EVALUATION OF COLLAPSE MARGIN FOR RC FRAMES DESIGNED BASED ON IRANIAN SEISMIC CODE

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ABSTRACT

One of the main goals of the seismic design philosophy is to design structures so that the structural collapse to be prevented under intense ground motions. Therefore it is important to quantify the margin of safety against structural collapse. Nonetheless due to high level of nonlinearity involved in vicinity of structural collapse the analytical modeling and assessment is complex and demanding, and includes several sources of uncertainties. Although this issue has attracted considerable interest among seismic engineers and researchers during several past decades no standard method has been introduced. During the past few years FEMA has published a guideline for quantification of the building Seismic Performance Factors, i.e. response modification factor, overstrength factor and displacement amplification factor (FEMA, 2009). As part of the proposed methodology one can assess the structural collapse potential. The approach includes a combination of incremental nonlinear dynamic analysis (Vamvatsikos and Cornell, 2002) and suggested criteria based on semi-probabilistic method to evaluate Collapse Margin Ratio (CMR).

The main objective of this research is to study the collapse margin ratio for reinforced concrete frame buildings designed according to Iranian seismic standard (Standard 2800). Incremental dynamic analysis (IDA) is carried out using 22 scaled natural ground motion records. The study includes RC moment resisting frames with 3, 6 and 10 stories considering two types of soil classifications (Type II and III) and two alternatives of ductility levels (Intermediate and high ductilties), according to standard 2800. It is concluded that the RC frame structures designed based on the Iranian Seismic code generally have sufficient margin against collapse based on the FEMA P695 approach. However the actual margin of collapse varies depending on the characteristics of the structures

INTRODUCTION

Providing sufficient energy dissipation capacity through plastic deformation is the main goal considered in designing seismic-load-resisting systems for a reduced seismic load. Seismic design response factors, namely overstrength (Ω_o), force reduction factor (R) and deflection amplification factors (C_d), are used to reduce the seismic forces and amplify deformations to arrive at cost-effective and safe designs. On the other hand, restricting the R and C_d values is necessary to prevent excessive inelastic deformations and loss of life, particularly in the event of a major earthquake. Seismic design response factors introduced in seismic codes do not necessarily offer a uniform margin of safety and economic C_d solution considering different seismic regions and the diversity of structural systems, construction practices and quality control. Moreover, modern design codes do not fully address all structural systems currently used in different parts of the world. The capability of these systems to meet the intended seismicdesign objectives is also not adequately understood (FEMA, 2009; Mwafy, 2011).

The primary method of achieving the safety of life, the performance function by having an acceptable low probability of collapse of the seismic force-resisting system for maximum considered earthquake ground motions.In general, collapse of a structure would primacy to very different numbers of mortalities, depending on the structural system type, the number of building occupants, etc. However, life safety risk is both harden to calculate accurately, due to uncertainty in mortality reckons given collapse, and even greater uncertainty in assessing the effects of falling dangers in the loss of collapse. Rather than attempting to provide uniform preservation of "life safety", the Methodology provides approximate uniform protection against collapse of the structural system. (Kircher and Heintz, 2008).

The objective of this study is to verify margin of collapse of the structures used in the seismic design of reinforced concrete (RC) multi-story buildings through incremental dynamic collapse analysis (IDA). All structures are first designed according to Standard 2800 and ACI 318-11. They are then modeled and analyzed using SAP2000 program and incremental dynamic analysis. The 22 ground motions used in this study are those suggested by FEMA P695. The collapse is assessed for each record and the median value is calculated among the 22 records (median value of collapse, S_{CT}). The ratio of median value of collapse to spectral response acceleration at the fundamental period (S_{MT}) is called collapse margin ratio (CMR) (FEMA, 2009).

