Life Cycle Cost-Benefit Evaluation of Self-centering and Conventional Concentrically Braced Frames

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ABSTRACT: Self-centering concentrically braced frame (SC-CBF) systems have been developed to increase the drift capacity of braced frames prior to structural damage. To achieve the improved seismic performance of SC-CBF system, the construction cost of an SC-CBF is expected to be higher than that of a conventional CBF. In this study, economic effectiveness of using an SC-CBF instead of a CBF in one prototype building is calculated to indicate the time that initial SC-CBF construction costs are compensated by lower earthquake-induced losses in the lifetime of the building (pay-off time). The results of this study show lower business interruption is the most significant component of the economic benefit of the SC-CBF compared to the CBF. Moreover, the pay-off time increases dramatically if the initial construction cost of the SC-CBF is more than 4% higher than the CBF.

Earthquake-induced damages of buildings can cause social and economic disturbances. Self-centering concentrically braced frame (SC-CBF) systems (Roke et al. 2009) have been developed to address the limitations of conventional CBFs by increasing drift capacity of the structure prior to damage and decreasing residual drift; thus SC-CBF can mitigate losses due to earthquakes. This improved seismic performance of the SC-CBF system has been found experimentally and numerically (e.g., Roke et al. 2009; Dyanati et al. 2014, 2015). However, the construction cost of an SC-CBF is expected to be higher than that of a conventional CBF due to the special details and elements required by the SC-CBF. Therefore, it is necessary to investigate if the higher construction cost of SC-CBF system would be offset by lower earthquake-induced losses (due to better seismic performance of SC-CBF) during the life time of the building, which would demonstrate the economic effectiveness of SC-CBF systems compared with conventional CBF systems.

Life cycle cost assessment has been used as a measure of the economic effectiveness of a structure. Wen & Ang (1991) and Wen & Shinozuka (1998) developed a life cycle cost formulation to investigate the cost effectiveness of an active control system in structures during earthquakes. Goda et al. (2010) used life cycle cost assessment to investigate the cost effectiveness of a seismic isolation technology. Kang & Wen (2000) used the minimum life cycle cost concept to develop an optimal design for structures under single and multiple hazards. Padgett et al. (2009) developed a retrofit strategy for bridges based on cost-benefit analysis using life-cycle cost to determine the most cost-effective retrofit method that differs based on the seismic hazard characteristics of the location.

Available software such as HAZUS (FEMA 2014) and PACT (FEMA 2012) have been used in the seismic performance and loss evaluation of buildings (Erberik & Elnashai 2006, Parvini sani & Banazadeh 2012) and can also be used for life cycle cost estimation. However, there is a major drawback in both software packages: they both define engineering demand parameter (EDP) models as a function of only one seismic intensity measure (IM), pseudo spectral acceleration (PSA), which may not be accurate for CBF and SC-CBF structures (as studied by Dyanati et al. 2015), eventually leading to inaccuracy in the loss estimation.

In this study, the economic benefit of the SC-CBF will be studied using life cycle cost formulation. The economic benefit of the SC-CBF, which is the difference between life cycle cost of SC-CBF and CBF structures, will clarify if the higher construction cost of SC-CBF will be compensated by better performance of SC-CBF.

1. SC-CBF SYSTEM

The general configuration of an SC-CBF is shown in Figure 1(a). There are two sets of columns in the SC-CBF: SC-CBF columns and adjacent gravity columns. As shown in Figure 1(b), the SC-CBF columns are allowed to uplift at the base, causing a rocking response under higher levels of lateral force. Vertically oriented post-tensioning (PT) bars and gravity loads are used to resist column uplift and provide self-centering (i.e., reducing residual drift). The rocking behavior softens the lateral force-lateral drift response of the system, thereby permitting larger lateral displacements while limiting the member force demands, avoiding yielding or buckling in the braces.

2. SEISMIC LIFE-CYCLE COST-BENEFIT MODEL

Life cycle cost of a building system subjected to seismic hazard includes three components (Kang & Wen 2000): initial construction cost, including structural and non-structural component costs (C_0); earthquake-induced losses or life cycle loss of the building (e.g., repair cost, business interruption, injuries) (LCL); and operation/maintenance costs during the life cycle of the building (C_m), as shown in Equation (1).

$$LCC(t,\mathbf{x}) = C_0(\mathbf{x}) + LCL(t,\mathbf{x}) + C_m(\mathbf{x}) \tag{1}$$

where LCC = life cycle cost of the structure; t = life time of the structure; and $\mathbf{x}$ = vector of design variables for the structure.

