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RAPID RISK ASSESSMENT OF BUCKLING RESTRAINED BRACED FRAMES, WITH FOCUS ON RESIDUAL DRIFTS

E. Almeter¹, K.F. Wade², C.B. Haselton³, B. Saxey⁴

ABSTRACT

This paper discusses a rapid method for seismic risk assessment of buckling restrained braced frame (BRBF) buildings. The “rapid” component of this assessment is from the structural response prediction method that was developed which allows engineers to obtain accurate structural responses without the time consuming process of developing a full nonlinear model of the structure. Once the structural responses are obtained from this simplified model, they can be easily run through the FEMA P-58 risk assessment framework to assess the seismic risk of the structure. For structural responses, residual drifts are investigated in detail and the study shows the beneficial effects that a moment resisting back-up frame, as well as gravity system components, have on reducing residual drift demands in BRBF systems, and thereby increasing their seismic resilience.

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ABSTRACT

This paper discusses a rapid method for seismic risk assessment of buckling restrained braced frame (BRBF) buildings. The “rapid” component of this assessment is from the structural response prediction method that was developed which allows engineers to obtain accurate structural responses without the time consuming process of developing a full nonlinear model of the structure. Once the structural responses are obtained from this simplified model, they can be easily run through the FEMA P-58 risk assessment framework to assess the seismic risk of the structure. For structural responses, residual drifts are investigated in detail and the study shows the beneficial effects that a moment resisting back-up frame, as well as gravity system components, have on reducing residual drift demands in BRBF systems, and thereby increasing their seismic resilience.

Introduction

In order to expedite the risk assessment of BRBFs, nonlinear time history analysis was performed using OpenSEES [1] on a set of BRBF archetypes to investigate trends in behavior with building height and shaking intensity. Based on the observed trends, a simplified response prediction model was created to allow for accurate prediction of structural responses without a nonlinear model. The structural response prediction method discussed here covers CoreBrace BRBF buildings from 1-story to 25-stories, without irregularities, and with a range of standard bracing layouts. The method covers response prediction for levels of ground motion ranging from elastic response to highly nonlinear response above MCE levels. The variants considered for each model in this study are listed in Table 1.

Table 1. Variants considered for each model.

Variant	Base Connection	Gravity System	Backup Frame
1	Pinned	None	None
2	Pinned	Present	None
3	Pinned	None	Present
4	Pinned	Present	Present
5	Fixed	None	Present
6	Fixed	Present	Present

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Structural Response Prediction Method

Method for Predicting Peak Interstory Drift (IDR)

Perhaps one of the most important structural responses of a building is the IDR. For the simplified model, the general process is to approximate the roof drift for a given intensity of ground shaking, then use that to scale the elastic drift profile (mode shape) to get the drift profile shown in Figure 1 as $IDR_{elastic}$. Once we obtain $IDR_{elastic}$, the final IDR profile is obtained by modifying that “elastic” profile to reflect the localization caused by the structure’s inelasticity.

The roof drift of the structure at the desired intensity is calculated using ASCE 41-13 and then modified based on the trends in the nonlinear analysis. When the structure is subject to shaking that causes inelastic response, the inelastic drift tends to localize in the lower levels of the structure. To reflect this in the peak IDR profile, the drift in the lower levels of the structure are increased relative to $IDR_{elastic}$ and the upper levels are decreased relative to $IDR_{elastic}$. This results in the IDR_{mod} shown in Figure 1.

The degree to which the peak IDR is localized is dependent on the strength ratio, S , defined as

$$S = \frac{S_a}{(V_y/W)} \quad (1)$$

Where S_a is the spectral acceleration (in g) at the fundamental period of the building at the assumed hazard level, V_y is the base shear capacity of the building, and W is the total weight of the building.

The location of the “lower” and “upper” levels depends on the presence or absence of a backup frame and, if the backup frame is present, the end condition at the base of the backup frame. Both pinned and fixed columns were considered as the end conditions at the base of the frame; the use of the proper model is to be determined at the engineer’s discretion.

