Estimating Seismic Performance Factors for a Dual System Comprising Buckling Restrained Brace Frames and Intermediate Moment Frames

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Abstract

Dual structural system is referred when two different lateral systems are combined together to provide the lateral force resisting system for a building structure. For different structural and architectural reasons, dual systems are used in building structures. The most common types of dual systems include special moment resisting frames (SMRF) combined with eccentric braced frames (EBF) or buckling restrained braced frames (BRBF) in steel buildings and special reinforced concrete moment frames combined with special reinforced concrete shear walls in reinforced concrete buildings. Buckling restrained braced frame is a lateral framing system that are being used in high seismic zones. According to American Society of Civil Engineers (ASCE), a dual system is permitted between buckling restrained braced frames (BRBF) and special moment resisting frames (SMRF) where SMRFs must be capable of resisting at least 25% of prescribed seismic force. Conventionally, dual systems are utilized at high seismic zones. For moderate seismic zones intermediate moment resisting frames (IMF) can be used instead of SMRF. But, ASCE does not provide any guideline to assess the structural responses when a dual system combining BRBF and IMRF are used in buildings located at moderate seismic zones. This research, shows a methodology to calculate the seismic parameters like Response Modification Coefficient (R), Over-strength Factor (Ωo) and Deflection Amplification Factor (Cd) which are not described by ASCE or FEMA guideline. Several archetypes of building structures are designed following FEMA guidelines with modified R as trial values for different seismic zones. To validate the trial values for R, system over-strength and period-based ductility, nonlinear 3D static (pushover) analyses were performed.

Keywords: *Buckling restrained braced frame (BRBF), Response modification factor, Over strength factor, Deflection amplification factor, Dual system, Pushover analysis*

1. Introduction

Buckling-Restrained Braced Frame (BRBF) was first developed in Japan, and has been used in North America since the beginning of the 21st century [1]. BRBF is a special class of concentrically braced frame that is composed of columns, beams and braces which mainly under axial forces. Neither X-bracing nor K-bracing configuration are used for BRBFs. In the United States BRBF systems are usually utilized in Seismic Design Category (SDC) D, E, or F. Buckling-Restrained Braces (BRBs) consist of a steel core, a buckling restraining system (concrete or grout) which effectively reduces the un-braced length of the compression member to zero and eliminates the buckling failure mode, and steel casing. Bonding of the steel core to the concrete is precluded to ensure that each element, specifically steel core, behaves separately and to prevent composite action that would change the brace behaviour to composite brace manner.

ASCE [2] currently permits the use of BRBF either as a single seismic force-resisting system or as a dual system in combination with Special Moment Frames (SMFs). The seismic performance factors for the dual system between BRBF and SMFs are tabulated but no values are tabulated when BRBFs are used in conjunction with IMF. This research aims at developing global seismic performance factors for the dual system where BRBFs are combined with IMFs. This study investigates the behaviour of building structures with dual combination of BRBFs and IMFs under seismic loading and estimates seismic performance factors such as Response Modification Factor (R), Over Strength Factor (Ωo) and Deflection Amplification Factor (Cd). Currently, ASCE recommends that when different lateral systems are used in a horizontal combination the designer should follow a more conservative approach in selecting the seismic response coefficients. For example, the R factors for BRBF system and IMF system individually are 8.0 and 4.5 respectively. According to ASCE [2], the recommended R should be 4.5 when both BRBF and IMF are used in a horizontal combination for the dual system. But ASCE [2] does not provide any insight regarding used of BRBF and IMF in combination of a dual system. In this research we studied the response of a building structure constructed with BRBF and IMF in combination and estimated the seismic performance factors namely, Response Modification Factor (R), Over Strength Factor (Ωo) and Deflection Amplification Factor (Cd) following the guidelines suggested by ASCE/SEI [3]. Since these response factors are not listed by ASCE, we will quantify their values for the BRBF/IMF dual system and compare the results with current ASCE code of practice and thus suggest their inclusion in future code of practice.

