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QUANTIFYING GLOBAL SEISMIC PERFORMANCE FACTORS IN DUAL SYSTEMS WITH BUCKLING RESTRAINED BRACED FRAMES

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Dual structural systems are commonly used in high rise buildings for various architectural reasons. Buckling Restrained Braced Frame (BRBF) is an emerging seismic force-resisting system that is currently being permitted by American Society of Civil Engineers (ASCE) to be used either as a single seismic force-resisting system or in combination with other seismic force resisting systems. In conventional practice, ASCE suggests that while using BRBF in conjunction with other lateral force resisting systems in a dual configuration, the lowest Response Modification Factor (R) pertaining to the softer system shall be used. This may result in significant overdesigning of structures as higher contribution from the BRBF system are often remain unutilized. This research aims at developing a methodology for calculating modified Response Modification Factor, R for structures where dual system occurs horizontally. This research investigates the effect of using the newly suggested Response Modification Factor (R) for dual systems, where a BRBF system is combined with an Intermediate Moment Frame (IMF). The study aims at proposing an innovative way of calculating Response Modification Coefficient (R), Over-strength Factor (Ω_o) and Deflection Amplification Factor (C_d) pertaining to the dual system. A wide variety of archetype sets 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. The nonlinear models directly simulate essential deterioration modes that contribute to collapse behavior. Afterwards, for collapse assessment, nonlinear incremental dynamic analyses are conducted.

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

1 INTRODUCTION

Dual seismic force-resisting systems are comprised of individual lateral force-resisting systems in complementary abilities. Presently, most of the steel dual systems suggested by ASCE/SEI 7 (2005) are combinations of primary steel Braced Frames (BFs) and secondary Moment Frames (MFs). Design of dual systems are challenging but offers significant benefits such as architectural openness, flexibility in interior design and appropriate building facade. From structural stand point, BRBFs can control inter-story drifts at lower levels that are critical for MFs. In designing dual systems, it is assumed that MFs remain elastic until Buckling Restrained Braces (BRBs) yield, which helps in the redistribution of forces from BRBFs to MFs and prevent the damage that BRBs can sustain due to their low post-yield stiffness (Maley *et al.* 2010).

ASCE/SEI 7 (2010) outlines directions for designing dual seismic force-resisting system comprising of BRBFs and SMFs but does not provide any conclusive suggestions regarding coupling of BRBFs with any other type of steel moment frames such as Intermediate Moment Frames (IMFs). This study investigates the behavior of building structures with dual combination of BRBFs and IMFs under seismic loading and develops global seismic performance factors such as Response Modification Factor (R), Over Strength Factor (Ω_o) and Deflection Amplification Factor (C_d). Current ASCE recommendation for horizontal combination of different structural systems is that the designer should use the 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, the recommended R should be 4.5 for the dual system. But, ASCE does not have any recommendation when BRBFs are used in combination with IMFs in a dual system. Since the Response Modification factor (R) is not listed by ASCE, we will quantify the values for the seismic response parameters for the BRBF/IMF dual system and compare the results with current ASCE code of practice.

2 GLOBAL SEISMIC PERFORMANCE FACTORS

Seismic performance factors like R, Ω_o and C_d greatly depend on structural seismic force-resisting system and structural material (Uang 1991). FEMA P695 and NHHRP Recommended Provisions (FEMA 451 2004) provide the definitions of R, Ω_o and C_d based on idealized pushover curve of a seismic force-resisting system. In this study, Global Seismic Performance Factors will be estimated for dual systems considering the Maximum Considered Earthquake (MCE) ground motion and collapse level ground motion. MCEs are 1.5 times the design level ground motions which are defined as mapped acceleration parameters. Collapse level ground motions are defined "as the intensity that would result in median collapse of seismic force-resisting system" (FEMA P695 2009). Equation 1 gives the mathematical expressions for R, Ω_o, and CMR where the definition of the terminologies can be found in FEMA P695 (2009).

$$R = \frac{V_E}{V} \qquad \Omega_0 = \frac{V_{\max}}{V} \qquad CMR = \frac{\hat{S}_{CT}}{S_{MT}} = \frac{SD_{CT}}{SD_{MT}} \tag{1}$$

3 MODEL AND ARCHETYPE DEVELOPMENT

The proposed methodology of quantifying performance factors involves the following major steps: (1) frame work and system information; (2) model and archetype development; and (3) nonlinear analysis and results. Since the BRBF/IMF dual system is comprised of two individual systems that are already established, the design requirements pertaining to each system are utilized. The BRB data were provided by StarSeismic® LLC for Powercat™ BRBs which were applied to both linear and nonlinear analyses.