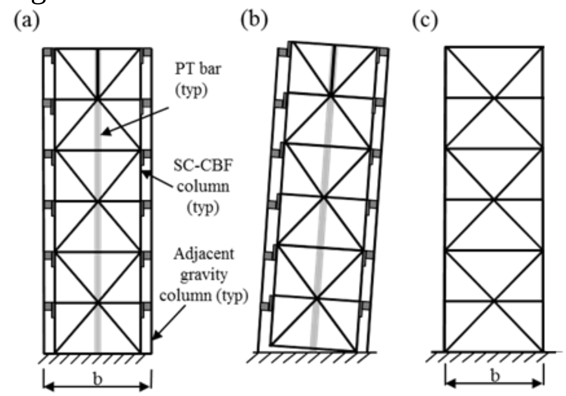

Figure 1: (a) Configuration of SC-CBF; (b) Rocking behavior of SC-CBF; (c) configuration of CBF.

Construction cost estimation is straightforward and can be generally estimated using expert opinions or tools such as R.S. Square Foot Costs (RS Means 2013). Maintenance and operation costs are highly related to the occupancy of the building, rather than the structural system, and can be estimated using handbooks and standards such as Facilities Maintenance & Repair Cost Data Online (RS Means 2013).

The life cycle loss (LCL) estimation, on the other hand, involves more complex procedures including hazard, response, damage, and loss analysis for calculating the losses from earthquakes. If the expected annual loss (EAL) from earthquakes is known, the expected value for life cycle loss ($E[LCL]$) can be evaluated as follows (Porter et al. 2004):

$$E[LCL(t,\mathbf{x})] = \frac{\left(1-e^{-\gamma t}\right)}{\gamma} EAL \tag{2}$$

where $e^{-\gamma t}$ = discounted factor over time t and γ = constant discount rate per year, which is used to calculate the present value of the future losses.

Assuming $C_{0,\text{SC-CBF}} = a\ C_{0,\text{CBF}}$ (a = relative cost coefficient and $a > 1$) and equal maintenance/operation costs for CBF and SC-CBF systems, the expected economic benefit of using an SC-CBF instead of a CBF in a building, $E[B_{\text{SC-CBF}}]$, can then be calculated as follows:

$$E\left[B_{SC-CBF}\right]=\left(1-a\right)C_{0,CBF} + \frac{\left(1-e^{-\gamma t}\right)}{\gamma}\left(EAL_{CBF}-EAL_{SC-CBF}\right) \quad (3)$$

$E[B_{\text{SC-CBF}}]$ is a function of a, $C_{0,\text{CBF}}$, t, γ,and the difference of EAL of the two systems. $E[B_{\text{SC-CBF}}]$ is expected to change over time, starting from a negative value because the initial construction cost of SC-CBF systems is expected to be higher than that of CBF systems (a > 1.0). However, $EAL_{\text{SC-CBF}}$ is lower than EAL_{CBF}, as SC-CBFs have better seismic performance, so E[$B_{\text{SC-CBF}}$] will increase over time. The time in the life cycle of a building when E[$B_{\text{SC-CBF}}$] = 0 is called the pay-off time or break-even point. In other words, at the pay-off time, the extra initial construction cost of the SC-CBF will be paid back by mitigating the losses due to earthquakes.

2.1. Expected annual loss

To calculate EAL, earthquake occurrences during the life time of the building must be predicted. Assuming a Poisson process for earthquake occurrence, the EAL of the building can be evaluated in a closed form as follows (Padgett et al. 2010, Ellingwood & Wen 2005):

$$EAL=\sum_{j=1}^{k}-\psi_j\left[\ln\left(1-P_{a,j}\right)-\ln\left(1-P_{a,j+1}\right)\right] \quad (4)$$

where ψ_j = cost associated with jth damage state; $P_{a,j}$ = annual probability of exceeding the jth damage state.

2.2. Annual probability of exceeding damage states

Damage states are normally defined based on exceeding certain values of EDPs such as peak inter-story drift (for structural and non-structural damage) and peak floor acceleration (for non-structural damage). Therefore, $P_{a,j}$ can be quantified as follows:

$$P_{a,j}=\int P\left(D>C_j \mid s\right)\left|d\lambda(s)/d\,s\right|\,d\,s \quad (5)$$

where, D = EDP of interest; C_j = capacity of EDP of interest associated with jth damage state; s = intensity measure (IM) of interest; $P(D > C_j|s)$ = seismic fragility; $\lambda(s)$ = distribution of mean annual frequency of exceeding IM (i.e., IM hazard), which can be estimated using a type II extreme value distribution (i.e., Frechet distribution) as follows (Song & Ellingwood 1999, Cornell 1968):

$$\lambda(s)=1-\exp\left[-\left(s/\mu\right)^{-k}\right] \quad (6)$$

where μ and k are the location and slope of the distribution, respectively.

