Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 555

ASSESSMENT OF DIFFERENT COLLAPSE MECHANISMS IN BRACED MOMENT RESISTING FRAMES USING SYSTEM SIMULATED RELIABILITY INDEX

M. Lotfollahi[1], M. Banazadeh[2] and M.M. Alinia[3]

ABSTRACT

An innovative methodology is developed for application of the simulation technique to structural system reliability assessment. The method incorporates two important features in design of steel Braced Moment Resisting Frames (BMRFs): (i) different collapse scenarios with multiple failure sequences; (ii) system reliability analysis through failure probability propagation from components to system and also from system to components. Different BMRFs are evaluated within several likely collapse scenarios. An applicable algorithm for the system reliability evaluation using the nonlinear finite element program within the Monte Carlo simulation algorithm has been established. In addition to primary collapse failure mechanisms, the effect of predefined precocious component failure related to other probable collapse scenario is evaluated with a new concept in this paper, namely, Reduction Yield Capacity (RYC) approach. The System Simulated Reliability Index (SSRI) is obtained through maximum probable system failure mechanisms. The outcomes of multi collapse scenarios then are compared with the codified collapse criterion. Finally, the fragility curves based on SSRI is compared with ones from Incremental Dynamic Analysis (IDA).

Introduction

The concept of Performances Based Earthquake Engineering (PBEE) requires estimation of the failure in a structural system for a specific level of performance desired to be met against a specific level of hazard. On the other hand, the system nature of a structural frame and a complicated interaction between component failure modes and system performance along with propagation of failure from component level to system is the matter of great attention in the concept of structural design evaluation. The effect of redundancy and local ductility capacity on the global performance would be the interesting research spot. For this purpose some research works have been performed for tension moment bracing frame (Lotfollahi & Alinia 2009a,b, 2008) and the other results for compression and also X bracing frame are under consideration.
The structural reliability method has been so far an important framework to deal with uncertainty

[1] PhD Candidate, Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran
[1] Ministry of Petroleum, National Iranian Oil Engineering and Construction Company (N.I.O.E.C.), Tehran, Iran
[2] Assistant Professor, Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran
[3] Professor, Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran

around the performance of a structural system in which the rational consideration of aleatory and epistemic uncertainty is proved to be vital in developing building codes. As a great illustration in this area some research work has been done by Liel et. al. (2009) to evaluate the significance of modeling uncertainties associated with component deformation capacity and other critical parameters to collapse prediction of reinforced concrete moment frame buildings by providing an overview of the collapse assessment procedure and proposing a procedure that combines response surface analysis and Monte Carlo methods. The existent of indeterminacy in a structural system and the random nature of forming the component failure modes would lead to the possibility of different failure scenarios which in turn would make the structural systems as the series systems (cut sets) of different possible ensembles of components failure modes (tie sets). Although there is a promising improvement in methodology and numerical algorithm, the cumbersome job of the system reliability assessment is the precise determination of minimum cut sets of tie sets, (Der Kiureghian 2008). The methodology proposed by Mahadevan et al. (2001) namely Branch and Bound has been implemented and improved in some ways in this research. The core of above method is the elimination of very low probable failure sequences which its influence on the system failure probability can be neglected.

In this study different steel Braced Moment Resisting Frames (BMRFs) have been selected, however the generality of proposed method can be kept for extended application. A comprehensive field of random variables has been selected and the system failure assessment of the BMRFs are considered with two different approaches: (i) consideration of both parametric (or epistemic) uncertainties as well as inherent uncertainties in term of seismic intensity measure through the System Simulated Reliability Index (SSRI); (ii) consideration of only inherent uncertainties (or Record to Record variability) through the Incremental Dynamic Analysis (IDA). Some recent guidelines (FEMA P695, 2009) have attempted to establish a recommended methodology for reliably quantifying building system performance. In this paper the structural system collapse reliability simulation and the probabilistic seismic demand have been evaluated during two different concepts: (i) breaking down the system collapse into several sequential components failure; (ii) using the current codified overall collapse criterion. Cumbersome theme of this method is mostly related to calculation of conditional probability of component failure incorporating the nonlinear finite element analysis into Monte Carlo simulations. Comparing the results of this method with the outcomes of IDA collapse fragility curves can establish a rational ground to develop more precise codified design procedure. Despite all strategies associated in new building codes, a realistic probabilistic calculation in structural systems and the contribution of both epistemic and aleatory uncertainties in overall performance should be greatly concerned. The proposed method can be considered as a rigorous base for seismic fragility assessment.