2. Seismic Performance Factors

For seismic design of structures, all seismic force-resisting elements are designed for substantially reduced seismic forces. By linear elastic response spectrum analyses, and utilizing response spectra that represents decreased anticipated ground motions, internal forces of seismic force-resisting components are computed. During a severe earthquake, therefore, the internal forces and deformations in most seismic force-resisting components start to reach a point at which they start to yield and behave inelastically. Seismic performance factors like R, Ω_o and C_d greatly depend on structural seismic force-resisting system and structural material

[4]. FEMA P695 [5] and NHHRP [6] Recommended Provisions, FEMA 451 [6], provide the definitions of R, Ω_o and C_d based on idealized pushover curve of a seismic force-resisting system.

The response modification coefficient, R, represents the value offered by seismic codes to reduce seismic force levels due to the fact that structures have considerable over-strength and capacity to dissipate energy by developing plastic hinges within seismic force-resisting elements. Response modification factor, R, is the ratio of V_E and V_S shown in Figure 1, and Equation (1). V_E is the force level that would be developed in the structure if the structure remains linearly elastic for design earthquake ground motions, and V_S is the seismic base shear required for design. System over-strength factor, Ω_o, are applied to structural components that are sensitive to overstress, and are under rapid deterioration such as special steel concentrically braced frame's columns. Over-strength factor is defined as the ratio of the maximum strength of the fully-yielded seismic force-resisting system, V_Y, to the design base shear, V_S [Figure 1 and Equation (1)].

The elastic deformations calculated under reduced seismic forces do not express the actual displacements. The values are much less than the actual values because structures will respond inelastically to the earthquake. These elastic deformations must be amplified by deflection amplification factor, C_d, to calculate the expected deformations likely to occur in response to the design ground motions. Then the product of those two values should be evaluated to check whether the value do not exceed the allowable story drift limits. The deflection amplification factor, C_d, is the ratio of the response modification factor, R, to the damping factor, B_I, relevant to the inherent damping of the seismic force-resisting system [5].

$$R = \frac{V_E}{V} \qquad \Omega_0 = \frac{V_{\max}}{V} \qquad C_d = \frac{R}{B_I} \tag{1}$$

3. Buckling Restrained Brace Frame

BRBFs are a special class of concentrically braced frames that are composed of columns, beams and braces all mainly under axial forces. Buckling-Restrained Braces (BRBs) consist of a steel core, a buckling restraining system (concrete or grout) which effectively reduces the un-braced length of the compression member to zero and eliminates the buckling failure mode, and steel casing. Bonding of the steel core to the concrete is precluded to ensure that each element, specifically steel core, behaves separately and to prevent composite action that would change the brace behaviour to composite brace manner.

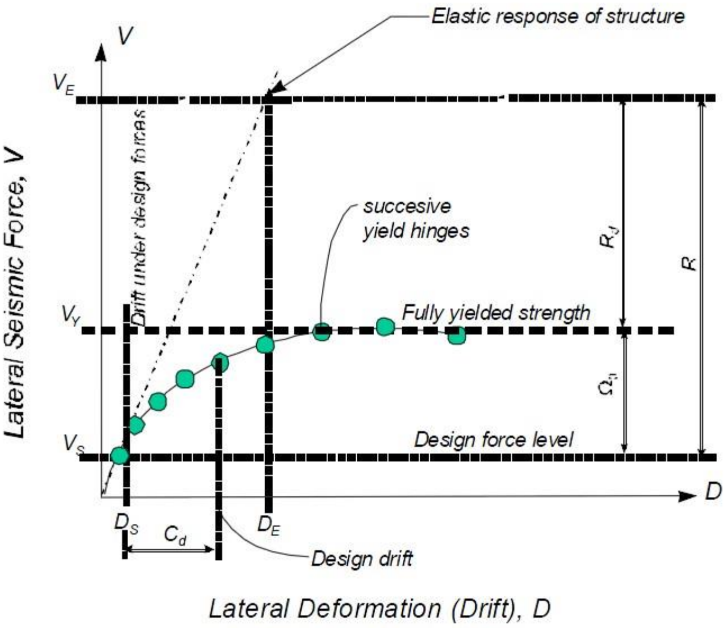

Fig. 1. Inelastic force-deformation curve (Courtesy to FEMA 450 [7]).