INCREMENTAL DYNAMIC COLLAPSE ANALYSIS

The Methodology consists of a probabilistic assessment of collapse risk. It utilizes nonlinear analysis techniques, and explicitly considers uncertainties in ground motion, modeling, design, and test data. The technical approach is a combination of traditional code concepts, advanced nonlinear dynamic analyses, and risk-based assessment techniques. Reliable analysis requires valid ground motions and representative nonlinear models of the seismic-force-resisting system. Development of representative models requires both detailed design information and comprehensive nonlinear test data on structural components and assemblies that make up the system of interest.

Each model is subjected to the predefined ground motions that are "systematically scaled to increasing intensities until median collapse is established. Collapse performance is evaluated relative to ground motion intensity associated with the MCE." The methodology defines the collapse level ground motions as, "the intensity that would result in median collapse of the seismic-force-resisting system" (FEMA, 2009).Response History analysis is used to calculate the median collapse capacities ($\hat{S}CT$) and the CMR. The ground motion sets are scaled based on the fundamental vibration period of the model being evaluated.

Two ground motion sets are provided for nonlinear dynamic analysis collapse assessment. One set includes 22 ground motion record pairs from sites located greater than or equal to 10 km from fault rupture, referred to as the "Far-Field" record set. The other set includes 28 pairs of ground motions recorded at sites less than 10 km from fault rupture, referred to as the "Near-Field" record. Far-Field ground motions, are supplied in the methodology to provide an unbiased group that "represents strong ground motion shaking with earthquake magnitudes of 6.5 to 7.9" (FEMA, 2009). Far-Field record sets are provided for two types of soil classifications (Type II and III).The records are scaled in a two-step process: normalizing and scaling. The normalization portion of the process was completed during the development of the record sets. Scaling is similar to that of Standard 2800.

System behavior is characterized through the use of structural system archetypes. Establishment of archetypes begins with identifying the confine of Patterns and behavioral characteristic that explan the bounds of the proposed seismic-force-resisting system.Archetypes provide a systematic abilities for characterizing admissible configurations and other significant Patterns of the proposed system. Structural system archetypes are assembled into bins called performance groups, which reflect major parts, or changes in behavior, within the archetype design space. The collapse safety of the proposed system is then evaluated for each performance group (Baker et al., 2010; Donovan and Memari, 2011).

An incremental nonlinear dynamic analysis of the models subjected to strong ground motions, matched with the design spectrum was carried out to calculate Vy (Mahmoudi and GhasemAbdi, 2012). The conversion to spectral coordinates is based on the base shear (V) and the assumption that all the effective seismic weight of the structure (W) participates in the fundamental mode at period (T) (FEMA, 2004). The SPF's are defined in terms of spectral coordinates in Figure 1.