Uncertainties Description and Model Properties

Single bay frames with 2, 4 and 6 stories have been designed based on the current codes of practice, AISC/LRFD 2005. European wide flange sections (IPB & IPE) are selected for beam, columns; and double channel sections (2UNP) are used for braces. The characteristics gravity loads consist of a total live load of 2 kN/m^2 on each floor and 1.5 kN/m^2 on the roof, plus a dead load of 5.5 kN/m^2 with 6 m spacing between transverse frames. The representative mean value for load pattern of a displacement control push over analyses and also the selected random variables in nonlinear model of the frames are shown in Fig. 1. The basic independent random variables are: lateral load distribution at each story (P_i); modulus of elasticity (E);

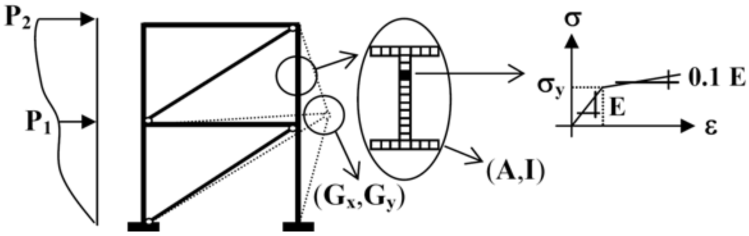

Figure 1. Braced Moment Resisting Frame (BMRF) and the selected random variables.

Table 1. Basic random variables parameters.

	Mean	Coef. of Var.	Prob. Dist.
A (Section Area)	Design Value	0.05	Normal
E (modulus of Elasticity)	Design Value	0.05	Lognormal
I (Section Modulus)	Design Value	0.05	Normal
G_x (Error in X Coordination)	Design Value	0.1	Normal
G_y (Error in Y Coordination)	Design Value	0.1	Normal
σ_y (Yield Stress)	Design Value	0.05	Lognormal
P_i (Lateral Force)	Design Value	0.1	Gumbel

Table 2. Design sections for 2, 4 and 6 story BMRF system.

	Columns			Beams	Braces		
	1st and 2nd	3rd and 4th	5th and 6th	All story	1st and 2nd	3rd and 4th	5th and 6th
2 Story BMRF	IPB 180	-	-	IPE 220	2UNP 60	-	-
4 Story BMRF	IPB 200	IPB 180	-	IPE 220	2UNP 80	2UNP 65	-
6 Story BMRF	IPB 220	IPB 200	IPB 180	IPE 240	2UNP 100	2UNP 80	2UNP 65

elements section area (A); yield stress of the material (σ_y); error joint coordination for the global horizontal and vertical direction (G_x, G_y), with the properties presented in Table 1. For push over load pattern a triangular shape based on ASCE07 2005 has been selected for mean values. The results of design with tension and compression bracing frames are shown in Table 2.

Sensitivity Analysis and Detection of Possible System Failure Modes

In order to distinguish the main failure scenarios and later conducting the Branch and Bound method by elimination less likely failure sequences a preliminary sensitivity analysis has been conducted. Two different main failure scenarios, tension braces yielding and compression braces buckling, by two different design approaches are considered. For each frame in each design case beside the design failure other kinds of failure by different plastic hinges propagation have been considered while the failure initiation are happened from the beams, columns and higher story braces using the Reduction Yield Capacity (RYC) approach. This way, all possible real collapse sequences that would be seen in practice representing all sources of error from conceptual design to final construction can be found out. The plastic hinges formation results for each intellectual failure scenario are shown in Table 3 by the frame numbering system in Fig. 2.

Uncertainty Modeling through Monte Carlo Simulation (MCS)

Different System failure scenarios are consisting of sequential failure of different components. Collapse would form through various likely path of damage propagation of component failure modes. As mentioned earlier, in this study, we have considered flexural failure of frame members represented by forming plastic hinges in each beam and column ends, tension failure of brace member by forming tension yielding in brace members and the compression failure of each brace represented by formation a flexural plastic hinge in the middle of each brace while an imperfection out of plane displacement is applied. The location and type of each component failure are shown through the numbering system in Fig. 2. The general format of performance functions of each components failure modes is $g_i = R_i - S_i$, $i = 1$ to n, where i is an index representing i^{th} component failure mode with its due resisting and load parameters. Failure of each component occurs when $g_i \le 0$. Each failure scenario would be initiated by forming the first component failure which be the first block of each minimum cut set. Minimal tie sets are generic parallel model representing each failure scenario. Minimal tie sets have been distinguished through a sensitivity analysis on frames with a realistic range of all possible design. Structure would end up to collapse if either of minimal tie set experience the collapse. The probability of the failure of structural system can be defined by Integral (Der Kiureghian 2008):

