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SITE SPECIFIC RECORD SELECTION AND SEISMIC FRAGILITY ANALYSIS

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Abstract: Seismic fragility of a 5-storey regular shear wall building was derived through nonlinear dynamic analysis and the effect of site specific record selection and direction of applied load were investigated. Two sets of twenty synthetic earthquake records compatible with western and eastern Canadian seismicity are applied to the structural model. Fragility curves of the building were developed having spectral acceleration at the fundamental period of the structure and peak ground acceleration as seismic intensity measures. The results indicated that fragility curves are less sensitive to record selection when spectral acceleration is chosen as the seismic intensity measure, as this parameter provides a normalized format of hazard intensity. On the other hand, when peak ground acceleration is chosen as seismic intensity indicator, significant change is observed in fragility curves derived for sites with different seismicity characteristics. Numerical simulation of the building was further analyzed under western seismic records applied at an angle of 45 degree and the results of dynamic analysis and fragility curves are compared to the case that records are applied parallel to one of the principle directions. Based on the result, applying bidirectional load would cause a delay in entering nonlinear range of behaviour for the structure and therefore is not a conservative approach at lower levels of seismic intensity.

1. Introduction

Damage observed after past earthquakes proved that many existing buildings are vulnerable while subjected to strong earthquakes. Therefore seismic performance of existing buildings needs to be assessed to decide on the necessity of retrofitting. Seismic vulnerability of buildings can be assessed through detailed nonlinear modelling and dynamic analysis. Before performing numerous time consuming analyses for several building cases, potential parameters affecting the results must be investigated to obtain results efficiently. Herein, two aspects of dynamic analysis that potentially contribute to the results of vulnerability analysis are studied; site specific record selection and direction of applied load.

Seismic assessment of buildings requires choosing earthquake records representative of seismicity of the region. If sufficient number of past earthquake records are not available, synthetic records compatible with site seismic characteristic are to be selected. Among previous researches on seismic assessment of concrete buildings Ramamoorthy et al. (2006) and Celik and Ellingwood (2009) derived fragility curves of two-dimensional frames using synthetic ground motions developed for the Memphis region (mid-America) with spectral acceleration at the fundamental period of the structure as hazard intensity parameter. Koduru and Haukaas (2009) modeled a 15 storey shear wall building using OpenSees in 3D and asessed the behaviour of the building under three different types of ground motions (crustal, sub-crustal and subduction zone). Zareian, and Krawinkler (2010) studied the collapse capacity of moment-resisting frame and shear wall structures applying Incremental Dynamic Analysis in Drain 2D. Instead of using scalar value of intensity measure (such as S_a), vectored-value of (S_a, Ɛ) was used, where Ɛ stands for the difference between S_a of a specific ground motion and the median of the spectral acceleration predicted by an attenuation relationship at the fundamental period of the structure. Another study using Perform 3D software was conducted by Pejovic and Jankovic (2015) to derive seismic fragility of reinforced concrete high rise-buildings in Southern euro-Mediterranean zone with core wall structural system choosing 60 ground motions with a wide range of magnitudes, distances to source and different site conditions.

Regarding direction of applied load, ASCE 7-10 (ASCE 2010) standard on minimum design loads requires applying time history records in both horizontal directions in 3D analysis, while there is no such requirement in Canadian Codes (NRCC 2010). In current investigation, the purpose is seismic assessment of building rather than design. Accordingly, a 5-storey shear wall building having 5 bays of 7.0 m length and 4.0 m storey height was selected as a reference building to analyze the effect of parameters mentioned. The building was designed based on 1990NBCC (NRCC 1990) load level for Ottawa. The building was analyzed under synthetic seismic records compatible with western and eastern Canadian seismicity to investigate the effect of site specific record selection. The effect of direction of the applied seismic load is also investigated through considering two cases; applying time history records in one of principle directions and applying them at 45 degree.