4. Archetype Model Configuration

An archetype is a prototypical representation of a seismic force-resisting system [5]. Archetype models are meant to represent the possible design space, design parameters and system features. They are intended to investigate a broad range of parameters and situations that are feasible and are permitted by the design requirements, but adequately limited to be practical to assess. The proposed seismic force-resisting system consists of Buckling-Restrained Braced Frames (BRBFs) with ordinary beam-to-column moment connections and Intermediate Moment Frames (IMFs) with prequalified Reduced Beam Section (RBS) moment connections capable of resisting at least 25% of seismic force. Figure 2 demonstrates plan view of typical archetype building with perimeter IMFs and non-perimeter BRBFs that is utilized in this research. In this study, factors that were reflected in establishing of performance groups were global seismic performance factors (R, Ω_o and C_d).

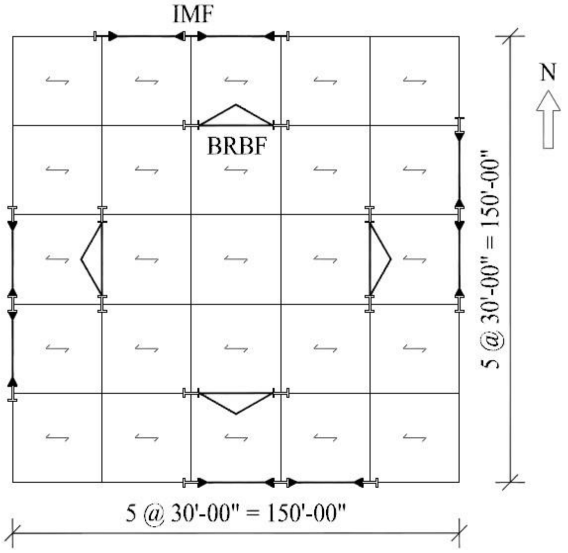

Fig. 2. Plan view of typical archetype building.

For performance evaluation, archetype models that share a common set of attributes or behavioural characteristics are classified as performance groups [5]. Performance groups reflect differences in configuration, structural period, and gravity and seismic load intensity. The proposed seismic force-resisting system consists of Buckling-Restrained Braced Frames (BRBFs) with ordinary beam-to-column moment connections and Intermediate Moment Frames (IMFs) with prequalified Reduced Beam Section (RBS) moment connections capable of resisting at least 25% of seismic force. For this study, the performance group was designed for the same seismic performance factors, but they were categorized as short-period and long-period archetype structures (Figure 3).

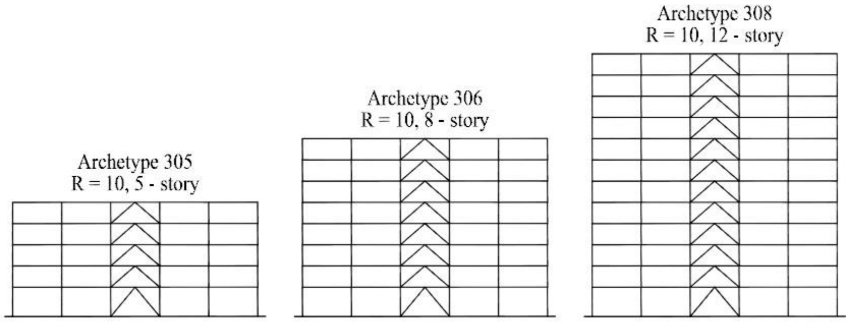

Fig. 3. Archetype building configurations and assigned IDs.

Tab. 1. BRBF sectional properties for archetype 305.