$$P_F = \int_{\Omega(x)} f_X(x)dx \tag{1}$$

Where P_F is the system failure probability which can be later converted to system safety index through converting rule of $\beta = \Phi^{-1}(1 - P_F)$. In Eq. 1 $f_X(x)$ is the joint probability density function (PDF) of the vector of basic random variables $X = [X_1, X_2, ..., X_n]^T$ representing the

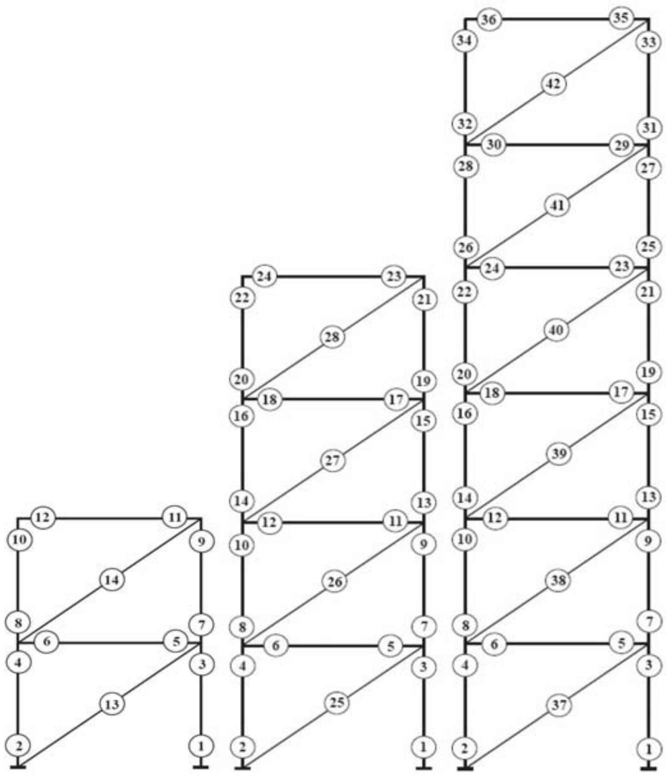

Figure 2. Numbering system for calculation the conditional probabilities referred to Tables 3.

uncertain quantity shown in Fig. 1. For the structural systems in this study, the failure domain consisting of all scenario in Table 3 that represented by a series of cut sets whose each block is a minimal tie sets can be analytically shown as:

$$\Omega(x) \equiv \bigcup_{k} \bigcap_{i \in C_k} \{g_i(x) \leq 0\} \tag{2}$$

Where $g_i(x)$, $i = 1,...,m$, are a set of limit sate functions formulated so that { $g_i \leq 0$ } indicates the failure modes of components i; m denotes the number of components and C_k is the index for k-th minimum cut set, where each minimum cut set represents a minimal tie set. Simply speaking the structure is a series system. The focal point of this research is calculation of Eq. 1 within a numerical framework named SSRI by combination of nonlinear finite element analyses and Monte Carlo simulation technique that main features are listed as follows:

1- The number of minimum cut sets each representing a failure scenario and the sequential component failures or tie sets (each cell in Table 3) within each cut set (each row in Table 3) has been recognized based on a sensitivity push over analyses. The initial failure point is dictated by RCA while the overall collapse is based on the following criteria: (i) target displacement (FEMA 356, 2000), and (ii) structural system instability due to formation of plastic hinges.

2- At first step incorporating the limit state function of each component failure mode into a finite element Mont Carlo simulation, the marginal probability of failure for all initial block of minimum cut sets is calculated. Basic random variables are assumed to be statistically independent, however within each failure scenario the conditional probability of *2-nd*, *3-rd*, …, and *i-th* component failure are calculated for proper consideration of probability propagation through a realistic damage propagation.

3- In the main frame elements (beams and columns) the limit state function is considered by flexural yielding of the elements. The following force limit state function for marginal probability of plastic hinge formation in the main frame elements is considered:

$$g_i(x) = M_i(x) - (M_P)_i(x) \tag{3}$$

Where $M_i(x)$ is demand flexural force on the component i; $(M_P)_i(x)$ is the capacity flexural force on the component i.

