Probabilistic seismic performance evaluation for yielding shear panel device

M. R. Hossain*, M. Ashraf* and J. E. Padgett**

** School of Civil Engineering, The University of Queensland, Brisbane, Queensland, 4072, Australia (E-mail: anup880@yahoo.com; m.ashraf@uq.edu.au)*
*** Department of Civil & Environmental Engineering, Rice University, 6100 Main Street, MS-318, Houston, TX 77005, USA (E-mail: jamie.padgett@rice.edu)*

ABSTRACT
Recent seismic activity in the Asia-pacific region identifies the need for developing efficient, easy-to-use and economical techniques to mitigate earthquake risk. Yielding shear panel device (YSPD) is envisaged to play an important role in effective seismic retrofitting. A probabilistic seismic performance evaluation, based on the limit state probability analysis, is presented herein to examine the suitability of YSPD as a passive control device. The annual exceedance probability of a specified damage level is calculated considering the uncertainties associated with the seismic demand and the structural performance. Results obtained for the seismic performance of structures retrofitted with YSPDs are compared with those built without YSPDs. The effect of site specific seismic hazard is also investigated considering four different sites with varying seismicity.

KEYWORDS
Earthquake; Passive control device; Probabilistic seismic performance; Seismic hazard; Yielding shear panel device.

INTRODUCTION
Recent seismic activities around the globe have prompted the need to identify sustainable solution for reducing the catastrophic impacts of earthquakes. Researchers, during the last few decades, proposed a variety of active, semi-active and passive energy dissipation devices to diminish the damaging seismic effects. Yielding shear panel device (YSPD) is a passive energy dissipating device that has recently been developed for seismic retrofitting of structures. A steel plate is encapsulated inside a square hollow steel tube to exploit the inelastic shear deformation capability of the steel diaphragm plate for energy dissipation. Previous research on this field was focused on experimental investigation and numerical modelling of YSPDs (Hossain and Ashraf 2011; Hossain et al. 2011), but uncertainties associated with the seismic demand and the structural performance were not considered whilst evaluating the performance of the device. Limit state probability analysis considering these uncertainties have recently been conducted to evaluate performance of various seismic retrofit techniques for buildings and bridges (Padgett and DesRoches 2008; Wong and Harris 2010). This paper uses a probabilistic approach to assess the performance of YSPDs using a benchmark structure to provide insights into the relative performance of an as-built structure and a structure retrofitted with YSPD. The limit state probability analysis identifies the annual exceedance probability for a specified damage level. A mathematical model to represent YSPDs in a finite element code is developed and has been used for analysing a case study steel moment frame.

PROBABILISTIC SEISMIC PERFORMANCE EVALUATION
Appropriate definition of the damage state of a structure and the intensity of earthquakes are key elements for seismic performance assessment. FEMA 356 (FEMA 2000b) suggests to adopt the

maximum drift ratio for assessing the structural performance levels and corresponding damage to structural components. The inter-storey drift ratio (θ) has been used as the damage measure in the present study following the FEMA guideline. θ is measured as the ratio of the relative displacement between the adjacent floors and the corresponding storey height. FEMA 356 (FEMA 2000b) proposed three structural performance levels i.e. Collapse Prevention (CP), Life Safety (LS) and Immediate Occupancy (IO) performance levels with corresponding maximum allowable drift ratios of 5%, 2.5% and 0.7%. Spectral acceleration (S_a) at the fundamental period of a structure (T_1) is considered as the earthquake intensity measure in the current study.

Limit state probability analysis requires the identification of seismic fragility of a structure and the seismic hazard of the site. Seismic fragility $F_r(x)$ calculates the conditional probability of meeting or exceeding different limit states (i.e. damage states) based on Equation 1, whilst seismic hazard H(x) is approximated using Equation 2, which offers the annual probability of exceeding a specific level of earthquake intensity (Ellingwood and Kinali 2009).

$$F_r(x) = \Phi\left[\left(\ln x - \ln \hat{S}_a\right)/\beta_R\right] \quad (1)$$
$$H(x) = k_0 x^{-k} \quad (2)$$

where $\hat{S}_a$ is the median value of the fragility of the structure in units of S_a, β_R is the lognormal standard deviation of the system fragility, Φ is the standard normal cumulative distribution function, k_0 and k are constants that depend on the site of the building. The dispersion β_R reflects uncertainties associated with seismic demand and the structural capacity may be calculated using Equation 3 (Ellingwood and Kinali 2009),

$$\beta_R = \sqrt{\beta_{D|S_a}^2 + \beta_c^2} \quad (3)$$

where uncertainty in seismic demand $\beta_{D|S_a}$ is represented by the dispersion in θ_{max} and uncertainty in structural capacity β_c depends on different structural damage states. β_c is set equal to 0.25 for IO and LS limit states, whilst 0.15 for CP limit state (Ellingwood and Kinali 2009; Kinali and Ellingwood 2007). The limit state for annual exceeding probability may be approximated by integrating fragility and seismic hazard as shown in Equation 4 (Ellingwood and Kinali 2009).