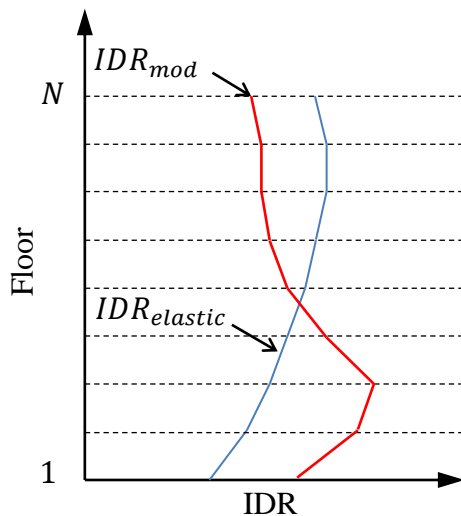


Figure 1. Peak interstory drift profile.

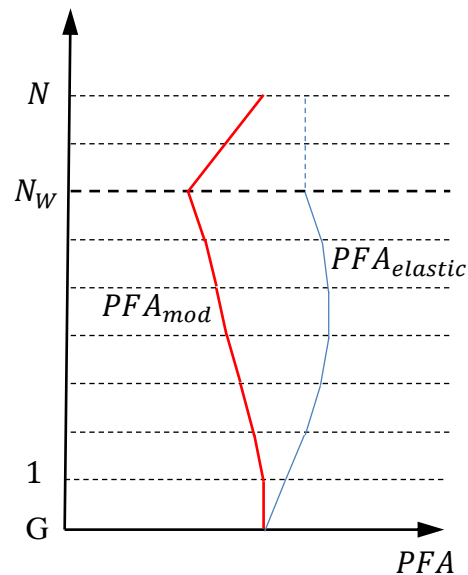


Figure 2. Peak floor acceleration profile.

Method for Predicting Peak Floor Acceleration (PFA)

Like the peak IDR prediction method, an “elastic” response is approximated and then modified to reflect the inelastic response. The elastic PFA profile, $PFA_{elastic}$ in Figure 2, is computed using elastic response history analysis with the first three modes of the structure. After that, the levels from the anchor level, N_w (selected based on the number of stories), and down are scaled based on the strength ratio of the building. The levels above the anchor level are scaled in such a way to reflect the “whip” experienced in the nonlinear time history analysis.

Method for Predicting Residual Interstory Drift

The residual drifts experienced in the model were monitored for all different configurations. Based on the 6 variants considered in the analysis, three total residual drift models are proposed.

- Model for CoreBrace BRBF with no backup frame and without gravity frame contribution
- Model for CoreBrace BRBF with no backup frame with gravity frame contribution
- Model for CoreBrace BRBF with backup frame (with or without gravity frame contribution)

The gravity system and base connection variants did not have a significant effect on the residual drifts for the structures with a backup frame, so no distinction is made in the proposed residual drift method.

The data used to fit the data for the different residual IDR models are shown in Figure 3. . The red points are binned medians. The red line is the fit from the proposed model.

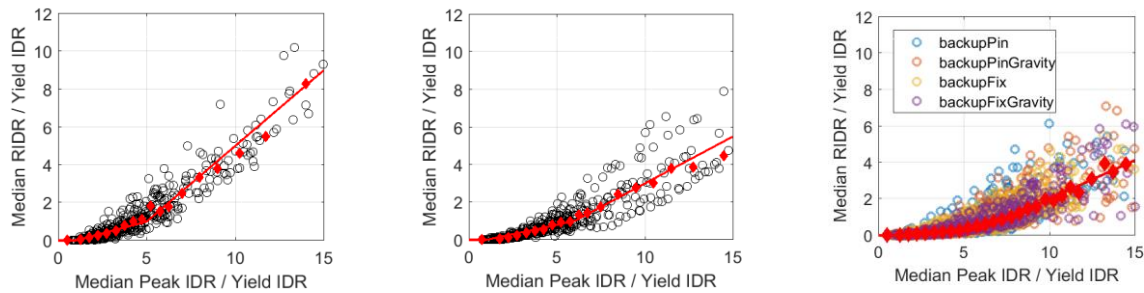


Figure 3. Residual drifts for frames with (left) no backup frame and no gravity, (center) no backup frame with gravity, (right) all configurations with backup frame

The three different residual drift models are shown in Figure 4. The results show that the residual drifts are not as severe as predicted using the FEMA P-58 [2] methodology, and improve considerably when considering the gravity system, and even more when a backup frame is added.