4- In tension bracings the limit state function is considered by tension yielding of the brace elements. Thus the ultimate failure state of the brace elements for the marginal probability of plastic hinge formation is computed by the following force limit state function:

$$g_i(x) = T_i(x) - (T_y)_i(x) \tag{4}$$

Where $T_i(x)$ is demand axial force on the component i; $(T_y)_i(x)$ is capacity axial force on the component i.

5- In compression bracings possible buckling of the brace elements is acceptable. The elastic buckling of the brace elements is not considered as the ultimate failure state of the bracings but the effect of post-buckling reserve and geometric nonlinearities on the failure of bracings as well as the response of the total system is evaluated. The limit state functions are considered while the plastic hinges in the middle point of the brace elements are formed after buckling. Thus the ultimate failure state of the brace elements for the first stage of plastic hinge formation is computed by evaluation the critical axial force or out of plane imperfection in the same time of plastic hinge formation in the middle point of the brace elements with the following force and displacement limit state functions:

$$g_i(x) = P_i(x) - (P_{cr})_i(x) \tag{5}$$

$$g_i(x) = \delta_i(x) - (\delta_{cr})_i(x) \tag{6}$$

Table 3. Different failure scenarios in 2, 4 and 6 BMRFs and the system simulated reliability index results for the collapse prevention limit state; I= design case; II=lower story beam failure; III=lower story column failure; IV= higher story beam failure; V=higher story column failure; VI=higher story brace failure; β_m on sequence n means the conditional reliability index for plastic hinge formation in node m while $n-1$ preceding sequences of component failure have been formed.

	Sequence of components failure in 2 story BMRF (Tension Bracings)					System Reliability Bounds	
	1	2	3	4	5	Upper	Lower
I	β13=1.37	β14=1.57	β5=1.74	β6=2.37	β1=2.87	0.002052	3.7114E-09
II	β6=1.53	β5=1.62	β13=1.86	β14=2.32	β6=3.24	0.000598	6.3361E-10
III	β2=1.46	β13=1.74	β14=1.83	β1=2.74	β6=3.76	0.000085	2.5913E-11
IV	β11=1.63	β13=1.76	β5=1.89	β14=2.34	β6=3.17	0.000762	4.3634E-10
V	β7=1.87	β13=1.97	β5=2.43	β14=2.74	β6=3.21	0.000664	1.1554E-11
VI	β14=1.71	β13=1.91	β6=2.13	β4=2.43	β1=2.94	0.001641	2.5164E-10

	Sequence of components failure in 2 story BMRF (Compression Bracings)					System Reliability Bounds	
	1	2	3	4	5	Upper	Lower
I	β13=1.42	β14=1.61	β6=2.36	β1=2.71	β4=3.13	0.000874	1.1225E-10
II	β6=1.63	β13=1.79	β5=2.11	β14=2.83	β1=3.26	0.000557	4.2783E-11
III	β2=1.68	β13=1.87	β14=2.38	β3=2.68	β5=3.52	0.000216	9.8241E-12
IV	β11=1.57	β13=1.81	β14=2.11	β12=2.43	β6=3.75	0.000088	2.3802E-11
V	β7=1.67	β13=1.93	β14=2.43	β5=2.77	β6=3.43	0.000302	8.1232E-12
VI	β14=1.73	β13=1.97	β5=2.52	β3=2.84	β2=3.12	0.000904	1.2221E-11

	Sequence of Components Failure in 4 story BMRF (Tension Bracings)							System Reliability Bounds	
	1	2	3	4	5	6	7	Upper	Lower
I	β25=1.23	β26=1.55	β27=1.73	β5=1.91	β6=2.11	β11=2.23	β1=2.51	0.006037	1.0529E-11
II	β11=1.33	β25=1.52	β26=1.86	β26=2.06	β28=2.28	β5=2.38	β12=2.71	0.003364	1.2022E-12
III	β9=1.35	β25=1.69	β27=1.96	β5=2.18	β11=2.38	β17=2.58	β6=2.84	0.002256	1.4209E-13
IV	β23=1.41	β25=1.61	β26=1.78	β27=1.96	β11=2.21	β5=2.45	β18=2.73	0.003167	1.2245E-12
V	β21=1.32	β25=1.52	β26=1.82	β27=2.17	β12=2.39	β5=2.69	β17=3.04	0.001183	1.1023E-13
VI	β27=1.37	β25=1.54	β26=1.71	β5=1.93	β12=2.27	β17=2.51	β28=2.78	0.002718	1.1740E-12