$$P_{LS} = k_0 \hat{S}_a^{-k} \exp\left[\frac{(k\beta_R)^2}{2}\right] \quad (4)$$

where $k_0 \hat{S}_a^{-k}$ represents the seismic hazard with zero dispersion and the exponential term is a correction factor for considering the variability of seismic demand and structural capacity.

YSPDs AND THE BENCHMARK STRUCTURE

Three different YSPDs made from structural grade hot-rolled steel sheet conforming AS/NZS 1594:2002 standard (AS/NZS 2002) are used in the current study for the limit state probability analysis. Table 1 summarizes the material and the physical properties of these YSPDs. Bouc-Wen-Baber-Noori (BWBN) hysteretic model has been used to represent YSPDs as spring elements in the finite element model (Baber and Noori 1986; Hossain and Ashraf 2011). Geometric parameters of a YSPD are explained using schematic diagrams in Figure 1 and Table 1.

The benchmark three storey SAC model structure designed for SAC II Steel Project (FEMA 2000a; Ohtori and Spencer Jr 2004), as shown in Figure 2, is selected for analysis to evaluate the performance of YSPDs. Applied lateral force is resisted by two peripheral three bay moment resisting frames in both north-south and east-west directions, whilst the other columns are designed for gravity loads. The north-south moment frame represents the critical structural element responsible for the seismic performance of the building. The fundamental period T_1 for the frame is 1.0 Sec. Two different installation configurations are considered for installing YSPDs within the moment frame using v-braces as shown in Figure 3. OpenSees finite element program (Mazzoni et al. 2005) has been used for the numerical simulation.

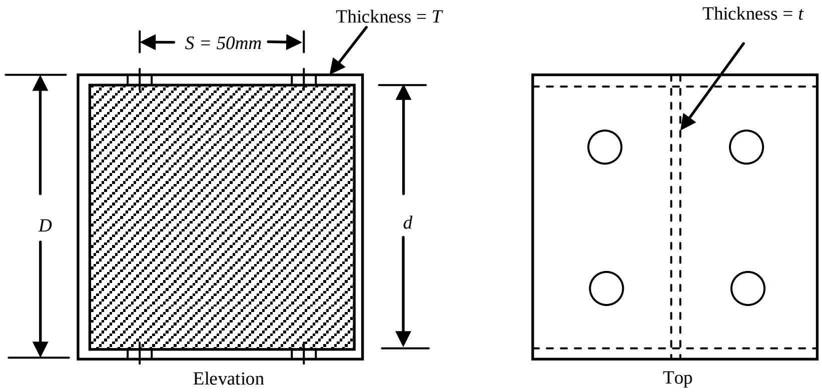

Figure 1. Yielding Shear Panel device (YSPD).

Table 1. Properties of YSPDs considered for Seismic Performance Evaluation.

YSPDs	Size, D (mm)	SHS Thickness, T (mm)	Diaphragm Plate Thickness, t (mm)	Yield Strength, f_y (Mpa)
YSPD 100×4×2	100	4	2	250
YSPD 110×5×3	110	5	3	300
YSPD 120×6×4	120	6	4	350