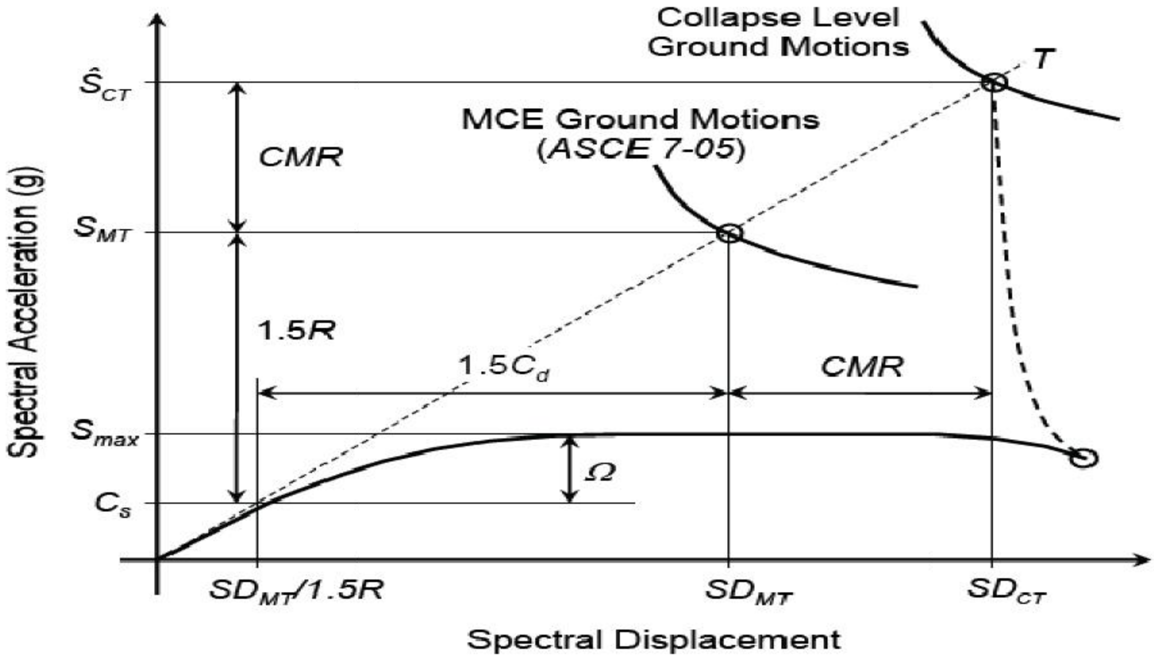


Figure 1: Methodology Illustration of Seismic Performance Factors (FEMA, 2004b)

In the following the main equations to defin SPFs are introduced based the methodology (FEMA, 2009). 1.5 times R is shown in the Figure 1 and defined as:

$$1.5R = \frac{S_{MT}}{C_S} \tag{1}$$

The collapse margin ratio is defined in terms of the ratio of median 5% damped spectral acceleration at the collapse level ground motions (ŜCT) (or corresponding displacement, SDCT) to the 5% damped spectral acceleration of the MCE ground motions (SMT) (or displacement, SDMT) (FEMA, 2009). The CMR is calculated as:

$$CMR = \frac{\hat{S}_{CT}}{S_{MT}} \tag{2}$$

Adjusted collapse margin ratio (ACMR) for each archetype is calculated using spectral shape factors (SSF) which are calculated based on fundamental period (T) and period-based ductility (μT). Tables 7-1a of FEMA (2009) provide the values for SSF.

$$ACMR_i = SSF_i \times CMR_i \tag{3}$$

Adjusted collapse margin ratio (ACMR) is modified to reflect modeling related and record to record and other sources of collapse uncertainties.Each system is assigned four numerical values based on the following: 1) the confidence in basis of design requirements related to the actual level of behavior to intended results (βDR); 2) the effectiveness of the testing program to quantify properties, behaviors, and failure modes of the system (βTD); 3) the accuracy and robustness of models to represent collapse characteristics (βMDL); and 4) total system collapse uncertainty based on record to record variability (βRTR), which is assigned a set value of 0.4 for the methodology. Since the four component Chancy variables are assumed to be statistically independent, the lognormal standard deviation parameter, βTOT, describing total collapse uncertainty, is given by equation 4. Values for total system collapse uncertainty (βTOT) is provided in Tables 7-2a, 7-2b and 7-2c of FEMA (2009). An increase in uncertainty will flatten the curve plotted from IDA. Increased uncertainty in turn increases the probability of collapse at the MCE intensity, SMT, and affects the CMR (FEMA, 2009).

$$ {}_{TOT} = \sqrt{ {}^{2}_{DR} + {}^{2}_{TD} + {}^{2}_{MDL} + {}^{2}_{RTR} } \qquad (4) $$

The Methodology defines acceptable values of the collapse margin ratio in terms of an acceptably low probability of collapse for MCE ground motions, given uncertainty in the collapse fragility. Systems that have more robust design requirements, more comprehensive test data, and more detailed nonlinear analysis models, have less collapse uncertainty, and can achieve the same level of life safety with smaller collapse margin ratios. Calculated values of collapse margin ratio are compared with acceptable values that reflect collapse uncertainty.