Archetype 305 (BRBF)						
Story	**N-S**			**E-W**		
	BRBF Column	**BRBF Beam**	**BRB (in^2)**	**BRBF Column**	**BRBF Beam**	**BRB (in^2)**
1	W14x176	W18x60	10	W14x176	W18x60	10.5
2	W14x132	W18x60	9	W14x132	W18x55	8.5
3	W14x82	W18x50	7	W14x82	W18x50	7
4	W14x48	W18x50	6	W14x48	W16x40	5.5
5	W14x48	W16x40	4	W14x48	W14x38	3.5

Tab. 2. BRBF sectional properties for archetype 306.

Archetype 306 (BRBF)						
Story	**N-S**			**E-W**		
	BRBF Column	**BRBF Beam**	**BRB (in^2)**	**BRBF Column**	**BRBF Beam**	**BRB (in^2)**
1	W14x311	W21x73	13	W14x311	W21x68	12
2	W14x233	W21x73	12	W14x233	W21x68	11
3	W14x193	W18x65	10	W14x193	W18x55	9
4	W14x145	W18x60	9	W14x145	W18x50	8
5	W14x132	W18x55	7.5	W14x132	W18x50	7
6	W14x82	W18x50	7	W14x82	W18x46	6
7	W14x48	W16x50	6	W14x48	W16x40	5.5
8	W14x38	W14x38	4	W14x38	W14x38	3.5

Tab. 3. BRBF sectional properties for archetype 308.

Story	Archetype 308 (BRBF)					
	N-S			**E-W**		
	BRBF Column	**BRBF Beam**	**BRB (in^2)**	**BRBF Column**	**BRBF Beam**	**BRB (in^2)**
1	W14x550	W21x83	13.5	W14x550	W21x73	12.5
2	W14x426	W21x83	13.5	W14x426	W21x73	12.5
3	W14x370	W21x68	11	W14x370	W21x62	10
4	W14x311	W21x68	10	W14x311	W18x60	9
5	W14x283	W18x65	9	W14x283	W18x60	8.5
6	W14x233	W18x60	8.5	W14x233	W18x55	7.5
7	W14x193	W18x55	7.5	W14x193	W18x50	7
8	W14x145	W18x55	7	W14x145	W18x50	6.5
9	W14x132	W18x55	6.5	W14x132	W18x50	6
10	W14x82	W18x50	6.5	W14x82	W18x46	5.5
11	W14x53	W16x50	5.5	W14x53	W16x45	5
12	W14x48	W14x38	4	W14x48	W14x38	3

PERFORM-3D program was used to develop models of the archetype buildings. Concentrated nonlinear hinges (lumped plasticity) were utilized to model BRBFs' and IMFs' beams and columns. The Ibarra-Krawinkler backbone curve model [8] was used to develop seismic force-resisting system's columns and beams behaviour [9]. The panel zone model proposed by Krawinkler [8] was used to explicitly simulate the panel zones shear distortion [9]. BRBs were modelled assuming two bars in series: a linear (non-yielding) portion and a nonlinear (yielding) portion [10]. In this study, 45% of node-to-node length was considered non-yielding region, and 55% of node-to-node length was deemed to be yielding region. The kinematic hardening and isotropic hardening [10] behaviour of BRBs were explicitly considered in this study. A small amount of viscous damping (0.3%) and Rayleigh damping (0.2%) were incorporated in order to dampen higher mode displacements. Entire archetype models were designed in accordance with the governing design requirements shown in Table 4. P-Δ critical effects were considered for designing of archetype models.

Tab. 4. Archetype seismic design criteria.