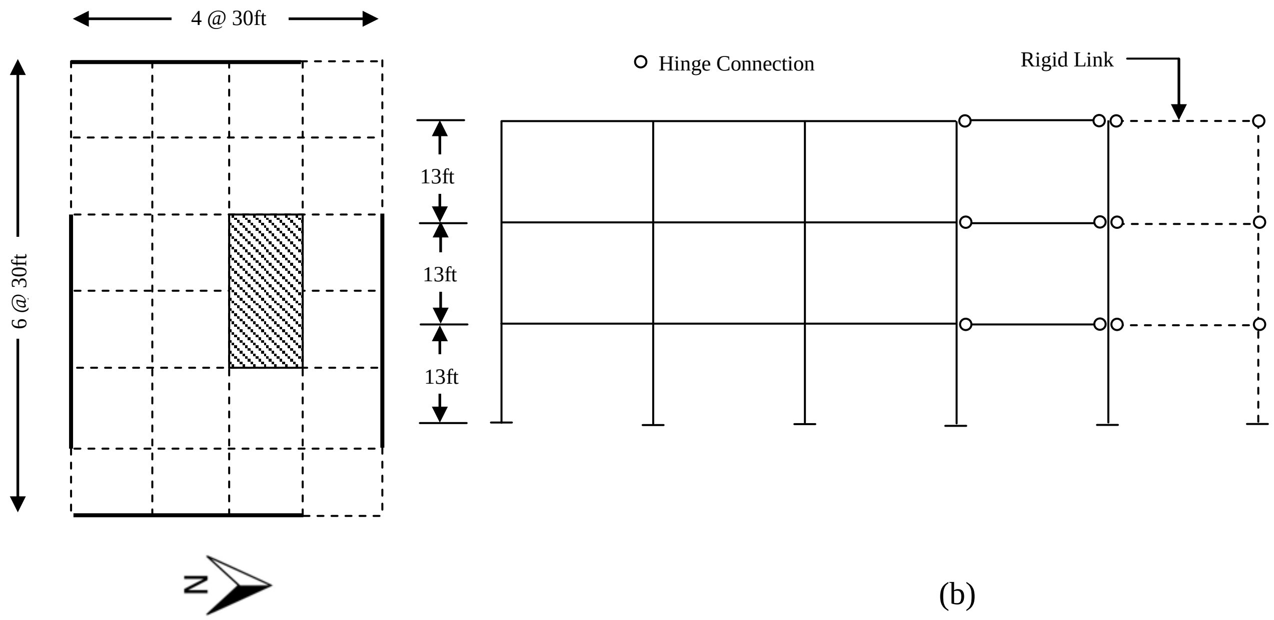

Figure 2. (a) Floor plan of the Los Angeles three storey SAC model structure, (b) Analytical model of the North-South lateral load-bearing moment resisting frame (FEMA 2000a; Ohtori and Spencer Jr 2004).

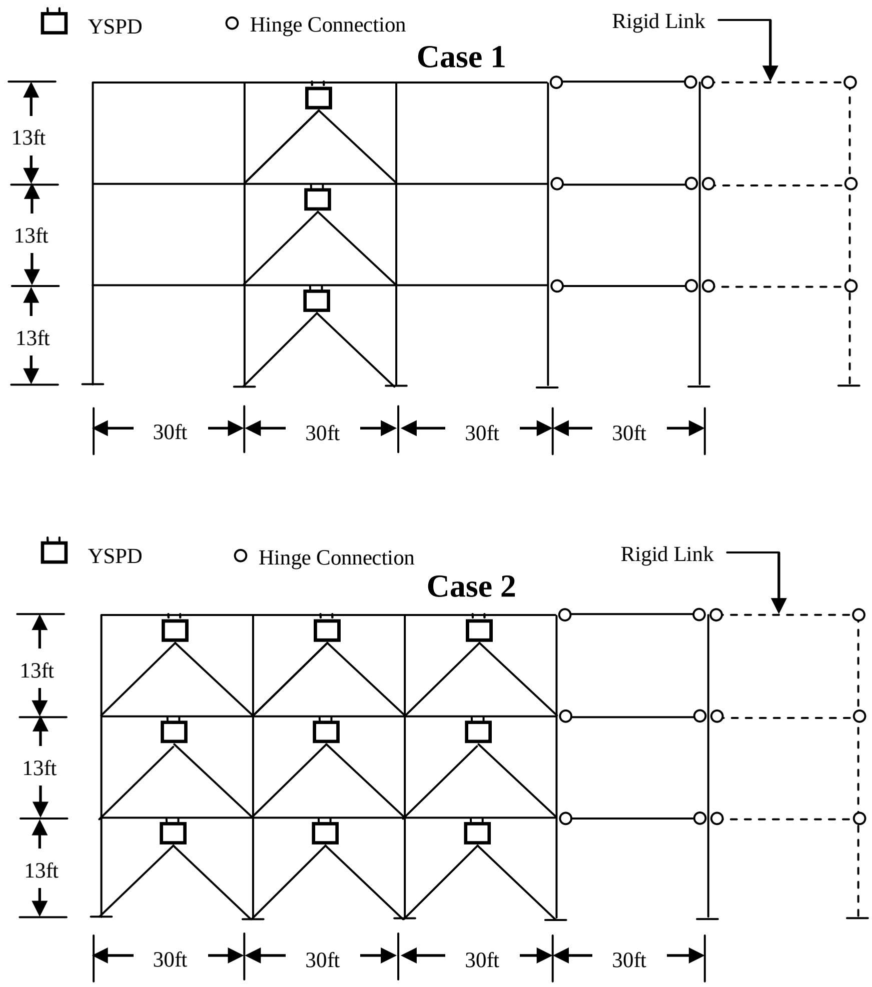

Figure 3. Analytical models for the North-South lateral load-bearing moment resisting frame equipped with YSPDs.

