that the structure without experience of LS service level enters to CP service level. Numerical expression of this issue is as follows: the structure reaches directly to drift=5% in a special scale factor without reaching to drift=2.5% (related to LS service level) in previous scale factors. It means that it shows weaker nonlinear behavior. The results and values obtained from the analysis show very high sensitivity of moment frame behavior in both linear and nonlinear sections compared to wrong implementation of clamped joints in floors 2 and 3. Structures with strong fragility curve (lower slope) show better response to progressive collapse. Mean increase in DCR in collapse of 10% compared to no damage for LS service level for all columns is equal to 21.21% and is equal to 12.73% for floor 1 columns and the values are respectively equal to 9.52% for all columns and 30.04% for floor 1 columns for the CP service level. In field of analysis of DCR of elements based on UFC-97, only the element No.19 is in S.F=2 for the mode of no damage and S.F=1.4 for 10% damage. It could be claimed based on obtained results that the structure designed for progressive collapse caused by terrorist accidents in accordance with UFC-97 shows good response to accidents after earthquake (fire or gas explosion) after earthquake and omission of critical column of the structure; although it is weakened and joints are formed.

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