*16th World Conference on Earthquake Engineering, 16WCEE 2017*

*Santiago Chile, January 9th to 13th 2017*

*Paper N° 3879 (Abstract ID)*

*Registration Code: S-E1462325179*

# Nonlinear Performance and Damage Potential of Degraded Structures under Long Duration Earthquake

Y. Pan[1], C.E. Ventura[2], F. Xiong[3], L. Xie[4], M. He[5]

[1] *Ph.D. Candidate, Department of Civil Engineering, The University of British Columbia, ypan@civil.ubc.ca*
[2] *Professor, Department of Civil Engineering, and Director of Earthquake Engineering Research Facility, The University of British Columbia, ventura@civil.ubc.ca*
[3] *Dean and Professor, College of Architecture and Environment, Sichuan University, fxiong@scu.edu.cn*
[4] *Professor, Center of CCUS and CO2 Mineralization and Utilization, Sichuan University, xielingzhi@scu.edu.cn*
[5] *Professor, College of Civil Engineering, Tongji University, hemj@tongji.edu.cn*

## *Abstract*

Occurrences of mega earthquakes have been reported more frequently in recent years. Due to their long duration and large number of cycles, the degradation of both stiffness and strength have significant effects on structural performance and damage accumulation. On May 12, 2008, a large Ms 8.0 earthquake occurred in the Longmenshan Fault zone in Wenchuan County, Sichuan Province, China. This earthquake lasted for over 350 seconds and caused more than 69,000 casualties and about 124 billion USD in financial losses. Just five years later, on April 20, 2013, a large Ms 7.0 earthquake occurred at the same Longmenshan Fault zone in Lushan County (about 90km from the Wenchuan epicenter) with a typical duration of 80 seconds. Both earthquakes hit rural countries in western China where low-rise buildings and self-built masonry in-filled reinforced concrete structures are prevalent. Significant damage and collapse were reported in many reconnaissance reports. For both earthquakes, a significant number of ground motion records have been obtained by the National Strong Motion Observation Network System of China. This invaluable data can be used to conduct a comparison study of the nonlinear dynamic response of structural systems at stations that recorded the two earthquakes. In this study the duration effects where decoupled from other ground motion characteristics by using a spectrally equivalent procedure applied to the Lushan records to be directly comparable with the corresponding ones from Wenchuan. Nonlinear time history analysis of various models was carried out. These models included, elastic, elastic-perfectly-plastic with hardening, and a degraded peak-oriented hysteretic model that accounts for strain hardening, post-capping, residual strength, cyclic stiffness and strength degradation. Both, elastic and inelastic response spectra were generated and compared in order to better understand the demands from each earthquake. The ductility demands, hysteretic energy demands, inelastic displacement ratio and residual displacement ratio were also compared for the two earthquakes. Sensitivity analysis of the inelastic response were studied in terms of the ductility, strength reduction factors, and the cyclic degradation level. Incremental dynamic analysis and fragility evaluation were also investigated on a typical wooden braced frame with masonry infill. The results indicated that long duration shaking has a significant impact on the structural inelastic response and the collapse capacity of structures with high degradation and pinching characteristics. The current design practice to estimate potential collapse of structures, which is based on the spectral demands, amplitude of ground motion and peak values of drift and forces may not be adequate to characterize the potential collapse of certain systems that are sensitive to ground motion duration effects. Accumulate inelastic response caused by long duration shaking should be included as part of the evaluation of these systems in order to have a more adequate way to estimate collapse potential.

*Keywords: Wenchuan earthquake; ground motion duration; degradation; hysteretic energy; incremental dynamic analysis*

## 1. Introduction

The answer to the question "does duration really matter" is becoming more relevant in recent years as researchers working on this topic have proposed ways to better correlate damage with ground motion duration. Furthermore, more advanced degraded models have been incorporated into numerical simulation tools that have helped understand better how duration affects the response of systems. It has been universally acknowledged that the key characteristics of ground motion: intensity of the shaking, frequency content reflected on the shape of the response spectrum and duration, played significant roles on the seismic design and collapse risk assessment of structural systmes [1]. The first two factors, which have been adopted in many current design codes and standards, are generally based on the maximum response of a linear single-degree-of-freedom system (SDOF) and the corresponding ductility demand [2, 3]. However, current code provisions tend to ignore duration effects and rely on peak response measures only [4]. Although decades of efforts have been spent by researchers studying the duration effects, there is no agreement on whether or not duration effects should be considered as part of the process of ground motion selection and nonlinear dynamic analysis to determine the potential collapse of structures, especially for mega earthquake events.

The major challenges in estimating the duration effects on structural response can be categorized as follows: 1) determination of the ideal duration metric; 2) uncertainty of the proper damage measures; 3) accurate nonlinear modeling techniques, 4) the scarcity of long duration ground motion records; and 5) ground motion selection and scaling techniques for isolating duration effects from other ground motion characteristics.

It has been reported that there are over 30 definitions of duration in the literature [5]. Some of these definitions may explicitly or implicitly capture the other characteristics of the ground motion as stated above (e.g. amplitude, frequency content or energy content), and other metrics may only consider the ground motion duration itself. Among them, the 5-95% (or 5-75%) significant duration $D_{5\text{-}95}$ [6] have been proven suitable indicators for evaluating the inelastic performance of structures [4]. Chandramohan et al. [7] confirmed this statement by comparing the coefficient of determination ($R^2$) of several duration metrics with a regression analysis. They concluded that significant duration is not strongly correlated to intensity measure, nor affected by scaling, [7].