Acceptable performance is achieved when the following two criteria is met for each performance group and each index archetype:

• The average value of adjusted collapse margin ratio for each performance group exceeds $ACMR_{10\%}$:

$$ \overline{ACMR}_{i} \geq ACMR_{10\%} \qquad (5) $$

• Individual values of adjusted collapse margin ratio for each index archetype within a performance group exceeds $ACMR_{20\%:}$

$$ \overline{ACMR}_{i} \geq ACMR_{20\%} \qquad (6) $$

Acceptable values of adjusted collapse margin ratio are shown in Table 29 of FEMA P695 data (FEMA, 2009).

NONLINEAR MODELING OF THE ARCHTYPES

As the first step, it is required to gather thorough data about the seismic-force-resisting system. These data includes type of construction materials, system possible configurations, inelastic energy dissipation mechanisms, and intended range of application. Structural system archetypes are developed according to these types of data in order to represent the bounds of proposed seismic-force-resisting system. Structural archetypes provide the basis for preparing a finite number of designs, and then provide a corresponding number of idealized nonlinear models. These models should appropriately represent nonlinear behavior of proposed seismic-force-resisting system (Farahi and Mofid, 2013).

The study includes RC moment resisting frames with 3, 6 and 10 stories considering two types of soil classifications (Type II and III) and two alternatives of ductility levels (Intermediate and high ductilties), according to standard 2800.In all the aforementioned RC two-dimensional frames, the height of the stories is equal to 3.2 m and the bay length is assumed to be constant and equal to 6 m for all of the archetypes and plans are depicted in Figure 2. The seismic performance factors are primarily assumed according to Standard 2800. The seismic design specification of the seven index archetype are shown in to Table 1.

After designing the aforementioned archetypes, nonlinear dynamic analyses should be performed to investigate system behavior in each case and in every performance group. It is required to prepare nonlinear models of the mentioned archetypes in order to carry out such analyses.In these analyses, particular ground motions are scaled in order to increase intensities until the structure reaches a collapse point which is considered as a story-drift ratio equal to 10% according to Vamvatsikos and Cornell. At this point, the simulation is stopped and the IDA begins again for the next acceleration spectra record. During IDA the collapse probability of the selected archetype is supervised at several levels of spectral acceleration. At each level the maximum interstorey drift experienced by the structure from each ground motion in the record set is plotted against the actual median spectral acceleration of the set. When a structure collapses its interstorey drift swiftly increases (similar-horizontal lines on the figure) (FEMA, 2009; Zsarnóczay Á, 2013).

This modeling was carried out using nonlinear modeling features of the SAP 2000 software.