Typically, when more than one IM is involved in the hazard analysis the previous studies have used conditional probability to transfer the multiple IM hazard to a single IM hazard (Baker 2007). Thus, for two IMs, Eq. (5) can be rewritten as follows:

$$P_{a,j}=\iint P\left(D>C_j \mid s_1\right)f_{s_2|s_1}\left(s_2 \mid s_1\right)\left|\frac{d\,\lambda(s_1)}{ds_1}\right|ds_1 ds_2 \quad (7)$$

where $f_{s_2|s_1}(s_2 \mid s_1)$ = conditional distribution of s_2 given s_1. Alternatively, Eq. (5) can be evaluated using the joint distribution of mean annual extremes of IMs as follows:

$$P_{a,j}=\iint P\left(D>C_j \mid s_1,s_2\right)\left|\frac{d\lambda\left(s_1,s_2\right)}{ds_1\ ds_2}\right|ds_1\ ds_2 \quad (8)$$

where $\lambda(s_1,s_2)$ = joint distribution of mean annual extremes of s_1 and s_2 that can be evaluated using an m-type bivariate joint extreme value distribution for Frechet marginal distributions (Elshamy 1992, Gumbel & Mustafi 1967). Note that Eq. (8) uses a joint distribution that has an analytical expression, while Eq. (7) requires a conditional probability distribution, $f_{s_2|s_1}(s_2 \mid s_1)$, which is usually approximated based on the available ground motion data. The values of $P_{a,j}$ obtained though Eqs. (7) and (8) are compared in Dyanati et. al (2015).

3. CASE STUDY

In this section, the proposed methodology in Section 2 is applied to one prototype building located in Los Angeles.

3.1. Prototype structure

The prototype structures in this study are same structures that were used for the structural and non-structural performance evaluation study of SC-CBFs by Dyanati et al. (2014, 2015). The prototype structures are 6-story office buildings designed for downtown Los Angeles using exclusively CBFs and exclusively SC-CBFs as the lateral-load-resisting systems, respectively. The design details can be found in Dyanati et al. (2015).

The construction costs of the prototype structure with CBF system are estimated using RS Means Square Foot Costs (RS Means 2013) to be \$174.35/ft^2 (\$1876.72/m^2). The costs of the contents of the building (e.g., desks, shelves, computers) are determined based on the recommendations of HAZUS (FEMA 2014) for business occupancy. The number of residents of the building is estimated as 2 people per 1000 square feet, following recommendations by Kang & Wen (2000).

3.2. Loss types and damage states

In this study, the *EAL* calculation is performed considering seven types of losses as follows: 1) structural damage (L_1) - repairs or replacement cost of damaged structural components; 2) non-structural damage (L_2) - repairs or replacement cost of damaged non-structural components (drift sensitive and acceleration sensitive); 3) content damage (L_3) - replacement of damaged content in the building; 4) relocation (L_4) - cost of relocating from the damaged building; 5) economic loss (L_5) - the losses of income and rental income in the period of repairs or replacement of the damaged building; 6) injury loss (L_6) - the cost of injuries of the inhabitants of the building; and 7) human fatality loss (L_7) - the cost of the fatalities of the inhabitants of the building.

Losses are evaluated based on the corresponding damage states (e.g., Kang & Wen 2000, and Ramirez & Miranda 2009). In this study, four damage states – slight, moderate, extensive, and complete (defined based on EDP capacities) – will be considered to estimate each type of loss following recent studies of seismic loss evaluation (e.g., Bai 2009 and FEMA 2014). For different losses, different EDPs are used to quantify the damage states, as shown in Table 1.