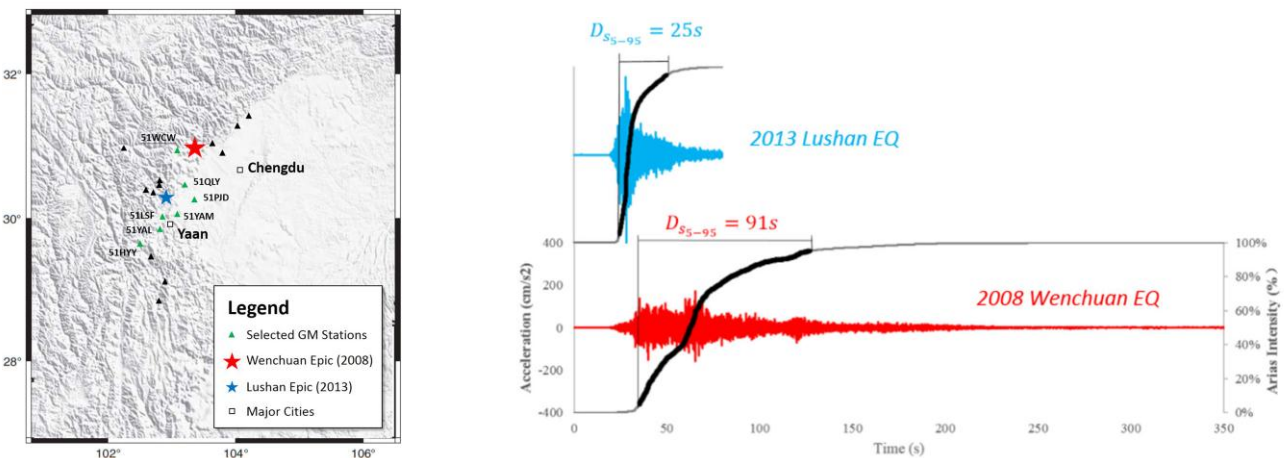
Another important issue in studying the effects of ground motion duration is the selection of a suitable damage measure for conducting structural assessments, especially the collapse capacity. There are a wide range of damage measures that have been proposed in the past, which can be grouped as follows: 1) maximum response measures; 2) energy measures; 3) cyclic fatigue measures; and 4) combined measures [8]. As stated above, current design codes use a forced-based approach where drift or displacement are set as design limit, but fail to account for cumulative damage. A number of studies based on maximum response measures have concluded there is no clear correlation between the chosen measure of structural response and the ground motion duration [9], except for the material models that incorporate the cyclic and in-cyclic degradation features [7]. In contrast, the energy-based damage index, such as the absorbed hysteretic dissipated energy and the cumulative damage, have shown a relatively good correlation with ground motion duration. This correlation is maintained even for the non-degraded model. According to statistical hypothesis tests, Iervolino et al. [10] confirmed the assumption that ground motion duration affects seismic response by adopting energy-based indices in all the investigated cases . More recently, Hou and Qu [1] simulated the nonlinear response of several representative SDOF with elastic-perfectly-plastic (EPP) non-degraded model. By performing statistical evaluations, they found longer duration leads to higher normalized hysteretic energy dissipation demands.

Recent earthquakes of large magnitude and long duration, such as the ones in Hokkaido, Japan (Mw 8.3, 2003), Sumatra, Indonesia (Mw 9.1, 2004), Wenchuan, China (Mw 7.9, 2008), El Maule, Chile (Mw 8.8, 2010), Tohoku, Japan (Mw 9.0, 2011), have once again arise people's concerns about significance of the long duration ground shaking and how damage and losses are related to this ground motion parameter. Fortunately, a number of long duration record data have been collected from some of these events and these sets of records can be used to study in detail the effects long duration shaking on structural response. The recent two major earthquakes that happened in China: the Wenchuan Earthquake and the Lushan Earthquake, have provided a great number of useful records that can be used for comparison studies of the inelastic structural response and collapse risk.

By adopting a "spectrally equivalent" method to compare duration of effects from suites of ground motions, the databases from Wenchuan and Lushan earthquakes have been used in this study to decouple the duration effect from other ground motion features. The ground motions resulting from this decoupling process are then used to investigate the inelastic responses of simple SDOF systems with elastic-perfectly-plastic (EPP) and degraded peak-oriented (PO) hysteretic models. The effects being studied are the ductility, hysteretic energy, inelastic displacement ratio and residual displacement ratio demands. The influences of the strength reduction factor and degradation parameters are also discussed. A case study of a typical local constructed wooden braced frame with masonry infill with degradation and pinching effects is then presented to demonstrate how long duration earthquakes may affect the structural collapse capacity.

## 2. Earthquake events and ground motion database

On May 12, 2008, a large Ms 8.0 earthquake occurred the Longmenshan Fault zone in Wenchuan County, Sichuan Province, China. The earthquake epicenter was located at latitude 31.0◦N and longitude 103.4◦E and the focal depth was 14 km. This earthquake resulted in more than 69,000 lives lost and about 124 billion USD in financial losses. Just five years later, on April 20, 2013, a Ms 7.0 earthquake occurred at the same Longmenshan Fault zone in Lushan County (30.3◦N, 103.0◦E). The epicenter of the Lushan Earthquake was only 90km from the Wenchuan Earthquake. For both earthquakes, a great number of ground motion records have been obtained by the National Strong Motion Observation Network System (NSMONS) of China. In this study, a total of 7 stations were selected for analysis since these stations recorded the highest peak ground accelerations (PGA) during the Lushan Earthquake, as seen in Fig.1 (a) and Table 1.




(a) Selected stations (b) Records from 51YAM station (E-W)

Fig. 1 – Locations of selected stations and ground motion records

Table 1 – Information of selected stations

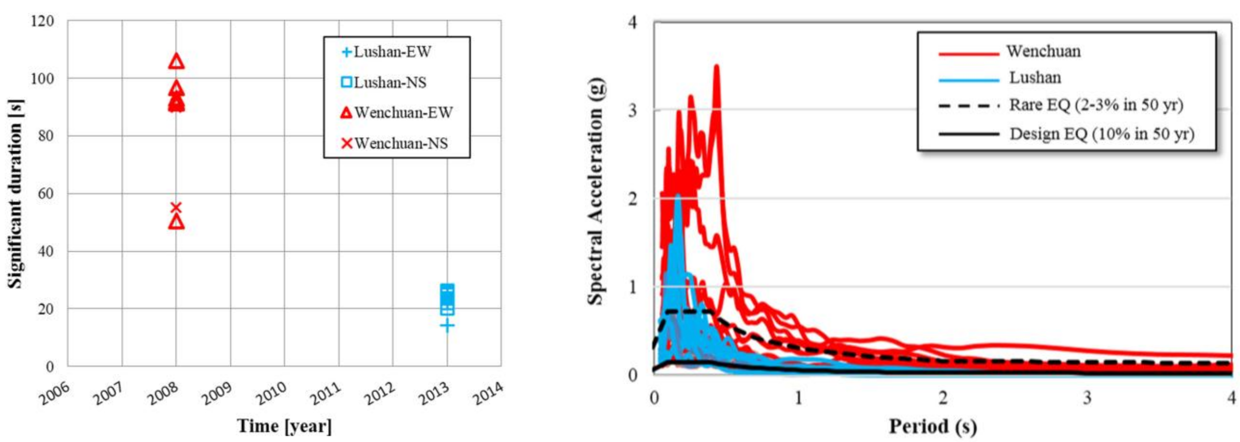
| No. | Station | Location | Site condition | Site-to-source Distance [km] | |
|---|---|---|---|---|---|
| | | | | Wenchuan [km] | Lushan [km] |
| 1 | 51YAM | 30.1N, 103.1E | soil | 104.2 | 27.2 |
| 2 | 51LSF | 30.0N, 102.9E | soil | 119.3 | 32.6 |
| 3 | 51QLY | 30.4N, 103.3E | soil | 67.2 | 28.2 |
| 4 | 51YAL | 29.9N, 102.8E | soil | 136.9 | 50.4 |
| 5 | 51PJD | 30.2N, 103.4E | soil | 89.0 | 40.8 |
| 6 | 51HYY | 29.6N, 102.4E | soil | 182.9 | 89.9 |
| 7 | 51WCW | 31.0N, 103.2E | soil | 19.1 | 80.2 |