Archetype ID	**No. of Stories**	R	Ω_o	C_d	T **(sec.)**	T_1 **(sec.)**	**IMF Seismic Force Capacity**
305	5	10	2.5	7	0.677	1.04	25% of prescribed seismic force
306	8	10	2.5	7	0.944	1.64	25% of prescribed seismic force
308	12	10	2.5	7	1.26	2.55	25% of prescribed seismic force

5. Results And Discussion

5.1 Nonlinear Pushover Analysis

Nonlinear Static Procedure (NSP) or Nonlinear Pushover Analysis is a mathematical model directly incorporating the nonlinear load-deformation characteristics of individual components of the building shall be subjected to monotonically increasing lateral loads representing inertia forces in an earthquake until a target displacement is exceeded [3]. Nonlinear pushover analyses were performed, to estimate parameters that are indispensable for quantifying global seismic performance factors as well as verify archetype structures. As recommended by FEMA [5] and ASCE/SEI [3], the first mode (fundamental mode) shape of each archetype model was used for vertical distribution of lateral loads. In addition, it is important to mention that nonlinear pushover analysis was carried out under gravity load intensity of 1.05D + 0.25L. Figure 5 shows the idealized pushover curve suggested by FEMA [5]. Table 5 includes the over-strength factor and period-based ductility corresponds to each archetype model extracted from pushover analysis curves, shown in Figures 5 & 6. As it can be seen, there are two values correspond to ultimate roof drift displacement.

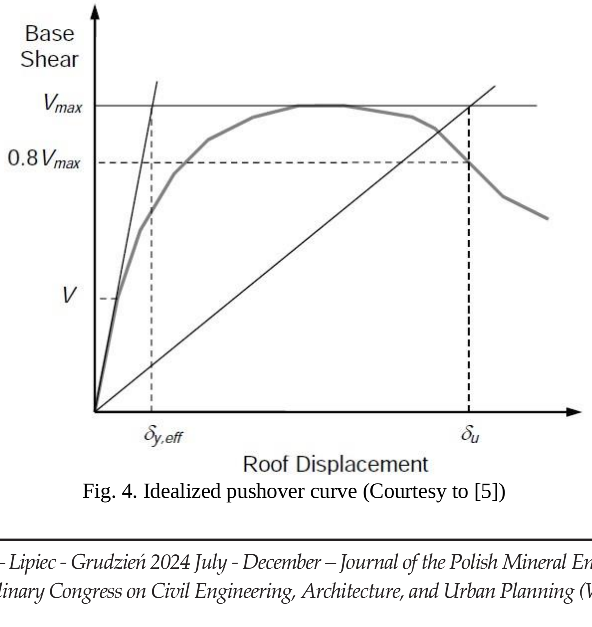

Fig. 4. Idealized pushover curve (Courtesy to [5])

Figures 5 & 6 show pushover curves of archetype structures (305, 306 and 308) in N-S and E-W directions. In order to quantify over-strength factor, Ωₒ, and the maximum base shear corresponding to each archetype's pushover curve were calculated. The final values for Ωₒ and period-based ductility (μ_T) were calculated by averaging the values from each of the principal directions (Table 5). A comparison between archetypes 305, 306 and 308 in N-S and E-W directions indicates that in both structures first yield occurs at the same roof displacement of approximately 3 in. Table 5 shows summary of the average values extracted from pushover analysis curves, shown in Figures 5 & 6 along both principal directions (N-S and E-W) for 305, 306 and 308 archetype models. As it can be seen, there are two values correspond to ultimate roof drift displacement, $(\delta_u)_{SC}$ and $(\delta_u)_{NSC}$. $(\delta_u)_{SC}$ represents ultimate roof drift relevant to Simulated Collapse (SC) and is taken as the roof displacement value at the point of 80% maximum shear capacity of archetype model. $(\delta_u)_{SC}$, indicates ultimate roof drift related to Non-Simulated Collapse (NSC). It was taken as the roof displacement at which non-simulated (ductile fracture of RBS connections) failure mode happens. Since limit states were defined to obtain the onset of ductile fracture, it would be easy task to find out the exact point (roof displacement) on the pushover curve at which the first fracture occurs.