	Sequence of Components Failure in 4 story BMRF (Compression Bracings)							System Reliability Bounds	
	1	2	3	4	5	6	7	Upper	Lower
I	β25=1.32	β26=1.58	β27=1.78	β6=1.94	β11=2.21	β5=2.42	β1=2.71	0.003364	1.8539E-12
II	β11=1.41	β25=1.59	β27=1.81	β26=2.03	β5=2.24	β28=2.48	β12=2.75	0.002980	8.1025E-13
III	β9=1.54	β25=1.73	β27=1.95	β6=2.21	β12=2.47	β17=2.69	β6=3.11	0.000935	2.0226E-14
IV	β23=1.43	β25=1.69	β26=1.92	β27=2.14	β11=2.36	β5=2.61	β17=2.89	0.001926	1.2288E-13
V	β21=1.35	β25=1.51	β26=1.78	β27=1.97	β6=2.47	β11=2.81	β18=3.21	0.000664	5.9038E-14
VI	β27=1.37	β25=1.52	β26=1.68	β6=1.83	β12=2.06	β18=2.78	β28=3.02	0.001264	5.7995E-13

	Sequence of Components Failure in 6 story BMRF (Tension Bracings)									System Reliability Bounds	
	1	2	3	4	5	6	7	8	9	Upper	Lower
I	β39=1.18	β37=1.29	β38=1.41	β7=1.57	β1=1.68	β40=1.81	β15=2.04	β3=2.21	β5=2.61	0.004527	1.1211E-13
II	β17=1.25	β38=1.36	β37=1.49	β39=1.64	β9=1.79	β3=1.96	β40=2.18	β5=2.38	β19=2.73	0.003167	1.1629E-14
III	β15=1.38	β37=1.51	β38=1.63	β39=1.75	β1=1.93	β40=2.08	β7=2.27	β10=2.46	β16=2.79	0.002635	1.2113E-15
IV	β35=1.27	β39=1.32	β38=1.48	β37=1.61	β13=1.76	β9=1.92	β1=2.18	β5=2.37	β40=2.78	0.002718	1.3516E-14
V	β33=1.39	β38=1.52	β39=1.65	β37=1.81	β40=1.97	β3=2.17	β7=2.29	β10=2.44	β16=2.64	0.004145	1.1287E-15
VI	β41=1.31	β38=1.38	β37=1.52	β39=1.69	β5=1.81	β40=2.04	β12=2.11	β3=2.36	β7=2.67	0.003793	1.0229E-14

	Sequence of Components Failure in 6 story BMRF (Compression Bracings)									System Reliability Bounds	
	1	2	3	4	5	6	7	8	9	Upper	Lower
I	β39=1.11	β37=1.28	β38=1.46	β9=1.61	β1=1.78	β40=1.94	β15=2.18	β1=2.38	β6=2.93	0.001695	1.0942E-14
II	β17=1.24	β38=1.41	β37=1.56	β39=1.71	β7=1.87	β40=2.14	β41=2.28	β6=2.41	β21=3.05	0.001144	1.1326E-15
III	β15=1.41	β37=1.54	β38=1.71	β39=1.86	β40=1.97	β41=2.18	β9=2.36	β10=2.52	β16=2.91	0.001807	2.3255E-16
IV	β35=1.31	β39=1.44	β38=1.56	β37=1.72	β40=1.83	β7=1.97	β3=2.23	β5=2.48	β41=2.96	0.001538	1.9306E-15
V	β33=1.42	β38=1.58	β39=1.76	β37=1.89	β40=2.05	β41=2.21	β7=2.37	β8=2.64	β14=2.88	0.001988	1.0252E-16
VI	β41=1.34	β38=1.49	β37=1.61	β39=1.75	β6=1.91	β40=2.1	β11=2.31	β1=2.51	β7=2.81	0.002477	1.0340E-15

Where $P_i(x)$ and $\delta_i(x)$ are demand axial force and out of plane imperfection on the component i; $(P_{cr})_i(x)$ and $(\delta_{cr})_i(x)$ are calculated axial force and out of plane imperfection on the component i in the time of plastic hinge formation in the middle of brace elements obtained from 3D finite element modeling of BMRFs through ABAQUS software and also the nonlinear post buckling analysis results.