Both earthquakes hit the rural countries in western China, where the most prevalent type of construction is characterized by low-rise buildings and self-built masonry in-filled reinforced concrete (RC) and timber structures. Significant damage and collapses for these types of construction have been reported in many reconnaissance reports. Fig.1 (b) presents the acceleration time histories and the corresponding significant durations of the 51YAM station for each of the two earthquakes. As a widely used duration measure, and adopted for this study, the significant duration $D_{5\text{-}95}$ represents the time interval over a specific percentage (e.g. 5-95%) of the total Arias Intensity, $I_A$, as seen in Eq. (1).

$$I_A = \frac{\pi}{2g}\int_0^{t_{\max}} a^2(t)dt \tag{1}$$

where a(t) = recorded ground acceleration, $t_{max}$ = length of record, g = gravitational acceleration.

Specifically, a threshold of 30 s was used to bin the short duration (Lushan) and long duration (Wenchuan) suites, respectively. The significant duration distribution for each event is shown in Fig. 2 (a). The elastic acceleration spectra of the selected stations are compared in Fig. 2 (b), and it can be seen that the Wenchuan Earthquake generates a broader frequency content at short period range and decays slower than the Lushan Earthquake. This is a typical trend of observed in long duration earthquakes. For better comparison, the design spectra and rare earthquake spectra based on the Chinese Code for Seismic Design of Buildings (CCSDB) were also plotted for station 51LSF [11]. It can be seen that both earthquakes exceeded the design level for a wide period range, even for the rare earthquake level at short periods.




(a) Significant duration (b) Elastic acceleration spectra

Fig. 2 – Distribution of significant duration and acceleration spectra

One major challenge in studying the effects of long duration ground motion is the isolation of duration effects from other basic features of ground motion (e.g. frequency content, energy content, amplitude). One possible solution is to adjust the original seed ground motions, to match the target spectra (e.g. uniform hazard spectra or design spectra) by either wavelets or other techniques [1]. Alternatively, a more optimal solution is that for each selected long duration records, a corresponding short duration ground motion with similar matched elastic acceleration spectra will be used for further studies. This “spectrally equivalent” matching process is very time demanding, but the coupling effect can be greatly reduced [7]. The records for each station from Lushan Earthquake were adjusted to the Wenchuan Earthquake using this method to develop a “spectrally equivalent” database of records, as illustrated in Fig. 3. Since the adjustment process would affect the ground motion characteristics to a certain extent and it is always recommended to examine the $D_{5\text{-}95}$ values after matching. In this study, an average increase in duration of 11% resulted for the Lushan records, thus this influence can be neglected.

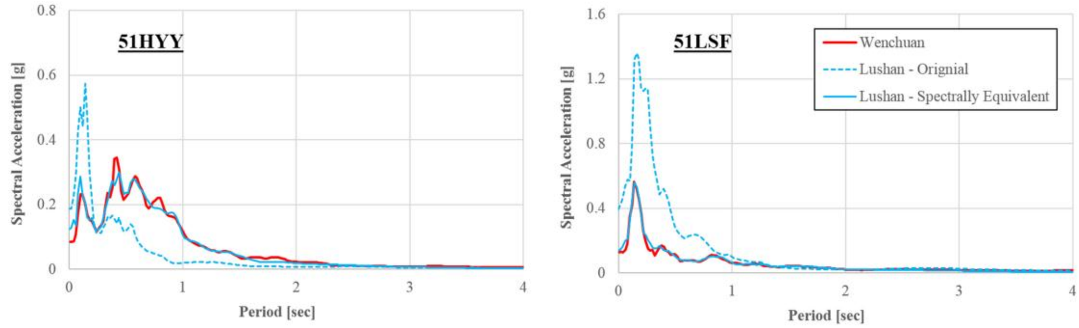



Fig. 3 – Spectrally equivalent records of 51HYY and 51LSF stations

## 3. Inelastic response history analysis (RHA)

With the establishment of the Wenchuan and "spectrally equivalent" Lushan ground motion database, the response history analysis (RHA) of nonlinear SDOF systems were conducted to investigate the influence of ground motion duration. Even though many reports have indicated that the displacement-based maximum value damage measures would only be correlated with duration when the advanced degraded hysteretic model is used, it is still of interests to study the EPP model with hardening. This model is simple and can adequately describe conventional steel or reinforced concrete structures with primarily flexural behavior [12]. The fundamental period of the systems investigated varied from 0.05s to 9s by maintaining the mass of the system constant and varying the stiffness. The influence of strength reduction factor, ductility and degradation parameters were taken into account for the estimation of the inelastic response demands. A 5% damping coefficient and rock/stiff soil site condition were assumed [3]. It should be noted that site effects are beyond the scope of this study, although some reports have argued that the site response analysis will greatly improve the accuracy in quantifying the influence of ground motion duration. One main reason is that soft soil conditions and basin effects would result in longer ground motions during a seismic event [13].

The SDOF systems are models as two-dimensional linear elastic beam-column element connected to the base using a lumped-mass zero-length rotational plastic hinge following the EPP and the Modified Ibarra-Medina-Krawinkler PO hysteretic model [14] in OpenSees [15]. The backbone curves and moment-rotation relationship of the EPP and PO models are presented in Fig. 4. A strain hardening ratio of 0.03 is used for both models. The elastic strength is reduced by $R_y$ factors of 2, 4 and 8 to achieve nonlinear behavior.