2. Site Specific Time History Records

In order to perform incremental dynamic analysis, a set of ground motion records representative of the building site are needed. Herein, artificial earthquake ground motions, generated by Atkinson (Atkinson 2009), were used. These records are compatible with the uniform hazard spectra (UHS) specified for seismic design in the 2005 and 2010 National building code of Canada. The records are generated for earthquakes having 2% probability of exceedance in 50 years. The target UHS depends on the location and the site condition, where the site condition is classified based on the time-averaged shear-wave velocities in the top 30 m of soil deposit (soil types A, C, D, and E specified in the building code NRCC 2010). Atkinson applied the stochastic finite-fault method to generate earthquake time histories matching the 2005 NBCC UHS for a range of Canadian sites and different soil types. In this study, the records generated for the reference soil type C were used.

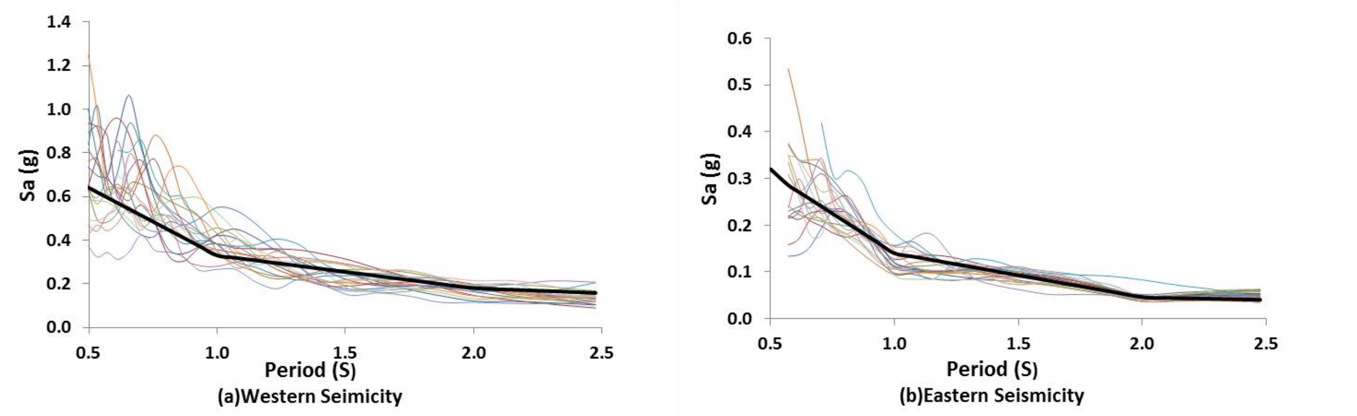
The records are provided in four sets of 45 time histories: M6.5 at 10 to 15 km, M6.5 at 20 to 30 km, M7.5 at 15 to 25 km, and M7.5 at 50 to 100 km for Western Canada and four sets of 45 time histories: M6.5 at 10 to 15 km, M6.5 at 20 to 30 km, M7.5 at 15 to 25 km, and M7.5 at 50 to 100 km for Eastern Canada. 5 records were selected from each of these eight groups (twenty records for each site), which matched the target spectrum in the period range of 0.5 to 2.5 for east and west. These records with lowest standard deviation with respect to target spectrum in the range of periods of interests were selected (minimum standard deviation for (Sa)target/(Sa)simulated). Figure1 shows the comparison between the uniform hazard spectrum (UHS) of Vancouver (western Canada) and Ottawa (eastern Canada) and spectral accelerations of selected records for each city while the records are scaled to the level of UHS.

3. Modelling and Analysis

A five storey shear wall building was selected as the representative building. Three dimensional nonlinear model of the shear wall building was simulated in PRFORM 3D (CSI 2013). Beam and column components were modelled assuming lump plasticity at member ends using FEMA beam FEMA column elements. Shear wall components were modelled through fiber sections by assigning constitutive material models to the fibers. Hognestad model (1951) was used for simulating concrete material and Yalchin model (2000) was used to represent steel material.