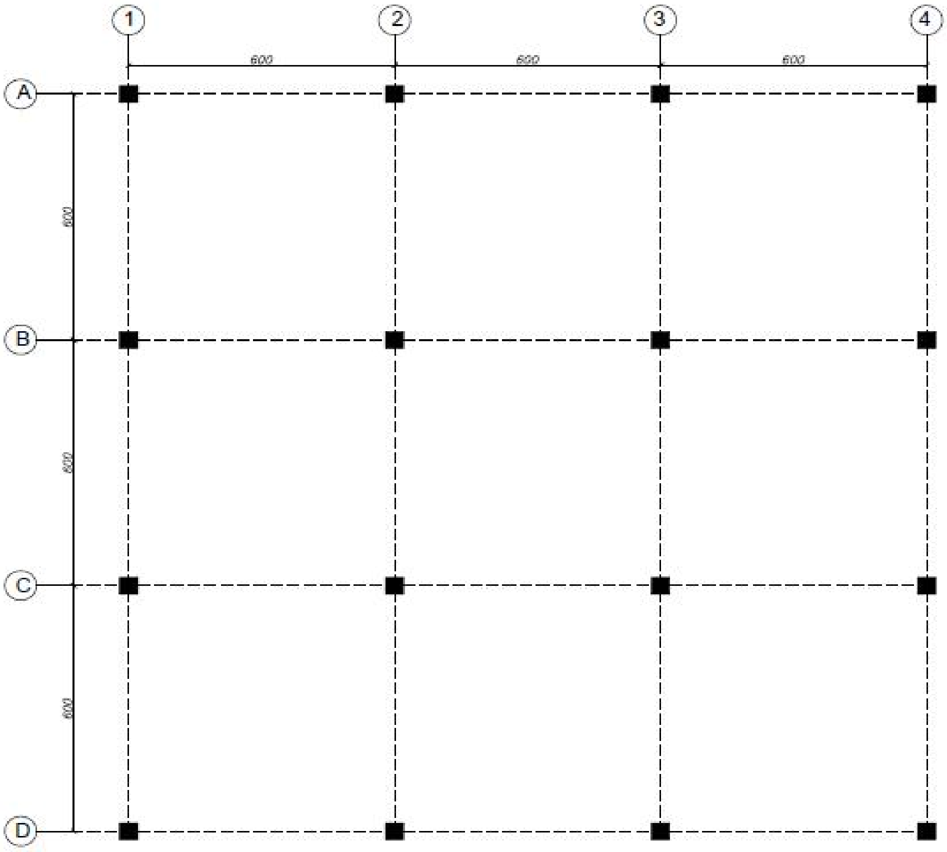
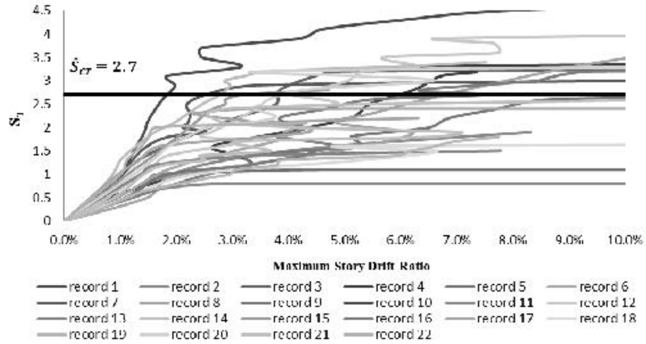


Figure 2.General form of RC plan under consideration in this study.

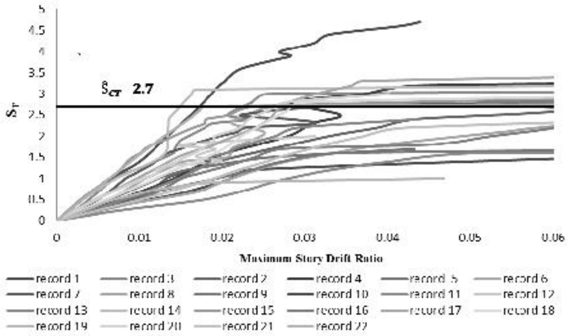
Table 1. Performance groups for evaluation of archetypes.

SeismicGroup		Number Of Storey	Height	Soil Classifications	ductility	W(ton)	I	A	R	T	B	C_S
1	1-A	3	9.6	II	Intermediate	128.7	1	0.3	7	0.38	2.5	0.107
	1-B	6	19.2	II	Intermediate	271.2	1	0.3	7	0.64	2.12	0.09
	1-C	10	32	II	Intermediate	451.8	1	0.3	7	0.942	1.64	0.07
2	2-A	6	19.2	II	High	260	1	0.3	10	0.64	2.12	0.0636
	2-B	10	32	II	High	449.16	1	0.3	10	0.942	1.64	0.049
3	3-A	6	19.2	III	Intermediate	274.7	1	0.3	7	0.64	2.75	0.1178
	3-B	6	19.2	III	High	272.21	1	0.3	7	0.64	2.75	0.0825