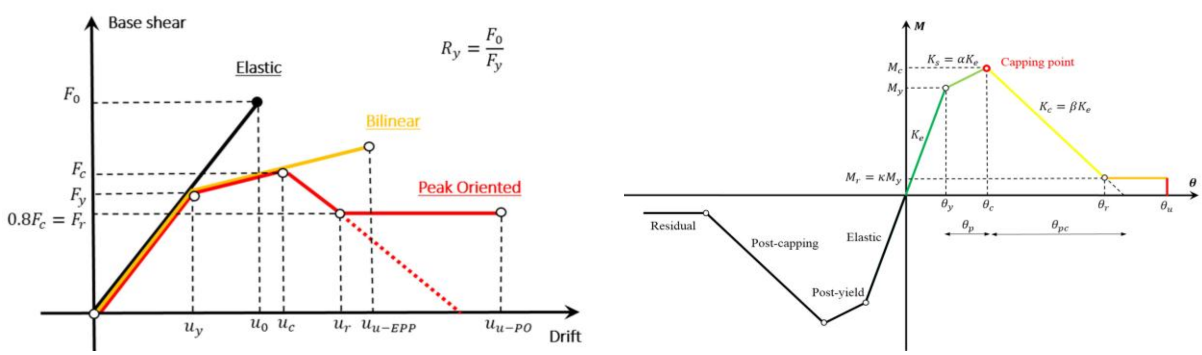



Fig. 4 – Backbone curves of EPP and PO models

### 3.1 Ductility and hysteretic energy demands of EPP model

Two quantities were chosen to examine the long duration effects of Wenchuan Earthquake: ductility μ and normalized hysteretic energy $E_N$. As an important displacement-based damage measure, the concept of ductility has been widely implemented into the seismic design standards in order to evaluate the seismic resistance. In fact, in early 90's, it was pointed out that it was unnecessary to be concerned about the duration since the right response measure had not been found to evaluating its influence [16]. It was argued that even though ductility is not a good measure of damage, the role of hysteretic energy in predicting physical damage is still not clear. However, more recently, it has been agreed that a seismic design procedure that does not take into account both the maximum and cumulative plastic deformation demands will lead to an unreliable performance of a structure when subjected to severe long duration ground motion [17], especially for simple non-degraded analytical models. According to statistical hypothesis tests, Iervolino et al [10] confirmed the assumption that ground motion duration affects seismic response by adopting energy-based indices in all the investigated cases.

The ductility demand μ and the normalized hysteretic energy demands $E_N$ are defined below for the EPP model:

$$\mu = \frac{u_{u-EPP}}{u_y} \qquad E_N = \frac{\int dE_H}{F_y u_y} \tag{2}$$

where $u_{u\text{-}EPP}$ = maximum inelastic displacement of EPP, $u_y$ = yield displacement, $F_y$ = yield strength by applying strength reduction factor, $E_H$ = hysteretic energy by cumulating.

For both earthquake suites, the mean value of μ and $E_N$ over the entire period range is calculated from the assumed $R_y$ values, as seen in Fig. 5. It can be observed from the ductility spectra that μ values decrease from infinite to a constant value for short period systems. For longer periods, the values converge to the strength reduction factor $R_y$, which is consistent with the classic "equal displacement rule" design philosophy for seismic design. By comparing the Wenchuan and Lushan earthquakes, there is not a significant difference for ductility spectra for $R_y$=2 and 4, for $R_y$=8. The Wenchuan records produce a slightly higher ductility demand for longer period, but the difference is negligible. The results are comparable with many existing publications, which conclude that there is no correlation between ground motion duration and ductility demand for non-degraded models.

The cumulative damage measure $E_N$ depends on ductile strength and deformation capacities under load reversals imposed by earthquake excitations, which, shows a strong correlation with ground motion duration, as illustrated in Fig. 5. Over the entire range of periods, the mean value of the normalized hysteretic energy $E_N$ under long duration excitation is consistently higher than that for short duration events, regardless of strength reduction factor. The $E_N$ decreases as the period of the system increase, which implies that the critical demand occurs for the structures with a low fundamental period. An average increase of 100% of $E_N$ is observed for long period systems. The effect of strength reduction levels can also be seen on the estimated values of $E_N$ which tend to be larger in weaker systems ($R_y$=8).