A series of nonlinear time history analysis (NTHA), known as incremental dynamic analysis (IDA) (Vamvatsikos and Cornell 2002), has been carried out with a range of ground motion records for the probabilistic performance evaluation. Ten scaled earthquake records are chosen from the PGMD database (PGMD 2011). The building is assumed to be located on stiff soil (site class D based on ASCE/SEI-7-05). Figure 4 shows the fault normal and the fault parallel spectral acceleration spectrum of these earthquakes (scaled to match the mean spectrum with the design spectrum) and compares to the design spectrum provided by the American design code (ASCE/SEI 2005).

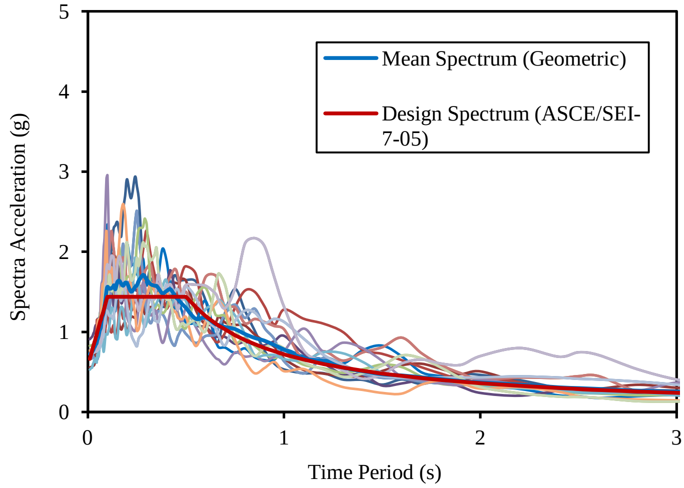

Figure 4. Response spectrum of the scaled ground motion records and the design response spectrum at downtown Los Angeles for the site class D (stiff soil).

PERFORMANCE LIMIT STATE EXCEEDING PROBABILITY

A seismic hazard curve provides the annual probability of exceeding earthquakes with a particular intensity. Hazard curves for fundamental period of 0, 0.2 and 1.0 sec and for damping of 5% are readily available from USGS (USGS); the seismic hazard curve for 2% damping may be easily generated using available information. The annual probability of exceedance of performance limit states for the SAC frame equipped with and without YSPDs are calculated based on Equation 4 and are summarized in Table 2. The annual probability of exceeding life safety limit state, or damage state, decreased from 1/250 to 1/290 for YSPD 100×4×2 (Case 1) and to 1/585 for YSPD 120×6×4 (Case 2). Similar reductions are also observed for immediate occupancy and collapse prevention limit states. This reduction in damage state exceedance probability indicates the capability of YSPDs to be used as an effective seismic control device.

Table 2. Annual probability of exceeding different performance limit states (P_{LS}) with and without YSPDs.

	P_{LS} for different performance limit states		
	IO	LS	CP
No YSPD	1/6	1/250	1/1550
YSPD 100×4×2 (Case 1)	1/7	1/290	1/1560
YSPD 110×5×3 (Case 1)	1/10	1/310	1/1680
YSPD 120×6×4 (Case 1)	1/13	1/350	1/1860
YSPD 100×4×2 (Case 2)	1/15	1/360	1/2206
YSPD 110×5×3 (Case 2)	1/22	1/480	1/2360
YSPD 120×6×4 (Case 2)	1/29	1/585	1/2760

Seismic hazard characteristics significantly vary between high-seismic zones and regions of moderate seismicity as the hazard curves in moderate-seismic zone are relatively flat with a lower k value compared with the considerably steeper hazard curves of high-seismic zones (Ellingwood and Kinali 2009). Four sites are chosen in the current study to identify the effect of seismic hazard on the performance of YSPDs; two sites from the moderate-seismic zone (Charleston, SC and Memphis, TN) and the other two are from the high-seismic zones (Seattle, WA and Los Angeles, CA). It is acknowledged that the Eastern US is characterized by large infrequent earthquakes and identified herein as moderate-seismic zone for the sake of modelling simplicity (Padgett et al. 2010). Seismic hazard parameters for these cities are summarized in Table 3.