Table 1: Damage state definitions for all loss types

Loss type	Damage state definition	
	EDP	Reference
L_1-Structural	ID	ASCE41, Baker (2007)
L_2-Non-struc.	ID	HAZUS (FEMA 2014)
	PFA	Ramirez & Miranda (2009)
L_3-Content	Same as L_2-acceleration sensitive	
L_4-Relocation	Same as L_1	
L_5-Economic	Same as L_1	
L_6-Injury	Same as L_1	
L_7-Fatality	Same as L_1	

ID: inter-story drift, PFA: peak floor acceleration

Inter-story drift is used to quantify the damage states of structural losses (L_1) and its capacities are defined based on the capacities for the performance levels of immediate occupancy, life safety, and collapse prevention from ASCE41 (2007), respectively, which has been used for the structural performance evaluation of CBF and SC-CBF in previous studies (Dyanati et al. 2013, 2014; Kafaeikivi et al. 2013). The damage state of complete collapse has not been defined in ASCE41 (2007); thus an inter-story drift limit of 10% (Baker 2007) is used to define the collapse limit for both CBF and SC-CBF. Table 2 shows the inter-story drift capacities for the structural damage states. Non-structural components are categorized into drift sensitive components (e.g., partitions, windows) and acceleration sensitive components (e.g. HVAC, plumbing) following the state-of-practice in this field (e.g., ASCE 2007). Capacity of a non-structural component depends on the type and make of the individual component. However, one can define capacities for generic components. Table 2 shows the inter-story drift capacities for drift sensitive non-structural components obtained from HAZUS (FEMA 2014) and the acceleration capacities for acceleration sensitive non-structural components following Ramirez & Miranda (2009). Damage states limits for calculation of other types of loss will be assumed to be the same as the ones for structural components, since they are closely related to the structural performance, as shown in Table 1.

Table 2: Inter-story drift and peak floor acceleration capacities for damage states

Damage States	Structural		Non-structural	
	CBF	SC-CBF	Acceleration Sensitive	Drift. Sensitive
Slight	0.5%	0.7%	0.7 (g)	0.4 %
Moderate	1.5%	2.5%	1.0 (g)	0.8 %
Extensive	2.0%	5.0%	2.2 (g)	2.5 %
Complete	10.0%	10.0%	3.5 (g)	5.0 %

3.3. Expected annual loss

For each type of losses, *EAL* will be evaluated based on Eq. (4), which needs ψ_j for each damage state and the annual probability of exceeding each damage states ($P_{a,j}$).

Table 3: Damage factors for structural and non-structural loss

Damage States	Structural	Non-structural	
		Acceleration Sensitive	Drift. Sensitive
Slight	0.4%	0.9%	0.7%
Moderate	1.9%	4.8%	3.3%
Extensive	9.6%	14.4%	16.4%
Complete	13.8%	47.9%	32.9%

Following HAZUS (FEMA 2014), ψ_j of structural and non-structural components are defined as a factor multiplied by the replacement cost (damage factor), as shown in Table 3. The damage factors for the content of the building are taken equal to the damage factors of acceleration sensitive components. The costs of relocation and economic loss are also calculated based on the HAZUS methodology. The relocation costs are calculated for moderate and higher damage states using unit costs of relocation (per square foot). The cost of economic loss is calculated using downtime of the building after an earthquake and the unit rental price (per square foot) for rental loss and unit income price (per square foot) for the income loss. Following Ellingwood & Wen (2005), the cost of injuries is assumed to be \$1000, \$5000, and \$10000 per person for slight, moderate, and severe injuries, respectively.The cost of human fatality is also assumed to be \$$10^6$ per person (Ellingwood & Wen, 2005). The number of injuries (with three levels of severity) and human fatalities after earthquakes can be estimated based on HAZUS methodology. As indicated in Table 2, the damage state quantification of loss types L_3-L_7 are defined using the damage state for L_1 or L_2. Therefore, $P_{a,j}$ only needs to be evaluated for structural and non-structural (drift sensitive and acceleration sensitive) damage states. Eq. (4) will be used to evaluate $P_{a,j}$, where the capacities are defined in Table 3. The probabilistic EDP models adopted here are developed in Dyanati et al. (2014, 2015) using vector valued IMs, which provide more accurate prediction compared with models using one IM and thus reduce epistemic uncertainties in the loss estimation. In particular, the probabilistic EDP model of inter-story drift is a function of PSA and peak ground velocity (PGV), while the probabilistic EDP model of peak floor acceleration is a function of PSA and peak ground acceleration (PGA). Note that the probabilistic models are constructed through a model selection process in which only the IMs with variance inflation factor lower than four are considered to avoid the multicollinearity issue (Dyanati et al. 2014, 2015).