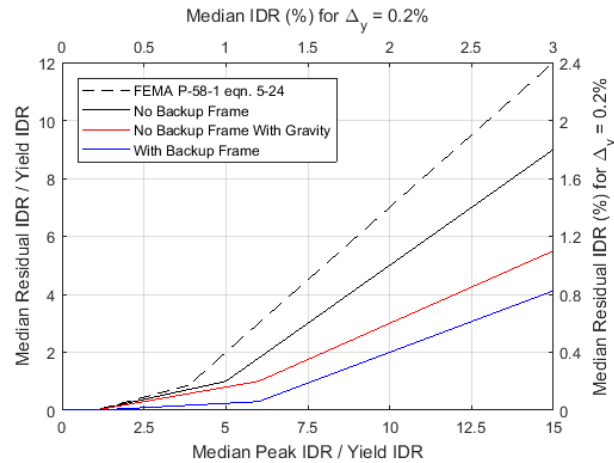


Figure 4. Residual drift model comparison.

CoreBrace Fragility Development

In contrast to the baseline FEMA P-58 fragility library, which only has one fragility function independent of brace geometry or brace ductility design, new CoreBrace fragilities were created to both reflect the specific test data from full-scale component tests, as well as the geometry of the brace as installed in the building (both the core area and the installation geometry). These results show that the CoreBrace fragility functions are substantially more ductile than the default BRBF fragility functions in the FEMA P-58 database, with the default functions having a mean drift capacity of 2% at brace fracture and the CoreBrace fragilities having a mean drift capacity ranging from 4% to 7%.

Test Data

CoreBrace specific fragilities were developed based upon six sets of laboratory test data, which were completed by the University of San Diego [3][4][5][6][7]. The testing protocol varied depending upon the intent of testing and included the standard protocol from the AISC Seismic Provisions for Structural Steel Buildings as well as protocols designed to be more similar to ground motions (greater amplitudes, fewer cycles, and asymmetric loading). The specimens are representative of the standard CoreBrace configurations.

Damage States

Damage progression in the buckling restrained braces (BRBs), subject to increasing cyclic displacements, may be represented by a single damage state; described as follows:

- Damage State One - Fracture of brace or gusset. Buckling of gusset. Severe yielding of beams and columns adjacent to the gusset with possibility of local buckling and cracking in the yielded areas. Severe loss of lateral resistance.

This damage state and associated repair actions inform the development of the fragility functions

representing the damageability of CoreBrace BRBs as well as damage consequences in terms of direct monetary loss, repair time, occupant casualties, and building unsafe placarding/red tagging.

Engineering Demand Parameter used for Fragility

The demand parameter selected to inform BRB damage is interstory drift ratio. The testing laboratory measured the strain in the yielding portion of the BRB steel core at increasing axial (and in several cases transverse) displacement demands. This brace strain in the yielding steel core length (L_{sc}) is translated to an interstory drift ratio (IDR) based upon the geometry of an assumed frame and the ratio of total brace length or working point length (L_{wp}) to the steel core length. This conversion is done using the geometry including the angle of the brace and the yielding code length of the brace, and is documented in the full report on this project.

Binning Fragilities

A subset of standard CoreBrace BRBs (132 fragilities in total) intended to blanket the most commonly used configurations are outlined in Table 2. The fragilities and consequences are individually calculated for each of the configurations outlined in Table 2.