Incremental dynamic analysis(IDA) (Vamvatsikos and Cornell 2002) was applied to the structural model to estimate structural performance under different intensities of earthquakes. These analyses involve subjecting the structural model to a set of ground motion records, each scaled to multiple levels of intensity, resulting in curves of response parameter versus intensity level. IDA involves selecting two parameters: seismic intensity measure and engineering demand parameter (damage indicator). Two different seismic intensity measures were considered consisting of; spectral acceleration of fundamental period with 5% of critical damping (Sa(T1),5%), and peak ground acceleration (PGA). Sa(T1) was used by previous researches including Vamvatsikos and Cornell (2002) and Ellingwood et al. (2007). This measure of intensity reflects both the characteristic of the earthquake and the structural period. It is defined in the National Building Code of Canada as a design parameter, and is frequently used by designers. On the other hand, scaling based on PGA gives a uniform format for the hazard, irrespective of the period of the structure, allowing comparison of the behaviour of buildings. Furthermore, scaling based on PGA is more straight forward and convenient to use. Inter-storey horizontal drift ratio was selected as the damage indicator. The use of inter-storey drift to define different limit states is quite common among engineers as it can be computed and rationalized easily.

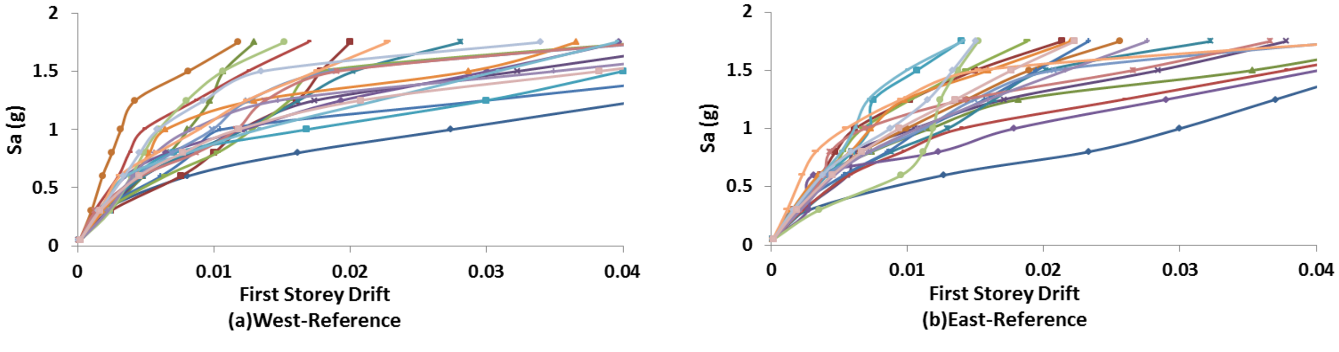
Each set of 20 records selected were applied to the structure choosing ten scale factors to cover the structural behaviour from linear behaviour to collapse range. The results are demonstrated in IDA curves under western and eastern seismicity in Figure 2.



(a)Western Seimicity

(b)Eastern Seismicity

Figure 1: Comparison of UHS and Spectral Acceleration of selected records for Vancouver and Ottawa



(a)West-Reference

(b)East-Reference

Figure 2: Result of IDA applied to reference building using western and eastern Canadian seismicity

4. Fragility Analysis under Different Seismicity

IDA results provide the input for developing fragility curves as probabilistic tools representing the probability of exceeding predefined damage states under different levels of ground motion intensity. Fragility function is described in the form of Eq. 1.

$$P[D > Di \mid IM] = \phi\left[\frac{\ln(x/Di)}{\sqrt{\beta_{d/IM}{}^{2} + \beta_{c}{}^{2} + \beta_{m}{}^{2}}}\right] \qquad \text{Eq. 1}$$

In the above expression, φ(.) is standard normal cumulative distribution function, Di is upper bound for each damage level, x is the median value of demand as a function of IM, βd/IM is the dispersion (logarithmic standard deviation) of demand conditioned on IM, βc is capacity uncertainty and βm is modeling uncertainty.

Seismic fragility curves of the buildings are derived using the results of IDA, under both western and eastern seismicity conditions. Fragility curves depict probability of exceeding predefined damage states under different level of seismic intensity. Three limit states of immediate occupancy, life safety and collapse prevention compatible with ASCE 41 definitions (ASCE 2007) were selected. More information on quantifying the limit states is available in authors' previous researches1.