6- For calculation the conditional probability of consequent component failure in each failure scenario, we change the structural model so that the previous failures are represented by a corresponding change in structural model. Such change could be allocation of a plastic hinge with its plastic moment (in a ductile component failure) while all other sections are deterministically loaded up to this point but in a sense that only remaining part of capacity are then would be loaded probabilistically in order to achieve the next component failure mode. This way the limit state function of the higher order failure formation are equal to:

$$g_i(x) = X_i(x) - (X_P)_i(x) = X_{i|j}(x) - (X_P)_i(x) = g_{i|j}(x) \tag{7}$$

Where $X_{i|j}(x)$ is demand on the component i while there is a residual deterministic demand due to earlier failure of j under the gravity and earthquake load combination; $(X_P)_i(x)$ is maximum capacity of similar action on the component i. It is clear that the calculation of conditional probability would let to have the effect of system redundancy on the probability of the total failure. The conditional probability in the tie sets will produce the correlation due to important features of the correlation between the failure modes.

7- There is a primary scenario (Case I in Table 3) without any strength reduction (Case II-VI in Table 3). However considering other collapse path is essential in order to calculate its probabilistic contribution in overall collapse. In order to force models to fail through pre-determined path beside the main failure path we have utilized RYC technique. The concept is based on the fact that in order to make the structure fail in other path except the main path there must be a possibility of wackiness in that path which leads the damage propagation passing through our failure modes.

8- The result of all marginal and conditional probability is shown in Table 3. The reliability analyses for the minimum cut sets of minimal tie sets is quite simple provided while the failure events of the different failure modes are uncorrelated. For series systems the probability of failure is then simply given as:

$$P_F = 1 - P_S = 1 - \prod_{i=1}^{n} (1 - P(F_i)) \tag{8}$$

Where P_S is the probability of system survival. For parallel systems the probability of system failure is given by:

$$P_F = \prod_{i=1}^{n} P(F_i) \tag{9}$$

For a series system as the correlation between the failure modes will be somewhere between zero and one, the simple bounds on the failure probability for a series system may thus be given as:

$$\max_{i=1}^{n}\{P(F_i)\} \le P_F \le 1 - \prod_{i=1}^{n} (1 - P(F_i)) \tag{10}$$

where the lower bound corresponds to the case of full correlation and the upper bound to the case of zero correlation. For a parallel system the same considerations apply leading to the observation that the upper bound corresponds to the situation where all failure modes are fully correlated and the lower bound to the situation where all failure modes are uncorrelated, i.e.:

$$\prod_{i=1}^{n} P(F_i) \le P_F \le \min_{i=1}^{n}\{P(F_i)\} \tag{11}$$

It is worth to mention that the independent failure for each cut set will obtain from two different cases; with full correlation (lower bound in Eq. 10 and upper bound in Eq. 11) and without correlation (upper bound in Eq. 10 and lower bound in Eq. 11).

System Failure Assessment by System Simulated Reliability Index (SSRI)

The system reliability assessment of different story BMRFs within SSRI has been evaluated. The results of above procedure for tension yielding and compression buckling systems after implementing the RYC technique to dictate pre-determined plastic hinges formation path in the models and also using the Branch and Bound method for elimination the very low probable failure sequences are shown in Table 3 with the following features:

- All conditional β in each component are larger than marginal one.
- The SSRI of higher story BMRF is less than the ones for lower story BMRFs which can be attributed to higher redundancy due to more statistical Indeterminacy.
- The upper/lower bounds of SSRI in 2, 4, and 6 story BMRFs are 5.7283/5.7811, 6.6527/6.6985, and 6.2945/7.3335 for tension yielding respectively. The results for compression buckling are 6.2471/6.3436, 6.8598/6.9478, and 7.5955/7.6390 respectively.