Table 2: Summary of CoreBrace BRB configurations represented by components

Brace Configuration		Connection Detail											
		Single Diagonal						Chevron/V					
Story Ht, H (ft)		14	16	20	14	16	20	14	16	20	14	16	20
Bay Width, B (ft)		30	30	30	20	20	20	20	20	20	15	15	15
Bay/Story Height Ratio		2.14	1.88	1.50	1.43	1.25	1.00	1.43	1.25	1.00	1.07	0.94	0.75
A_{sc} (in ²)	5	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted
		Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned
		Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded
	10	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted
		Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned
		Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded
	20	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted
		Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned
		Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded
	30	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted	Bolted
		Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned	Pinned

Fragility Functions – Example Function

The BRB fragility is created based on an axial strain demand (see Figure 6); that strain-based fragility is converted to an interstory drift fragility using the geometry of the specimen and an assumed frame. A single example fragility function is outlined in Table C and Figure C for a bolted diagonal brace (including comparison to the standard FEMA P-58 fragility for BRBs).

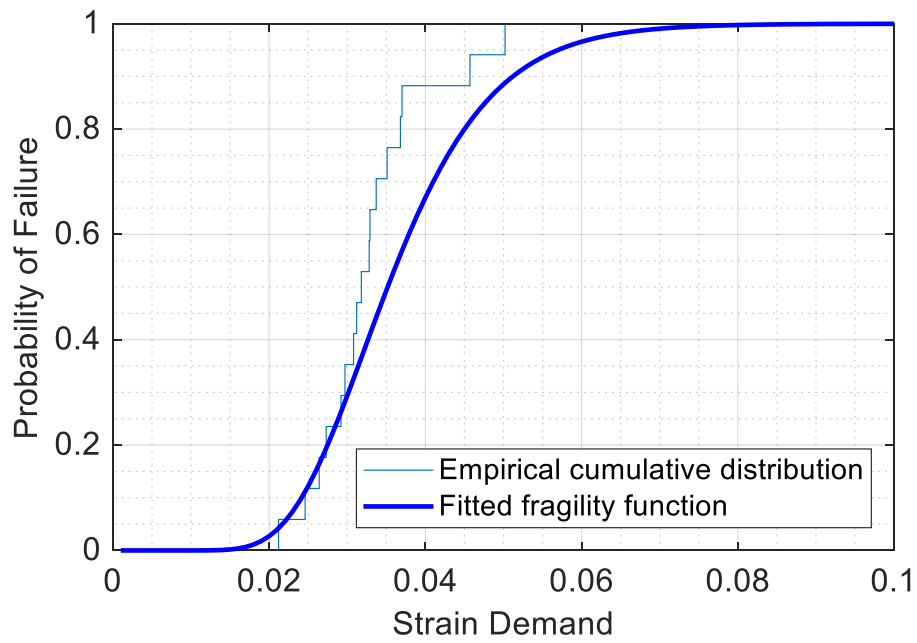


Figure 5. Fragility curve fitted to strain data CoreBrace BRB

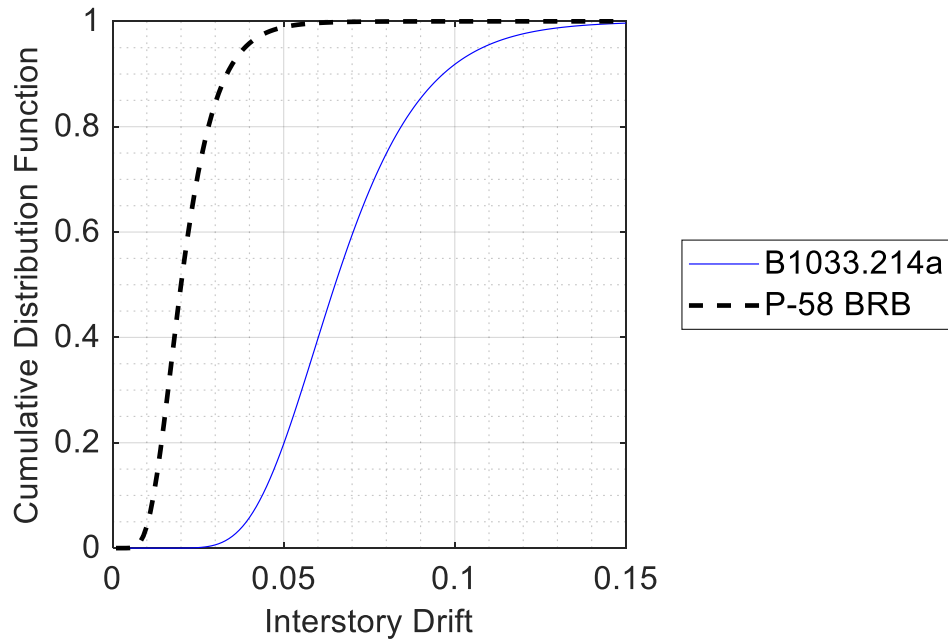


Figure 6. Fragility Function for example diagonal CoreBrace BRB fragility.

Fragility Functions – Full Set for all Geometries

The fragilities for all of the proposed CoreBrace BRB fragilities are outlined in tabular format in Table 3 and Figure 7, which shows the FEMA P-58 baseline fragility curve as compared with these many CoreBrace fragilities for the various geometries. Table 3 only includes functions for bolted braces (for brevity and based on space limitations of this paper).

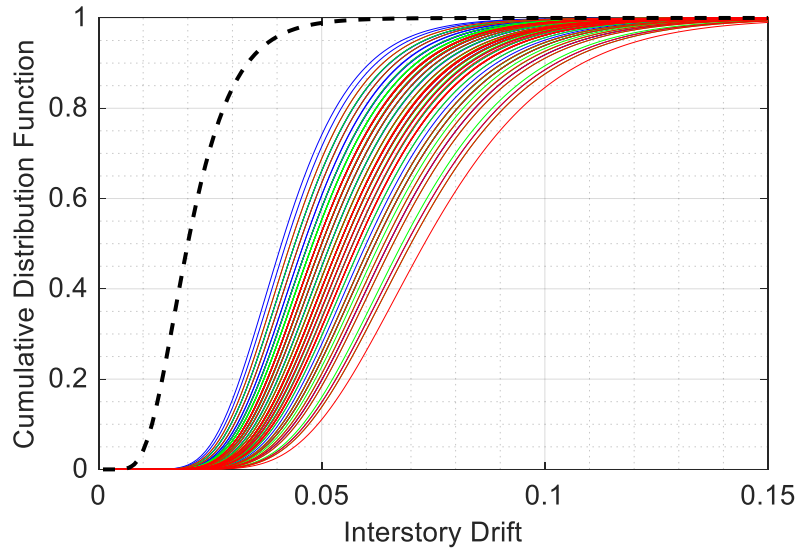


Figure 7. Fragility function for all geometries considered (dashed is the FEMA P-58 default).

Table 3. Bolted CoreBrace BRB median damage threshold and dispersion for damage threshold

		Median (IDR)											
		Single Diagonal					Chevron/V						
Story Ht, H (ft)		14	16	20	14	16	20	14	16	20	14	16	20
Bay Width, B (ft)		30	30	30	20	20	20	20	20	20	15	15	15
Bay/Story Height Ratio		2.14	1.88	1.50	1.43	1.25	1.00	1.43	1.25	1.00	1.07	0.94	0.75
A_{br} (in ²)	5	0.069	0.065	0.061	0.054	0.054	0.055	0.057	0.055	0.056	0.051	0.052	0.055
	10	0.065	0.062	0.058	0.049	0.049	0.051	0.052	0.051	0.052	0.046	0.047	0.050
	20	0.062	0.060	0.057	0.047	0.048	0.049	0.050	0.050	0.050	0.044	0.045	0.049
	30	0.059	0.056	0.054	0.044	0.044	0.047	0.047	0.047	0.048	0.041	0.042	0.046