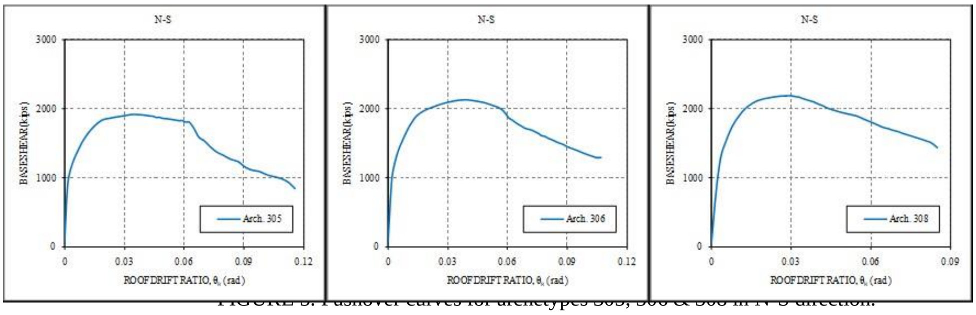

FIGURE 5. Pushover curves for archetypes 305, 306 & 308 in N-S direction.

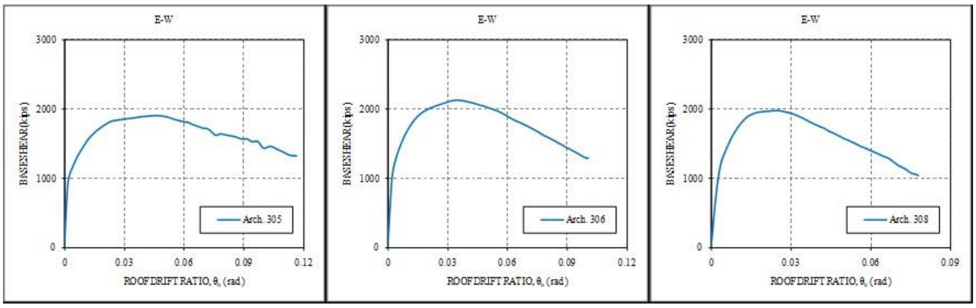

Fig. 6. Pushover curves for archetypes 305, 306 & 308 in E-W direction.

Tab. 5. Summary of over-strength and period-based ductility factors from pushover analysis.

Archetype ID	No. of Stories	Overstrength Ω_o	$(\mu_T)_{SC}$	$(\mu_T)_{NSC}$
305	5	2.25	25.2	14.2
306	8	2.05	20.5	12.5
308	12	1.90	13.7	8.3

5.2 Incremental Dynamic Analysis (IDA) and Collapse Margin Ration (CMR)

To quantify the median collapse capacity of each archetype model, a simplified IDA is required. A simplified IDA curve can be created by application of response history analyses. The main purpose of performing simplified IDA is to compute the collapse capacity of each archetype models. The essential aim of performing IDA is to obtain the median collapse intensity, $\hat{S}_{CT}$. The MCE ground motion intensity, S_{MT}, is obtained from the response spectrum of MCE ground motions at the fundamental period. **FIGURES 6 (a), (b)** and **(c)** depict the IDA curves, median collapse intensity, and the MCE ground motion intensity corresponding to archetype structures 305, 306 and 308 respectively. Majority of these curves seem to move around the initial elastic slope and follow closely the equal displacement rule. All the archetype structures were assessed for both simulated and non-simulated collapse modes (SCM and NSCM).

Table 6 indicates collapse margin ratios (CMRs) and adjusted collapse margin ratios (ACMRs) for both simulated and non-simulated collapse modes. Due to application of different global seismic performance factors for designing purpose, the CMR relevant to each archetype model is different. Subsequently it is shown, how calculated ACMRs were utilized to evaluate trial seismic performance factor acceptability.