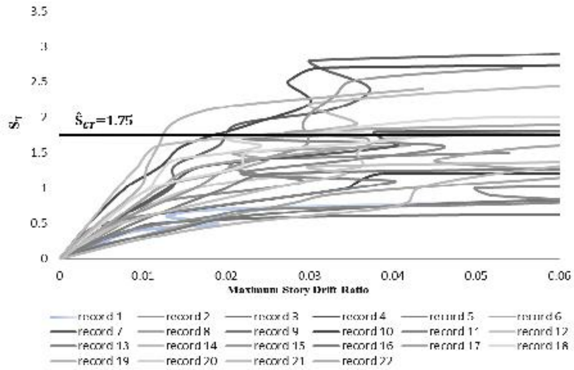
Nonlinear dynamic analyses are conducted under a gravity load combination and input ground motions which are selected from the Far-Field record set proposed by FEMA P695. This set consists of 22 pairs of earthquake records. These analyses are utilized to establish the Median Collapse Capacity, S_{CT}, and Collapse Margin Ratio, CMR, for each index archetype model. Median Collapse Capacity is the ground motion intensity in which half of the records in the set cause collapse of an index archetype model (Figure 3). Such intensity can be established through conducting Incremental Dynamic Analyses (IDA). Therefor, in this study, S_{CT} has been evaluated through the concept of Incremental Dynamic Analyses (IDA).



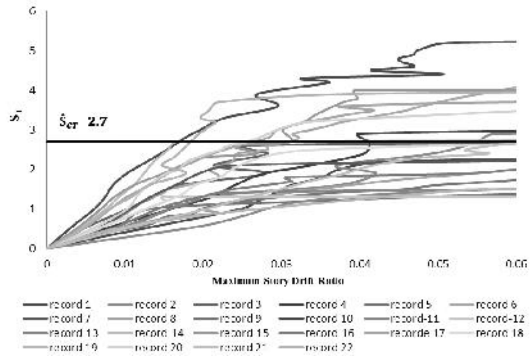
IDA Curve (1-A)



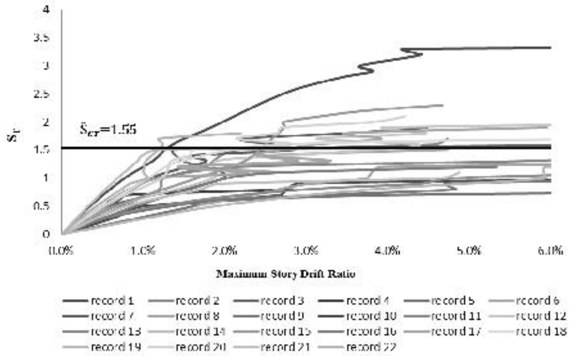
IDA Curve (1-B)



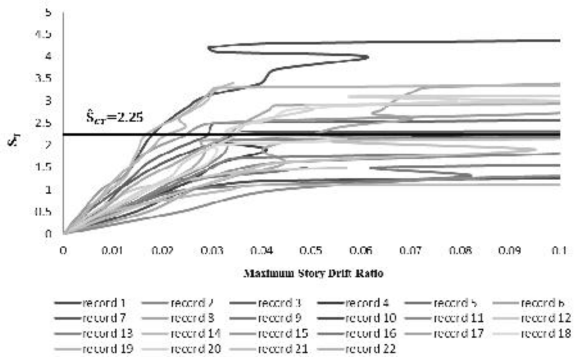
IDA Curve (1-C)



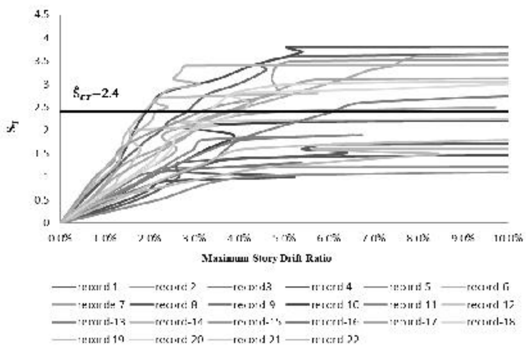
IDA Curve (2-A)



IDA Curve (2-B)



IDA Curve (3-A)



IDA Curve (3-B)

Figure 3. Incremental dynamic analysis response curves of archetypes models.