Comparison between SSRI and Main Collapse Mechanism

The SSRI of the BMRFs presented in Table 3 are considered. In order to investigate the results of system reliability assessment based on the component failure consequences and to evaluate the potential of the main collapse mechanism proposed by current guidelines (FEMA 356, 2000); a new main collapse mechanism is conducted and the limit state function is considered according to the maximum inter story drift ratio. Thus the ultimate failure state of the BMRF system performance is computed by the following deformation limit state function:

$$g_k(x) = \Delta_k(x) - (\Delta_{allowable})_k(x) \tag{12}$$

Where $\Delta_k(x)$ is drift demand of k-th story; $(\Delta_{allowable})_i(x)$ is FEMA recommended allowable inter story drift equals to 2% of story height in BMRFs. Fig. 3 illustrates the results of SSRI versus the normalized bracing section area. First, upper and lower bound failure probabilities are obtained from tension yielding and compression buckling SSRI, separately. Then, considering these two tension and compression oriented SSRIs in a series system, the upper and lower bounds of whole system failure is achieved (Fig. 3). Furthermore, the outcome of simulation for main collapse criteria: either FEMA suggestion (Eq. 12) or structural instability explained in preceding section is shown in Fig. 3 for comparison. Fig. 3 indicates that a FEMA performance criterion for CP is conservative above the design case. However for weaker brace members FEMA could not predict the probability of collapse in a conservative manner.

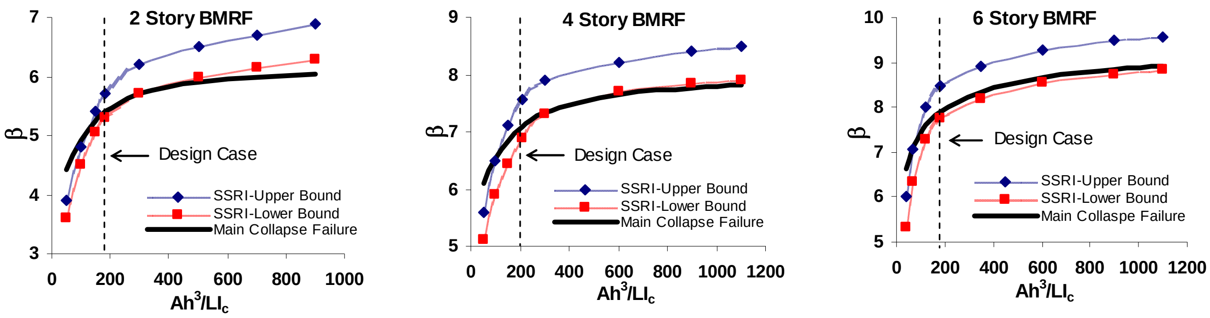

Figure 3. Comparing between the collapse probability with SSRI and main collapse failure.

Comparison between Collapse fragilities of IDA and SSRI

In IDA, the models of BMRFs, which captures both material and geometric nonlinearities, is analyzed for 40 recorded ground motions from Californian earthquakes of moment magnitude between 6.5 and 7.0 and closest distance to the fault rupture between 13 km and 60 km (Medina & Krawinkler 2004). These ground motions were recorded on NEHRP site class D (FEMA368, 2000). Regarding those uncertain parameters in SSRI (Fig. 1), the mean values are incorporated in IDA. Using the hunt & fill algorithm (Vamvatsikos & Cornell 2002) allows capturing each IDA curve with only 12 runs per record. Appropriate interpolation techniques allow the generation of a continuous IDA curve in the IM-EDP plane from the discrete points obtained by the dynamic analysis. In our study, the ground motion intensity measure is the spectral acceleration at the first mode period of the building [Sa(T1)]. The time-history analysis is repeated, each time increasing the scale factor on the input ground motion, until that record causes structural collapse, as identified by runaway inter story drift displacements. The results of the IDA and SSRI procedure can demonstrate, respectively, two different features of collapse fragility function for the BMRFs (a cumulative probability distribution that defines the probability of structural collapse as a function of the ground motion intensity): (i) IDA based fragilities; (ii) SSRI based fragilities. Fig. 4 shows the results of comparing between the collapses fragilities obtained from IDA and SSRI based with different level of ground motion intensity by the median spectrum of the considered IDA records and in the form of different lateral pushover force. The following consequences are obtained from the results of Fig. 4:

- For wide range of S_a the result of IDA and SSRI is almost the same which can be attributed to domination of overall collapse and forming large number of plastic hinges.
- The SSRI can evaluate the system reliability bounds of BMRFs with appropriate accuracy specifically for the lower story BMRF models .