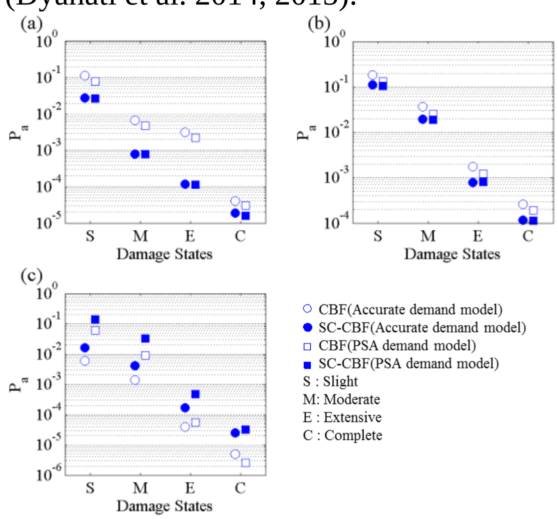

Figure 2: Annual probability of exceeding damage states for (a) structural damage (L_1, L_4-L_7), (b) non-structural drift sensitive damage (L_2), (c) non-structural acceleration sensitive damage (L_2, L_3)

Since both probabilistic demand models contain two IMs, the conditional formulation (Eq. (7)) or joint formulation (Eq. (8)) can be used for assessing $P_{a,j}$. To calculate $P_{a,j}$ of the damage states related to inter-story drift, Eq. (7) is used, as the USGS (2014) database does not provide hazard functions for PGV. To calculate $P_{a,j}$ of the damage states related to acceleration, Eq. (8) is used, as hazards functions for both PSA and PGA are available from the USGS (2014) database. Figure 2 shows the values of $P_{a,j}$ calculated for each damage state, where SC-CBF indicates better performance due to structural damage and drift sensitive non-structural damage as a result of higher $P_{a,j}$ for all damage states, but worse performance due to acceleration sensitive non-structural damage.

Table 4: Expected annual loss (EAL)

Loss type	*EAL* (× \$1000)			
	Accurate demand model		PSA demand model	
	CBF	SC-CBF	CBF	SC-CBF
L_1	27.624	10.131	18.993	9.688
L_2-drift. sens.	85.422	49.275	59.281	47.9
L_2- acc. sens.	3.854	11.529	30.722	92.333
L_3	4.232	12.761	33.275	100.128
L_4	13.490	1.038	9.399	1.046
L_5	41.704	10.472	28.817	10.043
L_6	0.090	0.031	0.064	0.028
L_7	1.601	0.734	1.200	0.627
Total	**178.000**	**95.968**	**181.740**	**261.789**

Using ψ_j and $P_{a,j}$ and assuming the construction cost of the SC-CBF building to be 4% higher than the CBF building (a = 1.04), *EAL* for each type of losses are calculated based on Eq. (4), and the results are shown in Table 4. Comparing the values of losses for the CBF and the SC-CBF shows that the losses due to acceleration sensitive non-structural components and contents of the building are higher in the SC-CBF as the result of the higher $P_{a,j}$ values in the SC-CBF, as indicated in Figure 2(c). As the *EAL* for all other types of losses (that are related to the drift) are lower in the SC-CBF, the total *EAL* of the SC-CBF becomes lower than the CBF. Moreover, as shown in Table 4, for both systems, the types of losses that contribute most to the total losses are non-structural component loss, economic loss, and structural loss, while the losses due to human fatality and injuries are negligible comparing to other types of losses.

3.4. Economic benefit of SC-CBF

Using the values of *EAL* shown in Table 4 (assuming a = 1.04) and discount rate of 5% (Ellingwood & Wen 2005), the economic benefit of using SC-CBF, $E[B_{\text{SC-CBF}}]$, is evaluated based on Eq. (3). Figure 3 gives the $E[B_{\text{SC-CBF}}]$ vs time based on *EAL* of all the seven types of losses and based on *EAL* of each individual type of losses. As shown in Figure 3, $E[B_{\text{SC-CBF}}]$ starts from a negative value since the initial construction cost of the SC-CBF is higher than the CBF. The value of $E[B_{\text{SC-CBF}}]$ increases through the life time of the building by mitigating earthquake-induced losses (i.e., $EAL_{\text{SC-CBF}} < EAL_{\text{CBF}}$), until reaching $E[B_{\text{SC-CBF}}] = 0$ at the pay-off time.