To verify the seismic behavior of the lateral-force-resisting system which is under consideration, it is required for the ACMR values of each index archetypes and the average of these values in each performance group to be greater than the acceptable values proposed by FEMA P695. These acceptable values of Adjusted Collapse Margin Ratio are based on the total system collapse uncertainty and the values of acceptable collapse probabilities. The lesser probability of collapse accepted, the larger collapse margin ratio is required to validate the seismic behavior of a system.

Through these assumptions the lognormal standard deviation parameter, β_{TOT}, which is calculated in this study is equal to 0.6. Collapse margin ratios and adjusted values of these ratios for individual archetypes and different performance groups have been summarized in Table 2. Acceptance criteria for each archetype and performance group have been further illustrated in this table in order to be compared with the obtained results. As it is evident from Table 1, acceptable performance was achieved by all of index archetypes and performance groups, which are investigated.

Table 2. Adjusted collapse margin ratio (ACMR)

SeismicGroup		S_{MT}	$\hat{S}_{CT}$	CMR	SSF	ACMR	B_{TOT}	$\overline{ACMR}_i$	$ACMR_{10\%}$	$ACMR_{20\%}$
1	1-A	1.125	2.7	2.4	1.113	2.67	0.6	2.93	2.16	1.66
	1-B	0.954	2.7	2.83	1.215	3.44	0.6		2.16	1.66
	1-C	0.738	1.75	2.37	1.13	2.68	0.6		2.16	1.66
2	2-A	0.954	2.7	2.83	1.213	3.43	0.6	2.89	2.16	1.66
	2-B	0.738	1.55	2.1	1.118	2.35	0.6		2.16	1.66
3	3-A	1.2375	2.25	1.82	1.218	2.21	0.6	2.325	2.16	1.66
	3-B	1.2375	2.4	1.94	1.22	2.36	0.6		2.16	1.66

The average value of Adjusted Collapse Margin Ratio for each performance group exceeds the acceptable values of Adjusted Collapse Margin Ratio considering 10% acceptable collapse probability which is equal to 2.16 in this study.

The individual values of Adjusted Collapse Margin Ratio for each index archetype exceeds the acceptable values of Adjusted Collapse Margin Ratio considering 20% acceptable collapse probability which is equal to 1.66 in this study.

Therefore, it can be inferred from this table that the RC frame systems designed according to standard 2800 has sufficient and acceptable margin of collapse.

CONCLUSIONS

The values of Adjusted Collapse Margin Ratio for all of index archetypes which were calculated according to the results of nonlinear dynamic analyses exceeded acceptable collapse margins as well as the average values of these ratios for all of performance groups. Hence, the presumed Response Modification Factor equals to R=7 for Intermediate ductility level and R=10 for high ductility level are appropriate for RC systems.

As the height of the systems of interest increased, the collapse margins decreased; therefore, long period systems are more vulnerable to collapse under severe ground motions compared to short period ones according to the results found in this investigation.

It can also be seen that the two alternatives of ductility levels (Intermediate and high ductilties) of the systems have sufficient margin against collapse and there is no meaningful difference between different ductility levels.

It is worth noting that extensive nonlinear dynamic analyses were carried out in this study to compute the collapse margin ratio for the RC frame structures designed according to the standard 2800. Although the results appears to be sufficiently indicative with regards to the collapse margin ratio of the considered systems, however to generalize the conclusions of this study further investigations may be required to include more extensive performance groups.

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