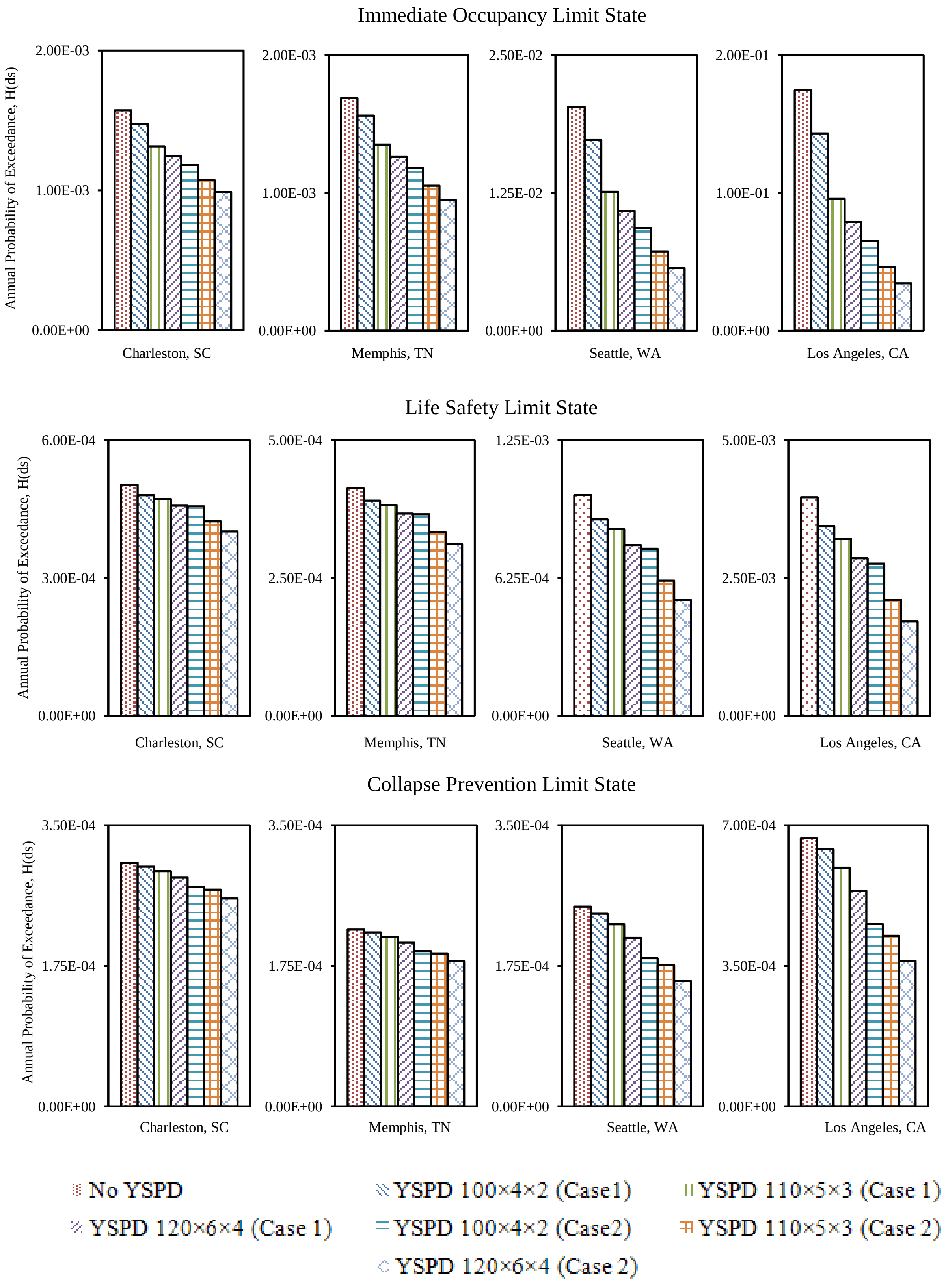

Figure 5. Annual performance limit state exceeding probability (P_{LS}) for regions of moderate seismicity and high seismicity. (Note: scales vary per limit state and site)

Table 3. Seismic hazard parameters k and k_0 (T_1 = 1 sec and 2% damping) (Ellingwood and Kinali 2009)