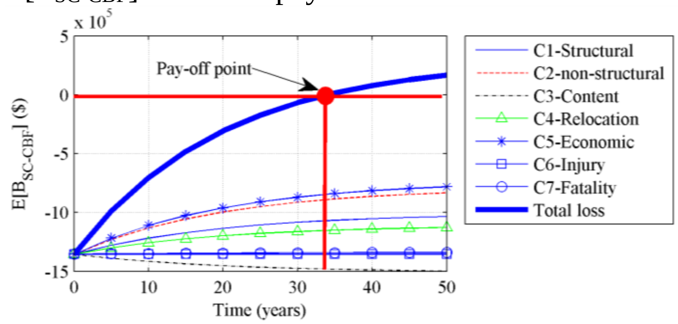

Figure 3: Economic benefit of SC-CBF

As shown in Figure 3, the curves of $E[B_{\text{SC-CBF}}]$ based on each individual type of losses do not reach pay-off points, indicating the higher initial construction cost of the SC-CBF cannot be paid off by considering only one type of loss mitigation. When considering mitigating all types of the losses, the pay-off time is about at 35 years. Furthermore, among all types of losses, mitigating the business interruption loss (i.e., economic losses) contributes most to $E[B_{\text{SC-CBF}}]$, and the next two factors that contribute most are mitigating non-structural damage and structural damage.

Figure 4 plots the relationship between the pay-off time and a. As expected, the higher initial construction cost of SC-CBF (higher value of a) necessitates a longer pay-off time, especially when a > 1.04. Therefore, the construction cost of the SC-CBF is a critical factor in determining the economic benefit of the system.

3.5 Effect of demand model accuracy

As mentioned earlier, software such as HAZAUS and PACT define EDP models as functions of PSA, which may not provide enough accuracy for the demand predictions. In order to examine the impact of the accuracy of demand models on the cost-benefit analysis, we also calculated *EAL* based on the EDP models (peak inter-story drift and peak floor acceleration) as functions of PSA. The corresponding $P_{a,j}$ are also shown in Figure 2. These changes in values of $P_{a,j}$ affects the values of *EAL*, as shown in Table 4.

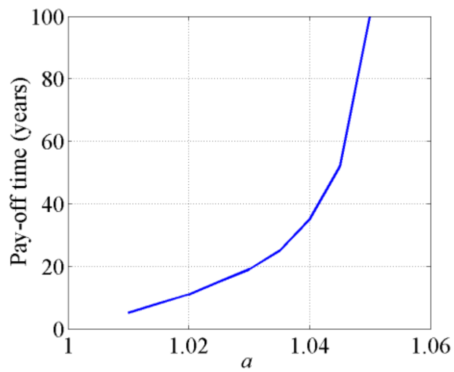

Figure 4: Pay off time versus various a values

Considering total *EAL* calculated by PSA demand models for both structures results in $EAL_{\text{SC-CBF}} > EAL_{\text{CBF}}$. This means less economic effectiveness of SC-CBF with respect to the CBF, which counters the results using the accurate demand model. Therefore, the choice of accurate demand model for demand prediction is critical and may highly affect the results of performance and loss estimation studies.

4. CONCLUSIONS

Self-centering concentrically braced frame (SC-CBF) systems have been previously developed to increase the drift capacity of the braced frames prior to structural damage. To achieve the better seismic performance of the SC-CBF system, the construction cost is expected to be higher than that of a conventional CBF due to the special details and elements required by the SC-CBF. To investigate the economic effectiveness of the SC-CBF, the economic benefit of using an SC-CBF instead of a CBF for one prototype structure is calculated in this study to examine the pay-off time when the higher construction cost of an SC-CBF would be paid back by the lower earthquake-induced losses during the lifetime of the building. Seven types of losses are calculated and compared in terms of the contributions to the total loss. A parametric study on the economic effectiveness of the SC-CBF is conducted based on variations in the initial construction cost of the SC-CBF. Moreover, to investigate the effect of the accuracy of the EDP model on the economic benefit result, two types of demand models are adopted and the results are compared.

The results of the economic benefit study show that the most losses in CBF and SC-CBF are due to the non-structural component damages during the earthquakes. However, the benefit from mitigating business interruption contributes most to the economic benefit of using SC-CBF. Finally, the pay-off time increases dramatically if the initial construction cost (both structural and non-structural) of the SC-CBF is more than 4% higher than the CBF. Moreover, it is found that developing an accurate demand model (that reduces epistemic uncertainties) is very critical in the loss estimation analysis. This case study shows that using the formulation adopted in HAZUS and PACT may result in reverse conclusions about the benefit of the SC-CBF.

5. ACKNOWLEDGEMENT

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