		Beta _T (IDR)											
		Single Diagonal					Chevron/V						
Story Ht, H (ft)		14	16	20	14	16	20	14	16	20	14	16	20
Bay Width, B (ft)		30	30	30	20	20	20	20	20	20	15	15	15
Bay/Story Height Ratio		2.14	1.88	1.50	1.43	1.25	1.00	1.43	1.25	1.00	1.07	0.94	0.75
A_{br} (in ²)	5	0.309	0.309	0.308	0.308	0.308	0.306	0.308	0.308	0.306	0.307	0.306	0.304
	10	0.309	0.309	0.308	0.308	0.308	0.307	0.308	0.308	0.306	0.307	0.306	0.304
	20	0.309	0.309	0.308	0.308	0.308	0.307	0.308	0.308	0.307	0.307	0.306	0.305
	30	0.309	0.309	0.308	0.308	0.308	0.307	0.308	0.308	0.307	0.307	0.307	0.305

Damage Consequences

Repair consequences for BRB fracture include replacement of the brace itself and heat straightening of the frame members around the brace, as well as implied work to access the damaged components. These consequences are translated to repair cost, repair time, red tagging, and casualty consequences using the FEMA P-58 Method. Repair costs and times are estimated using a detailed repair plan on a line-by-line basis and costing information from CoreBrace.

Unsafe placarding is possible in the case where the structural stability is compromised, the threshold for red tagging based upon BRB fracture is set similar to other brace configurations at 20% damaged components. In other words, a red tag will be triggered in a FEMA P-58 analysis in which 20% or more of the BRBs in the building fracture.

Non-collapse casualties are generally associated with falling hazards; BRB are not expected to cause casualties based on falling hazards.

Case Study with Response Prediction Method and New CoreBrace Fragilities

This new structural response prediction method, new fragilities, and most importantly the updated residual drift prediction method were used to completed risk analyses of an example new 12-story BRB building in Riverside, CA. Figure 8 shows the results of these risk analyses, showing the loss curve predicted from the baseline FEMA P-58 residual drift method, as well as the loss curves computed with the updated residual drift models provided in this report. This shows that the updated residual drift models used in the loss assessment have a significant impact on the overall losses at both the 10% in 50 and 2% in 50 hazard levels.

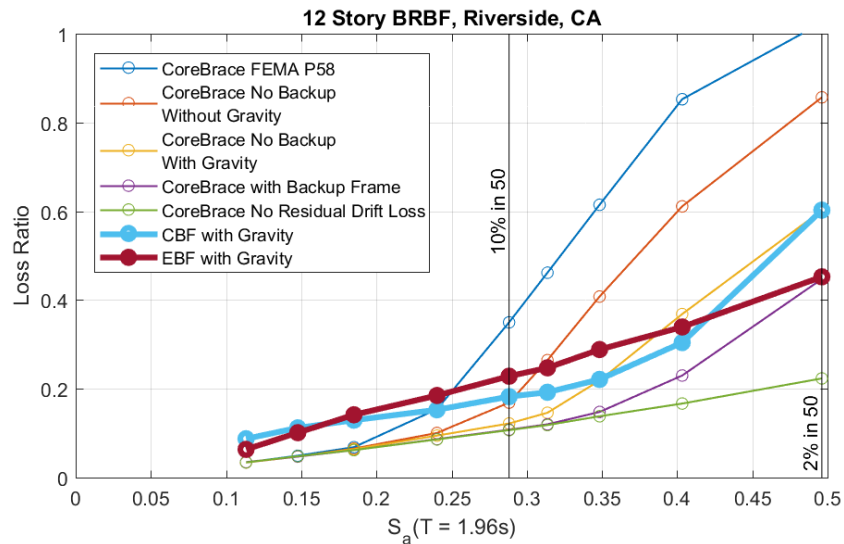


Figure 8. Loss curves for different residual drift models

Conclusion

The findings in this report show that the CoreBrace BRBs have significantly more capacity than predicted by the default FEMA BRB fragility. The structural responses of a CoreBrace buckling restrained brace frame (BRBF) building were approximated based on a suite of nonlinear time history analysis for variants with and without a backup frame, considering and not considering the gravity frame contribution to the response. The residual drifts were also investigated and found to be significantly lower than the values predicted by FEMA P-58 when the contribution of a gravity system is considered, and lower yet if a backup frame is included. This is a significant finding for risk assessment since the loss due to residual drift can be a significant portion of the total expected loss, so the lower residual drift demands increase the seismic resilience of the structure.

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