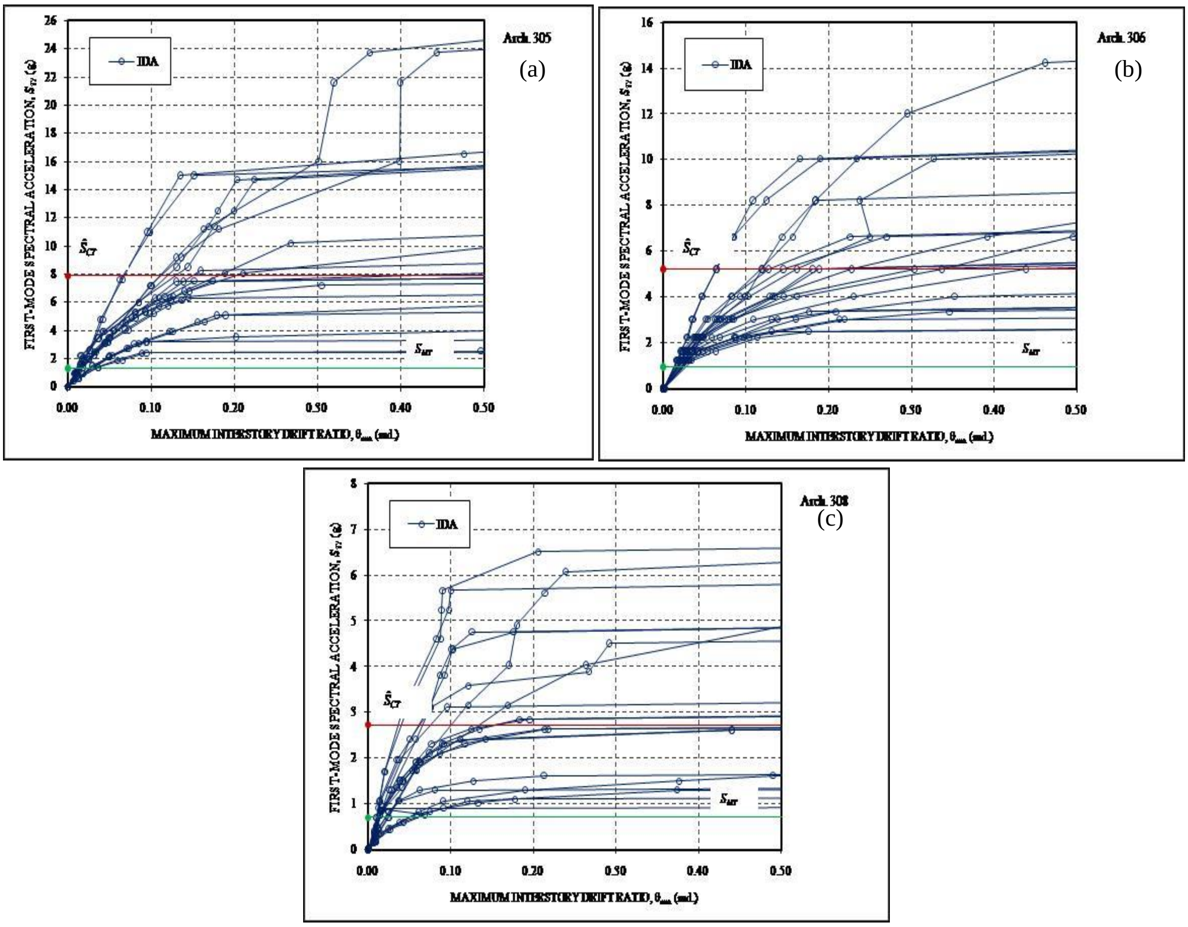

Fig. 6. IDA to collapse for Archetypes (a) 305 (5-story), (b) 306 (8-story) and (c) 308 (12-story).