The dual BRBF/IMF system used for evaluation comprises of non-perimeter BRBFs with ordinary beam-to-column moment connections and perimeter IMFs with prequalified Reduced Beam Sections (RBSs) (ANSI/AISC358 2005) as shown in Figure 1. IMFs are designed so that they are capable of resisting at least 25% of prescribed seismic forces. The story height is 13 feet except for the first story, which is 18 feet high. Chevron type BRBs are used and all floor diaphragms are assumed to be rigid. The building is used as an office building with an Occupancy Category II. The intended range of application is for upper bound of Seismic Design Category D (SDC D_{max}) and Site Class D (stiff soil). The mapped MCE spectral response acceleration were taken at short period, S_S = 1.5 g and at 1-second period, S_1 = 0.59 g. Floor and roof dead loads (excluding frame elements self weight) are taken 80 and 66 psf, respectively. For the sake of simplicity, all live loads were assumed to be non-reducible and taken as 50 and 20 psf for floor and roof, respectively.

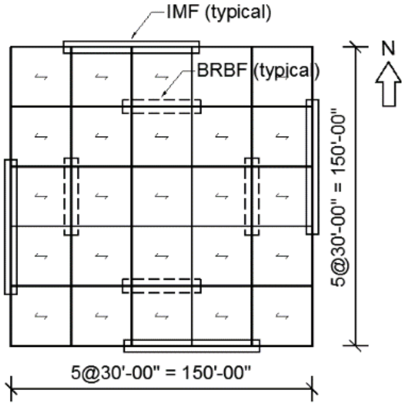


Figure 1. Plan view of typical archetype building.

In this study, three 8-story dual BRBF/IMF structures have been designed based on three different series of seismic performance factors. Table 1 shows three 8-story archetype IDs, pertinent to seismic performance factors, and secondary moment frames (IMFs) seismic force capacity. The seismic designs of BRBFs and IMFs were based on Seismic Provisions for Structural Steel Buildings ANSI/AISC 341 (2005) and Seismic Design of Buckling-Restrained Braced Frames by Lopez and Sabelli (2004).

4 ANALYSIS

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 was used to develop seismic force-resisting system's columns and beams behavior (PEER/ATC-72-1 2010). The panel zone model proposed by Krawinkler (1978) was used to explicitly simulate the panel zones shear distortion (PEER/ATC-72-1, 2010). BRBs were modeled assuming two bars in series: a linear (non-yielding) portion and a nonlinear (yielding) portion (Moehle *et al.* 2011). 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 (Fahnestock *et al.* 2003) behavior of

BRBs were explicitly taken into account 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.

Table 1. Archetype seismic design criteria.

Archetype ID	R	Ω_0	C_d	IMF Seismic Force Capacity
Archetype 106	6.25	3	6	25% of Prescribed Seismic Force
Archetype 206	7	2.5	6	35% of Prescribed Seismic Force
Archetype 306	10	2.5	7	25% of Prescribed Seismic Force