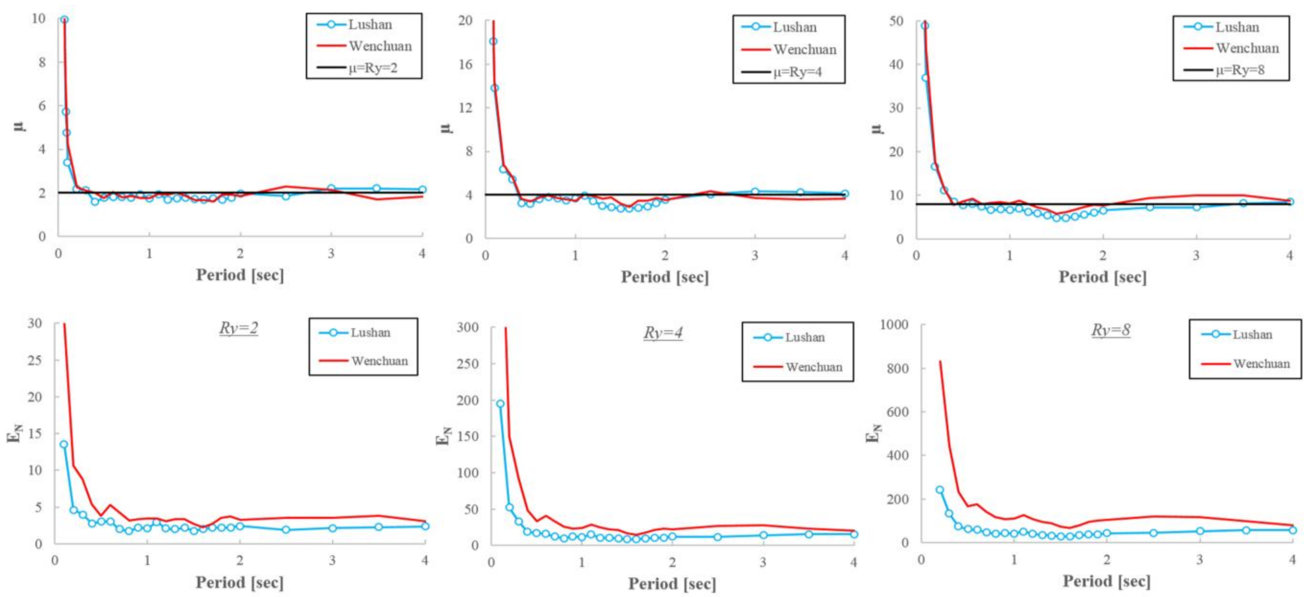



Fig. 5 – Ductility spectra and hysteretic energy spectra from EPP

### 3.2 Inelastic and residual displacement demands of PO model

It has been widely recognized that the influence of material degradation, both cyclic and in-cycle, is strongly affected by ground motion duration, especially when maximum response of selected responses is used as damage measures for assessment purposes. Cyclic degradation is characterized by loss of strength and stiffness occurring in subsequent cycles. In-cycle degradation is characterized by loss of strength and negative stiffness occurring within a single cycle [18]. The longer the duration shaking, the more deformation cycles each component is subjected, and as a result, more strength and stiffness will be lost, and less energy dissipation capacity is left in the structure [7]. It should be noted that the degradation characteristics will have great impact on structural collapse risk, which is a critical metric of life safety, only if the structure deforms beyond the post-yielding point or reaches a post-capping state under earthquake shaking. To conclude, duration may be more critical for collapse stage rather than the linear limit states [19].

An analytical moment-rotation model that accounts for strain hardening, post-capping strain softening, strength and stiffness degradation has been adopted in this study, as seen in Fig. 4. Two levels of cyclic degradation (no degradation and severe degradation) are chosen for further analysis to examine the effect on different earthquakes on structural response. This modified peak-oriented model defines four types of cyclic degradation with similar analytical algorithm: strength degradation ($\Lambda_s$), post-capping strength degradation ($\Lambda_c$), unloading and reloading stiffness degradation ($\Lambda_k$ and $\Lambda_a$). An inherent reference hysteretic energy dissipation capacity $E_t$ is first defined regardless of the loading history applied to the structure. The cyclic degradation is then defined by an energy-based degradation parameter $\beta_i$ for each excursion i, as expressed in Eq. (3), Eq. (4) and Eq. (5) [14].

$$E_t = \gamma M_y \theta_y = \Lambda_{s,c,k,a} \cdot M_y \tag{3}$$

$$M_i = (1-\beta_i) M_{i-1} \tag{4}$$

$$\beta_i = \left( \frac{E_i}{E_t - \sum_{j=1}^{i} E_j} \right)^c \tag{5}$$

where $M_y$ = yielding moment, $\theta_y$ = yielding rotation (drift), $E_i$ = hysteretic energy dissipated in excursion i, c = degradation rate (normally set as 1.0), $\Lambda_{s,c,k,a}$ = key parameter that defines the degree of degradation.

With the increase of $\Lambda$, hysteretic dissipation energy capacity gets larger and the rate of degradation gets slower. Normally, if the same rate of degradation is expected in four degradation modes, $\Lambda_k$ should be about twice as large as the other $\Lambda$ values, as seen in Eq. (6). In this study, $\Lambda$=0.2 and $\Lambda$=infinity represent severe degradation and no degradation scenarios, respectively.

$$\Lambda_k = 2\Lambda_{s,c,a} \tag{6}$$

Like in the EPP model, the predetermined ductility $\mu$ in the PO model is defined as the ratio of the maximum displacement to the yield displacement. Many reports have suggested that the maximum ductility capacity be calculated when the strength degraded to not less than 75% - 90% of the peak value. In this study, a 20% loss in load-carrying capacity was used. Three target strength reduction factors of 2, 4 and 8 are also considered. The in-cycle strength degradation can be achieved by adjusting the post-capping stiffness ratio, but many studies suggested that the inelastic response is very sensitive to this parameter only when it is small. A constant value of -10% is used for simplicity.

For the PO model, two displacement-based inelastic indicators were selected to evaluate the influence of ground motion duration: the constant-strength residual displacement ratio ($C_r$) and the inelastic displacement ratio (IDR).

Large permanent lateral deformation at the end of ground excitation may lead to the conclusion that a damaged structure may have to be demolished, even though the structure did not collapse during the strong shaking. Furthermore, large residual displacements may result in a loss of functionality of buildings. And the potential of aftershocks or repeated earthquakes may lead to unpredictable collapse for those structures that have experienced large inelastic deformation. Therefore, it is important to investigate the $C_r$ and IDR demand under long duration ground shaking. Also, knowledge of the IDR allows the determination of its maximum inelastic response directly from the response of the equivalent elastic system. This has been adopted to evaluate the effects of multiple repeated earthquake successfully [12]. The definitions of $C_r$ and IDR are as follows:

$$C_r = \frac{\Delta_r}{u_0} \qquad IDR = \frac{u_{u-PO}}{u_0} \tag{7}$$

where $\Delta_r$ = residual displacement at last cycle, $u_0$ = elastic displacement, $u_{u\text{-}PO}$ = maximum inelastic displacement of PO systems. It should be noted that $\Delta_r$ is different from $u_r$ which is the displacement that the strength drops to a certain percentage. Fig. 6 compares the mean values of $C_r$ and IDR under both the Lushan and the Wenchuan earthquakes with different parameters. The dash lines represent the severe degradation cases and the solid lines mean no degradation.