Tab 7. Summary of over-strength and period-based ductility factors

Arch. ID	**No. of Stories**	S_{MT}	***SSF***	**Simulated Collapse Mode**			**Non-Simulated Collapse Mode**		
				S_{CT}	***CMR***	***ACMR***	S_{CT}	***CMR***	***ACMR***
305	5	1.32	1.375	7.88	5.9	8.19	4.69	3.5	4.88
306	8	0.953	1.449	5.23	5.4	7.82	3.03	3.1	4.59
308	12	0.714	1.538	2.73	3.8	5.84	1.91	2.6	4.00

Per FEMA [5], acceptability of calculated *ACMR*s are based on total system collapse uncertainty, β_{TOT}, and acceptable collapse probability values [5]. To evaluate Response Modification coefficients (R), and achieve acceptable performance each archetype model must meet the following two criteria: (1) the value of adjusted collapse margin ratio ACMR corresponding to each archetype must exceed the value of $ACMR_{20\%}$; and (2) calculated average value of adjusted collapse margin ratio for each performance group must exceed the value of $ACMR_{10\%}$ [5]. Archetype models that fulfil the above mentioned two basic collapse prevention objectives, are considered to have acceptable performance.

6. Conclusion

For the proposed dual system, total system collapse uncertainty was calculated based on corresponding uncertainty values, and Record-to-Record (RTR) uncertainty. RTR uncertainty, β_{RTR}, was accounted for variability in response of each archetype model in IDA to different ground motions. It was considered $\beta_{RTR} = 0.4$ for systems with $\mu_T \geq 3$. The total system collapse uncertainty for each archetype, β_{TOT}, is shown in Table 7. Acceptable Adjusted Collapse Margin Ratios (ACMRs), are calculated based on total system collapse uncertainty, β_{TOT}, and established values of acceptable probabilities of collapse. Relevant values to 20% probability of collapse for MCE ground motion, $ACMR_{20\%}$, was selected for each archetype structure. The Adjusted Collapse Margin Ratio, ACMR, for each model was computed as the multiple of the Spectral Shape Factor, SSF, CMR and 1.2 (effect of 3-D nonlinear dynamic analysis) and table 7 shows that they all pass the criteria.

This paper presents BRBF/IMF dual system assessment to develop global seismic performance factors. The major objectives of this research are to quantify the seismic performance factors (R, Ω_o and C_d) for dual systems, which are not described by the available codes or listed in any standards. We ascertained the values for the seismic performance factors for the proposed dual system and later verified the assumptions. From the study it can be observed that all three archetype structures being evaluated fulfil the requirement of collapse performance (Table 7). It can calculations were performed considering a value of R = 10, Ω_o = 2.5 and C_d = 7.0. Even though, ASCE [2] suggests a maximum value of, R = 8, this research estimates a value of, R = 10 can be safely used for a dual system comprising of BRBF and IMF. Although proposed system is not an explicit model representing a horizontal combination of two different seismic force-resisting systems, it indicates that ASCE suggestion to utilize the least value of R for horizontal combination of different seismic force-resisting systems could be deficient of realistic approach.

Tab. 7. Summary of final collapse margins and comparison to acceptance criteria

Archetype ID	**No. of Stories**	**Over-strength *Ω***	**Simulated Collapse Mode**		**Non-Simulated Collapse Mode**		**Accept. *ACMR***	**Pass/Fail**
			CMR	***ACMR***	***CMR***	***ACMR***		
305	5	2.25	5.9	8.19	3.5	4.88	1.76	Pass
306	8	2.05	5.4	7.82	3.1	4.59	1.76	Pass
308	12	1.90	3.8	5.84	2.6	4.00	1.76	Pass
Mean		2.06	5.03	7.28	3.06	4.49	2.38	Pass

This research aims of at developing global seismic performance factors for a dual system where a BRBF system is combined with an Intermediate Moment Frame (IMF). 3 archetype structures were designed by considering various Response Modification Coefficients, R. The intended range of application is for upper bound of Seismic Design Category D (SDC D_{max}). Nonlinear static analyses (Pushover) and Incremental Dynamic Analyses (IDAs) were carried out to validate and to compute the collapse capacity of each archetype, respectively. In conclusion, Response Modification Coefficient, R = 10, Over-strength Factor, $\Omega_o = 3.0$, and Deflection Amplification Factor, $C_d = 7.0$, are suggested for design of BRBF/IMF dual systems.

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