Site	k	k_0
Charleston, SC	0.81	2.66×10^{-4}
Memphis, TN	1.00	1.85×10^{-4}
Seattle, WA	2.14	1.44×10^{-4}
Los Angeles, CA	2.69	3.03×10^{-4}

Figure 5 shows the limit state annual exceeding probability of SAC frame for different performance limits of these sites. Reduction of the limit state probability is higher for high-seismic zones when compared with moderate-seismic zones for increasing size and number of YSPDs. The higher value of k indicates a higher reduction in annual probability of exceedance for all performance limit states considering a particular YSPD configuration. This phenomenon indicates that YSPDs should perform better in the high- seismic zones.

CONCLUSIONS

Limit state probabilistic analysis of a benchmark structure has been conducted to evaluate the seismic performance of a newly developed passive energy dissipation device yielding shear panel device (YSPD). An incremental dynamic analysis has been carried out using a group of available earthquake records. A finite element model of the considered case study SAC building has been developed with modified BWBN model (Baber and Noori 1986; Wen 1976) introduced in the OpenSees platform to simulate the experimentally observed behaviour of yielding shear panel device. The case study presented in the current paper evaluates six different YSPD configurations including three different YSPD sizes. Considerable decrease in the annual exceeding probability of damage stages has been identified. The effect of seismic zone on the retrofitted building in different hazard conditions is also evaluated by considering moderate and high seismic zones for limit state probability analysis. The results reveal that YSPDs show better damage state risk reduction in the high-seismic zone compared with moderate-seismic zones. The proposed method could be developed as a risk based decision making tool for seismic response evaluation of structures equipped with YSPDs.

REFERENCES

AS/NZS. (2002). "AS/NZS 1594:2002." *Hot-rolled steel flat products, Standards Australia/Standards New Zealand*.

ASCE/SEI. (2005). "ASCE/SEI-7-05: Minimum Design Loads for Buildings and Other Structures."

Baber, T., and Noori, M. (1986). "Modelling general hysteresis behavior and random vibration application." *Journal of Vibration, Acoustics, Stress and Reliability in Design*, 108, 411-420.

Ellingwood, B. R., and Kinali, K. (2009). "Quantifying and communicating uncertainty in seismic risk assessment." *Structural Safety*, 31(2), 179-187.

FEMA. (2000a). "355-C: State of the Art Report on Systems Performance of Steel Moment Frames Subject to Earthquake Ground Shaking." *Federal Emergency Management Agency, Washington, DC*.

FEMA. (2000b). "356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings." *Federal Emergency Management Agency, Washington, DC*.

Hossain, M. R., and Ashraf, M. (2011). "Mathematical modelling of Yielding Shear Panel device." *Thin-Walled Structures (In Review)*.

Hossain, M. R., Ashraf, M., and Albermani, F. (2011). "Numerical modelling of yielding shear panel device for passive energy dissipation." *Thin-Walled Structures*, 49(8), 1032-1044

Kinali, K., and Ellingwood, B. R. (2007). "Seismic fragility assessment of steel frames for consequence-based engineering: A case study for Memphis, TN." *Engineering Structures*, 29(6), 1115-1127.

Mazzoni, S., McKenna, F., and Fenves, G. L. (2005). "OpenSees command language manual." *Pacific Earthquake Engineering Research (PEER) Center*.

Ohtori, Y., and Spencer Jr, B. (2004). "Benchmark control problems for seismically excited nonlinear buildings." *Journal of Engineering Mechanics*, 130, 366.

Padgett, J. E., Dennemann, K., and Ghosh, J. (2010). "Risk-based seismic life-cycle cost-benefit (LCC-B) analysis for bridge retrofit assessment." *Structural Safety*, 32(3), 165-173.

Padgett, J. E., and DesRoches, R. (2008). "Methodology for the development of analytical fragility curves for retrofitted bridges." *Earthquake Engineering & Structural Dynamics*, 37(8), 1157-1174.

PGMD. (2011). "http://peer.berkeley.edu/peer_ground_motion_database/."

USGS. "http://earthquake.usgs.gov."

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

Wen, Y. (1976). "Method for random vibration of hysteretic systems." *Journal of the Engineering Mechanics Division*, 102(2), 249-263.

Wong, K. K. F., and Harris, J. L. (2010). "Seismic damage and fragility analysis of structures with tuned mass dampers based on plastic energy." *The Structural Design of Tall and Special Buildings*.