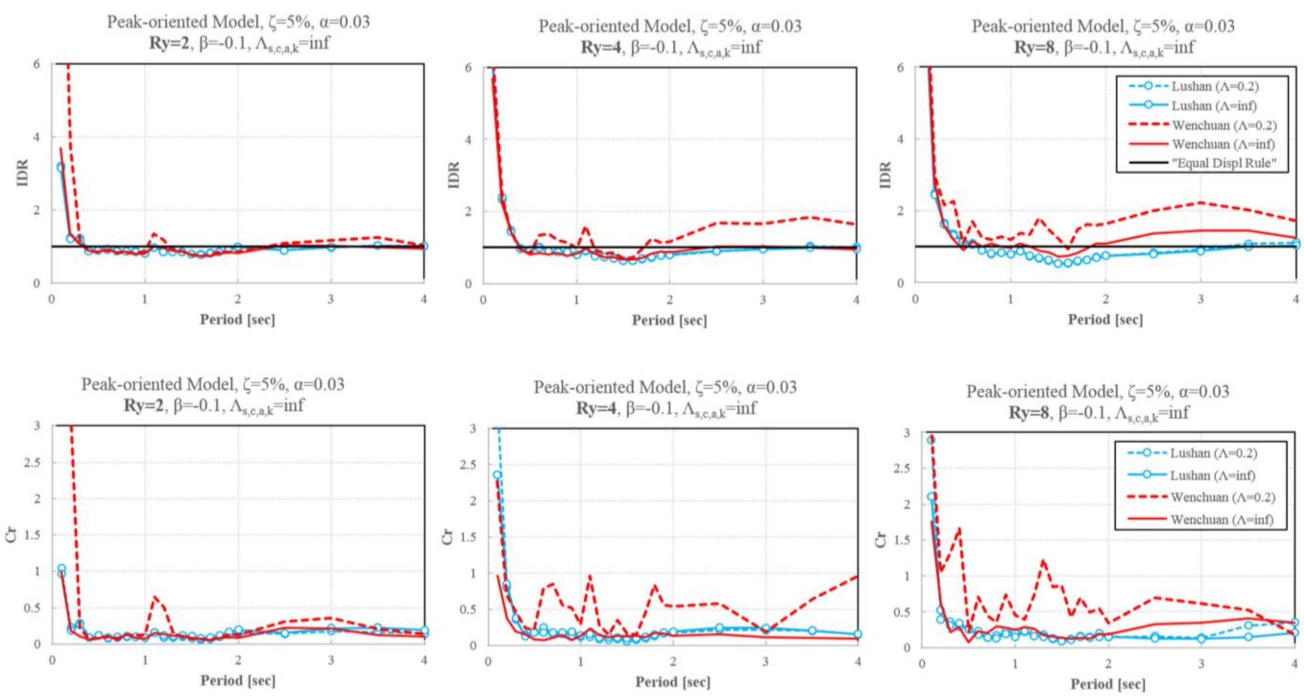



Fig. 6 – IDR and $C_r$ spectra from EPP

By looking at the IDR spectra for $R_y$=2, 4 and 8, the IDR curves for non-degraded systems converge to 1.0, where maximum inelastic displacement equals to the maximum elastic displacement. By comparing the Lushan and Wenchuan earthquakes, cyclic degradation has little impact on the short duration records, while an obvious increase by 50% of IDR can be identified for long duration records with severe degradation, indicating the influences of long duration ground motion on displacement demands on realistic degraded structures. Moreover, the weaker the systems, the higher the influences are.

Similar findings can be obtained from $C_r$ spectra where the degradation plays a more important role in residual displacement demands. For short duration records and the Wenchuan Earthquake records, for systems without degradation, an average 0.25 of residual displacement ratio is calculated for all three strength levels of structures. For the Wenchuan Earthquake with severe degradation, the $C_r$ values could exceed 1.0 over the entire periods range for weaker systems ($R_y$=4 and 8), which implies that the permanent deformation could be equal to or higher than the maximum elastic displacement. A higher capacity will be required to prevent collapse or secondary damages during further aftershock events.

## 4. Collapse capacity of a masonry-infilled timber frame

Most of the residential houses in rural regions in Southwestern China are occupied by self-built with little construction supervision. Low-rise unreinforced masonry, confined masonry and masonry-infilled reinforced concrete and timber frames have been widely adopted by local residents. These tend to have inadequate seismic resistance due to poor material properties, construction quality and seismic design [20, 21]. After the 2008 Wenchuan Earthquake, several design guidelines were implemented to improve the seismic resistance of those residential buildings. However, in the 2013 Lushan Earthquake hit the same region and the situation did not change as expected. Hybrid construction structures that were not designed properly and the self-built upper floors had suffered severe damage or collapse due to significant vertical stiffness nonlinearity, as seen in Fig. 7.


Fig. 7 – Damage of masonry-infilled timber frames

The influence of ground motion duration on the collapse capacity of a typical wooden braced masonry-filled frame structure is discussed next. The nonlinear hysteretic behavior is calibrated using the reverse cyclic tests conducted at the Earthquake Engineering Center (EEC) at KP UET Peshawar [22]. A hysteretic Pinching4 model in OpenSees was employed to simulate the cyclic strength and stiffness degradation and pinching behavior of a typical hybrid timber structures [23]. This model is composed by piece-wise linear curves involving 16 parameters to define the cyclic envelope and the unload-reload paths are defined with 6 parameters that related to the pinched ratio of the deformation. Energy-based degradation is controlled by 16 parameters. In order to investigate the effects of cyclic degradation on collapse risk, a non-degraded cyclic response is also calibrated for further study. Fig. 8 presents the hysteretic behavior of both experimental and numerical results.

The seismic response of the model is then evaluated by conducting the incremental dynamic analysis (IDA) [24] for both “spectrally equivalent” short records and long duration records. For each ground motion record, the intensity level (e.g. the elastic spectral acceleration at fundamental period with 5% damping) is scaled linearly until the collapse of the structure is approached. The selection of proper engineering demand parameter (EDP) may affect the collapse estimation under long duration excitation since IDA linearly scaled the amplitude of a fixed set of ground motion, while other characteristics (frequency and energy content) are assumed to remain same. It is suggested to choose the spectral displacement as EDP or using the multiple strip analysis (MSA) where different sets of records will be scaled at different intensity level [25]. Here, the roof drift was selected as primary EDP.