Conclusions

The reliability index for the collapse failure of BMRFs has been proposed. The main features of this method, named System Simulated Reliability Index (SSRI), is probability failure estimation while possible transition from component level to system level and evaluation the most probable system failure scenario are considered. Parametric uncertainties in modeling such as geometry, seismic load pattern, section properties of the members and material specifications as well as inherent uncertainty in seismic intensity measure associated in a probabilistic seismic

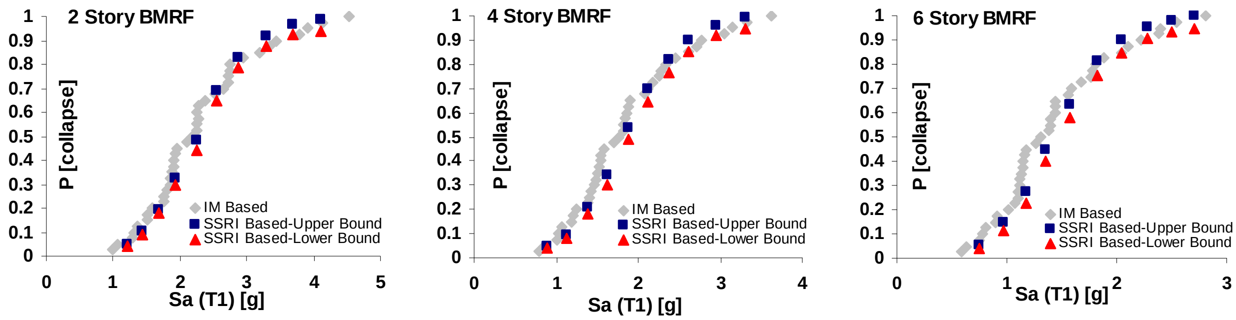

Figure 4. Collapse fragilities for 2, 4 and 6 BMRF system based on IDA and SSRI procedures.

assessment can be properly taken into account using SSRI. The outcomes of SSRI for minimum lower bound and maximum upper bound system failure probabilities in tension and compression bracing phases have been evaluated and the results are compared with the main collapse mechanism obtained via simulated failure probabilities. The SSRI can demonstrate a great basis for evaluation the system reliability assessment and also it can utilize as a good appraisal for development a new main collapse in the structural systems.

References

ABAQUS Standard, *User Manual*, Version 6.5, Hibbitt, Karlsson, and Sorensen Incorporation.

AISC, Steel Construction Manual, 2005. 13th ed. Chicago (IL): *American Institute of Steel Construction*.

ASCE/SEI 7-05, 2006. Minimum Design Load for Buildings and other Structures, *American Society of Civil Engineering*, ASCE.

Der Kiureghian, A., 2008. Analysis of structural reliability under parameter uncertainties, *Probabilistic Engineering Mechanic*, 23, 351-358.

FEMA 356, 2000. Prestandard and Commentary for the Seismic Rehabilitation of Buildings, *Federal Emergency Management Agency*, Washington D.C..

FEMA 368, 2000. NEHRP recommended provisions for seismic regulations for new buildings and other structures, *Building Seismic Safety Council*, Washington D.C..

FEMA P695, 2009. Quantification of Building Seismic Performance Factors, *Federal Emergency Management Agency*, Washington D.C..

Liel, A. B., Haselton, C. B., Deierlein, G. G., Baker, J. W., 2009. Incorporating modeling uncertainties in the assessment of seismic collapse risk of buildings, *Structural Safety*, 31, 197-211.

Lotfollahi, M., Alinia, M.M., 2009a, Effect of Tension Bracing on The Collapse Mechanism of steel moments frames, *Journal of Constructional Steel Research*, 65, 2027-2039.

Lotfollahi, M., Alinia, M.M., 2009b, Sequential Failure Analysis of Tension Braced MRFs, *Proceeding of 5th Inter. Struc. Engineering & Construction Conf.*, ISEC-5, Las Vegas, USA, 181-187.

Lotfollahi, M., Mofid, M., Alinia, M.M., 2008, Brace-Frame Interaction in Tension Braced MRFs, *Inter. Conf. on Numerical Analysis & Applied Mathematics*, *ICNAAM*, *Proceedings of American Institute of Physics*, Kos, Greece, 364-367.

Mahadevan, S., Zhang, R., Smith, N., 2001. Bayesian Networks for System Reliability Reassessment, *Structural Safety*, 23, 231–251.

Medina, R., Krawinkler, H., Seismic Demands for Nondeteriorating Frame Structures and Their Dependence on Ground Motions, *PEER 2003/15*, May 2004.

Vamvatsikos, D., and Cornell, C. A., 2002. Incremental dynamic analysis, *Earthquake Engineering and Structural Dynamics*, 31 (3), 491–514.