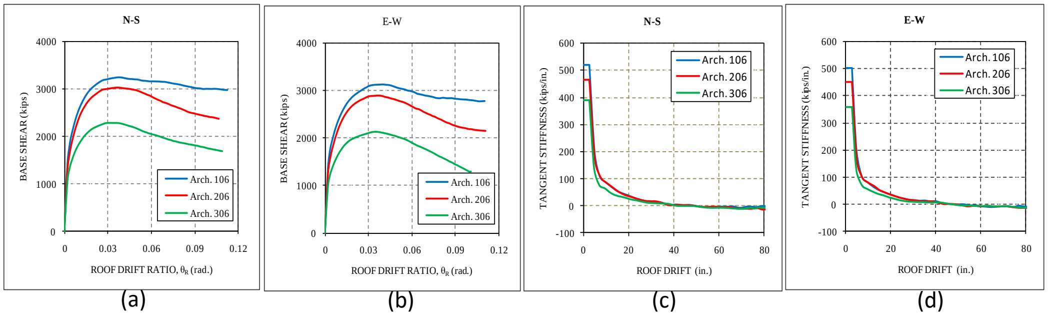
5 RESULTS

Nonlinear static (pushover) analyses were performed with a combination of 105% dead load and 25% live load, and static lateral forces (FEMA P695 2009). Figures 2(a) and (b), shows pushover curves of archetype structures in N-S and E-W directions. In order to quantify over-strength factor, Ω_0, and the maximum base shear corresponding to each archetype's pushover curve were calculated. The final values for Ω_0 and period-based ductility (μ_T) were calculated by averaging the values from each of the principal directions (Table 2).

Table 2. Summary of final collapse margins and comparison to acceptance criteria.

ArchID	Design Configuration		Computed Over-strength and Collapse Margin Parameters								Acc. Check
	# of Stories	R	δ_U	$\delta_{y,eff}$	β_{TOT}	μ_T	SSF	Static Ω	CMR	$ACMR$	$ACMR_{20\%}$
106	8	6.25	248.5	5.23	0.6	47.0	1.45	1.95	9.44	16.4	1.66
206	8	7	120.2	5.36	0.6	22.1	1.45	2.20	8.73	15.1	1.66
306	8	10	105.4	5.16	0.6	20.5	1.45	2.05	5.48	9.5	1.66

Figures 2(c) and (d) show plots of the tangent stiffness history versus roof drift for archetype buildings. A comparison between archetype 106 and 306 in E-W direction indicates that in both structures first yield occurs at the same roof displacement of approximately 3 in. However, the tangent stiffness at the first yield displacement are 359 and 503 kips/in. for archetype 306 and 106, respectively. Both structure's original stiffness were used up by the time the roofs displacement reach 18 in., but archetype 106 has 2% more tangent stiffness than archetype 306 at that point. Archetype 306 reaches the negative residual stiffness at a displacement of approximately 45 in., and archetype 106 attains that point at a displacement of approximately 54 in. The spectral acceleration at collapse (S_{CT}) due to the 20 ground motions of the far-field set was computed. The median collapse level ($\hat{S}_{CT}$), as it is shown in Figure 3, was computed for each individual archetype building. The CMR, defined in Eq.(3), are calculated to be 9.44, 8.73 and 5.48 for archetype 106, 206 and 306, respectively.



(a) (b) (c) (d)

Figure 2. (a) Pushover curve of archetype structures in N-S, (b) E-W direction, (c) Tangent stiffness history of archetype structures for N-S, and (d) E-W direction.

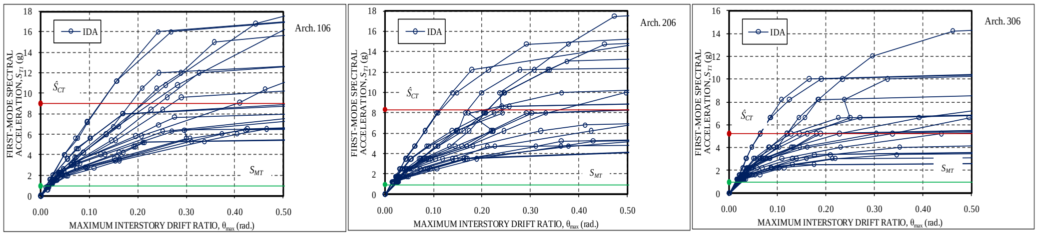


Figure 3. IDA to collapse, showing S_{MT} and $\hat{S}_{CT}$ for each archetype structure.

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 2. Acceptable Adjusted Collapse Margin Ratio, *ACMR*, 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).

This paper presents BRBF/IMF dual system assessment to develop global seismic performance factors. The major objectives of this research is 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 fulfill the requirement of collapse performance, but the one with the lowest *CMR*, archetype 306 with *R* = 10, would be the best option for further assessment. 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.

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