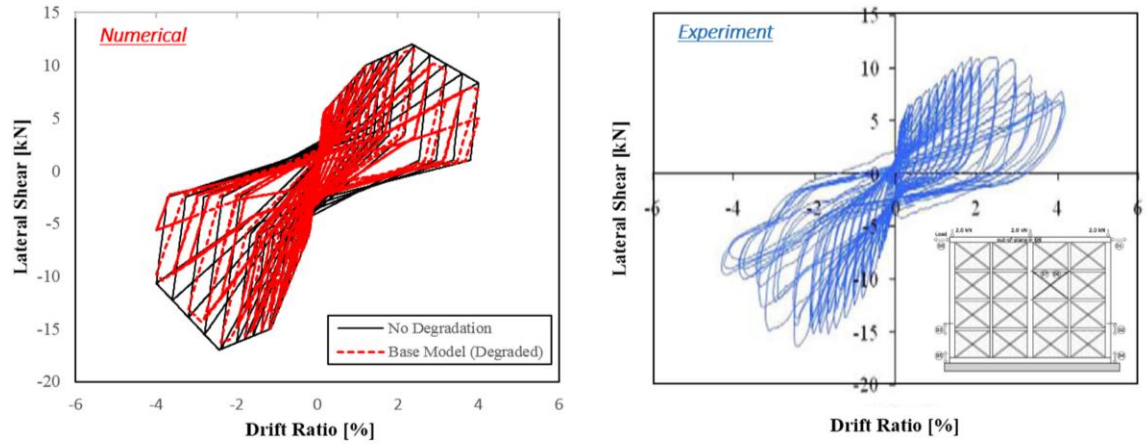



Fig. 8 – Hysteretic behavior of Pinching4 model and experiment test

Fig. 9 shows the results of IDA plots of the degraded base model for both the Lushan and Wenchuan earthquakes. Overall, the spectrally equivalent short duration records will lead to collapse at a higher intensity level. The average mean of collapsing roof drifts for both events were calculated and the long duration records produce a 2.78% drift level before collapse, while a larger capacity of 3.26% is obtained when subjected to short duration suite. To compare, the drift capacity of non-degraded systems increased to 4.0% and 3.6% for the Wenchuan and Lushan earthquakes, respectively. It is clear that the cyclic degradation in these low-rise self-built masonry-filled timber frames play a critical role in the estimation of collapse capacity, especially for long duration ground motions.

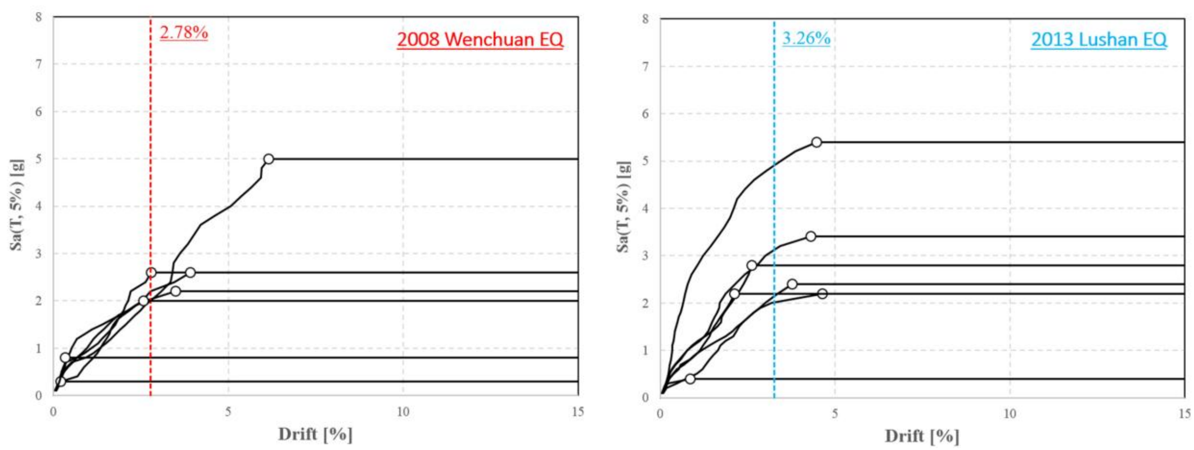



Fig. 9 – IDA results of base model (degraded)

Based on the analysis results presented above, it can be concluded that long duration ground motion has a significant impact on structural collapse capacity, especially for degraded systems. To quantify the influence, collapse fragility curves for both ground motion suites are generated from the IDA results. By incorporating a lognormal distribution function of ground motion intensity $S_a(T, 5\%)$, the cumulative probability of collapse can be calculated accordingly. Fig. 10 presents the collapse fragility distribution of both degraded base model and the non-degraded reference model. It can be seen that regardless of cyclic degradation behavior, long duration suite has higher probability of collapse than the short duration suite, where the pinching mode may affect the energy dissipation capacity under many inelastic cycles. For the Lushan Earthquake with "spectrally equivalent" records, cyclic degradation increases little collapse probability. On the contrary, the degraded structure will suffer much higher collapse potential when subjected to long duration ground shaking, as seen in the dash line. The results are consistent with many recent publications, demonstrating that the neglect of duration effects on seismic design and assessment will greatly underestimate the collapse risk of the structures, especially for those masonry-filled timber and reinforced concrete structures.

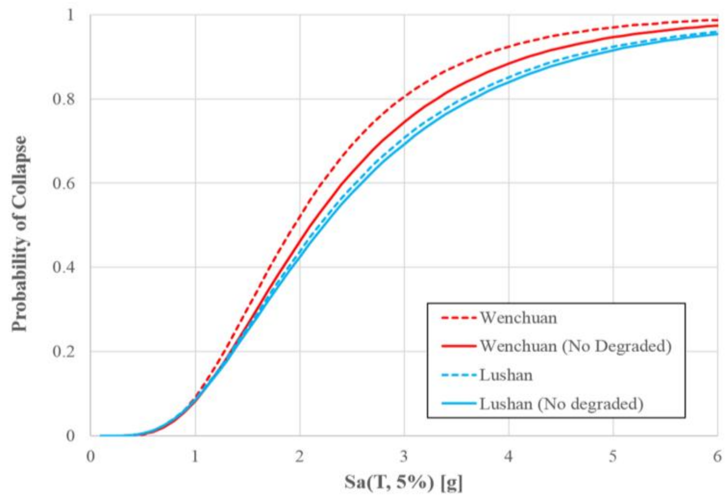



Fig. 10 – Collapse fragility curves developed for both earthquakes (degraded and non-degraded)

## 5. Conclusions

This paper studied the effects of long duration ground motion on structural performance and collapse capacity. The long duration Wenchuan Earthquake motions and the "spectrally equivalent" short duration Lushan Earthquake motions that happened in Sichuan, China in 2008 and 2013 were used for the analysis work. The 5-95% significant duration was chosen as a duration measure. Different damage measures and hysteretic models were investigated by conducting a great number of nonlinear time-history analysis using various SDOF systems to quantify the influences of long duration earthquake. The inelastic response spectra and the fragility evaluation were generated based on the numerical analysis. The following conclusions can be drawn from this study:

1. For non-degraded elastic-perfectly-plastic model, the ground motion duration has no correlation with the ductility demands, but a strong correlation with the cumulative normalized hysteretic energy demands, which would be increased with the strength reduction factors.
2. By taking into account of cyclic degradation, both the inelastic displacement ratio and the residual displacement ratio have been significantly affected by the long duration records. Similarly, the increase of the strength reduction factor also leads to the increase for these two displacement-based demands in severe degraded structures.
3. The incremental dynamic analysis of a typical masonry-infilled timber frame indicated that long duration records would result in smaller collapsing drift demand than the short duration sets, and accordingly, a higher potential for damage would exist under long duration shaking.
4. By comparing the collapse risk of the base model and a non-degraded model, an increase of probability of collapse was found for the degraded structure under the Wenchuan Earthquake, while the corresponding increase of probability of collapse for the Lushan Earthquake can be neglected, demonstrating the importance of using appropriate cyclic strength/stiffness degradation parameters when evaluating the effects of long duration ground motion.

## 5. Acknowledgements

The financial supports from the Natural Sciences and Engineering Research Council (NSERC) of Canada and the Chinses Scholarship Council (CSC) for this study are gratefully acknowledged.

## 6. References

[1] Hou, H., Qu, B., (2015): Duration effect of spectrally matched ground motions on seismic demands of elastic perfectly plastic SDOFS. *Engineering Structures*, 90, 48-60.

[2] ASCE (2010): *Minimum Design Loads for Buildings and Other Structures*, Structural Engineering Institute of ASCE, ASCE/SEC 7-10, Reston, VA.

[3] National Research Council of Canada (NRC) (2010): *User's Guide - NBCC 2010, Structural Commentaries (part 4)*, Issued by the Canadian Commission on Buildings and Fire Codes, National Research Council of Canada.

[4] Foschaar, J. C., Baker J. W., Deierlein, G. G., (2012): Preliminary assessment of ground motion duration effects on structural collapse. *In Proceedings of the 15th world conference on earthquake engineering*, Lisbon, Portugal.

[5] Bommer, J. J., Martinez-Pereira, A., (2000): Strong-motion parameters: definition, usefulness and predictability. *In 12th World Conference on Earthquake Engineering*, Auckland.

[6] Trifunac, M., Brady, A. G., (1975): A study on the duration of strong earthquake ground motion. *Bulletin of the Seismological Society of America*, 65(3), 581-626.

[7] Chandramohan, R, Baker, J. W., Deierlein, G. G., (2015): Quantifying the influence of ground motion duration on structural collapse capacity using spectrally equivalent records. *Earthquake Spectra*, In-press.

[8] Hancock, J., Bommer, J. J., (2007): Using spectral matched records to explore the influence of strong-motion duration on inelastic structural response. *Soil Dynamics and Earthquake Engineering*, 27(4), 291-299.

[9] Hancock, J., Bommer, J. J., (2006): A state-of-knowledge review of the influence of strong-motion duration on structural damage. *Earthquake Spectra*, 22(3), 827-845.

[10] Iervolino, I., Manfredi, G., Cosenza, E., (2006): Ground motion duration effects on nonlinear seismic response. *Earthquake Engineering & Structural Dynamics*, 35(1), 21-38.

[11] GB50011-2010 (2010): *Code for seismic design of buildings*, China Architecture & Building Press, Beijing, China.

[12] Hatzigeorgiou, G. D., Beskos, D. E., (2009): Inelastic displacement ratios for SDOF structures subjected to repeated earthquakes. *Engineering Structures*, 31(11), 2744-2755.

[13] Kempton, J. J., Stewart, J. P., (2006): Prediction equations for significant duration of earthquake ground motions considering site and near-source effects. *Earthquake spectra*, 22(4), 985-1013.

[14] Lignos, D. G., Krawinkler, H., Whittaker, A. S., (2011): Prediction and validation of sideway collapse of two scale models of a 4-story steel moment frame. *Earthquake Engineering & Structural Dynamics*, 40(7), 807-825.

[15] McKenna, F., Fenves, G. L., (2000): *The OpenSees command language manual*. University of California, Berkeley.

[16] Cornell, C. A., (1997): Does Duration Really Matter? *Technical Report NCEER-97-0010*, Proceedings of the FHWA/NCEER Workshop, Burlingame, California, pp. 125-133.

[17] Teran-Gilmore, A., Bahena-Arredondo, N., (2008): Cumulative ductility spectra for seismic design of ductile structures subjected to long duration motions: concept and theoretical background. *Journal of Earthquake Engineering*, 12(1), 152-172.

[18] Federal Emergency Management Agency (2009): Effect of Strength and Stiffness Degradation on Seismic Response, *Technical Report FEMA P440a*. Prepared by ATC, Redwood City, CA.

[19] Raghunandan, M., Liel, A. B., (2013): Effect of ground motion duration on earthquake-induced structural collapse. *Structural Safety*, 41, 119-133.

[20] Qu, Z., Dutu, A., Zhong, J., Sun, J., (2015): Seismic Damage to Masonry-Infilled Timber Houses in the 2013 M7. 0 Lushan, China, *Earthquake Spectra*, 31(3), 1859-1874.

[21] Xiong, F., Xie, L., Ge, Q., Pan, Y., Cheung, M. S., (2015): Reconnaissance report on buildings damaged during the Lushan earthquake, April 20, 2013. *Natural Hazards*, 76(1), 635-650.

[22] Ali, Q., Schacher, T., Ashraf, M., Alam, B., Naeem, A., Ahmad, N., Umar, M., (2012): In-plane behavior of the dhajji-dewari structural system (Wooden Braced Frame with Masonry Infill). *Earthquake Spectra*, 28(3), 835-858.

[23] Lowes, L. N., Mitra, N., Altoontash, A., (2003): A beam-column joint model for simulating the earthquake response of reinforced concrete frames. *Technical Report 2003/10*, Pacific Earthquake Engineering Research Center, College of Engineering, University of California.

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

[25] Chandramohan, R., Lin, T., Baker, J. W., Deierlein, G. G., (2013): Influence of ground motion spectral shape and duration on seismic collapse risk. *In 10th International Conference on Urban Earthquake Engineering*. Tokyo, Japan.