As Figure 3 indicates, the comparison between the fragility considering western and eastern seismicity shows that the difference between fragilities for the two case fall in the range of 5% having Sa(T) as seismic intensity measure. One should be aware that the difference in seismicity dictates different probability of occurrence of each level of spectral acceleration for eastern and western site condition. Therefore this observation does not mean that the building is vulnerable to the same level whether it is located in Vancouver or Ottawa. In fact, comparing UHS for Vancouver and Ottawa indicates that the spectral acceleration of seismic event with 2475 years return period (2% probability in 50 years) for Vancouver is almost twice the value for Ottawa, dictating that the building has higher risks of failure if located in Vancouver rather than Ottawa. On the other hand, choosing PGA as the seismic intensity measure indicates remarkable difference for the same model under western and eastern seismicity as demonstrated in same figure. The reason behind this observation is the difference in the nature of seismic events in western and eastern Canada. The generated records for Vancouver and Ottawa have different characteristic specifically longer duration of records generated for Vancouver compared to the ones generated for Ottawa. Having PGA as the seismic intensity measure reflects these differences, while having Sa(T) as the seismic intensity measure decreases the effects of site specific record selection.

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[1] Rafie Nazari and Saatcioglu. 2016. Fragility curves for Canadian shear wall buildings conforming ductile requirements. Submitted for publication in *Canadian Journal of civil Engineering*.

Rafie Nazari and Saatcioglu. 2017. Seismic performance assessment of shear wall buildings through fragility analysis. Submitted for publication in Engineering Structures.

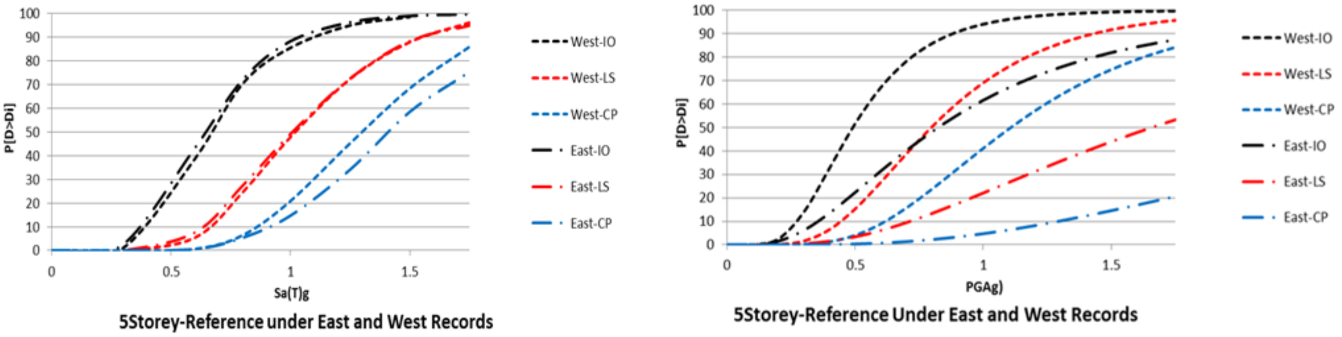

Figure 3: Comparison of Behavior of Reference building subjected to seismicity of East and West

5. Direction of Applied Load

In previous sections, time history records were applied in one direction. ASCE 7-10 standard on minimum design loads requires applying time history records in both horizontal directions in 3D analysis, while there is no such requirement in Canadian codes. In this study, the purpose was seismic assessment of building as opposed to design. Therefore, the effect of direction of applied load needed further investigation to find the detrimental condition. Hence, the reference structure was analyzed under time histories applied in X direction, and it was also analyzed under records at 45 degree direction. Figure 4 demonstrates the results of IDA while time histories are applied at 45 degree, and Figure 5 shows comparison of derived seismic fragility curves for reference building under applied records at different directions. Based on the results, when scale factors are smaller and the structure is essentially in linear behaviour range, applying the time history records in the X direction enforce the structure to go under higher drifts resulting in higher damage, compared to the case that the same load is applied in 45 degree. Applying the load in 45 degree direction results in lower values of drift, as the load in each direction is about 70% of the load of the unidirectional case. Moreover, changing the behaviour to nonlinear range is delayed in such analyses for the same reason. However, in higher range of spectral acceleration especially near collapse, the behaviour of the building under bidirectional load becomes worse and it leads to collapse at earlier values of drift. Therefore, as a general conclusion for shear wall buildings without torsional sensitivity, applying seismic load in one direction is accurate and safe enough.

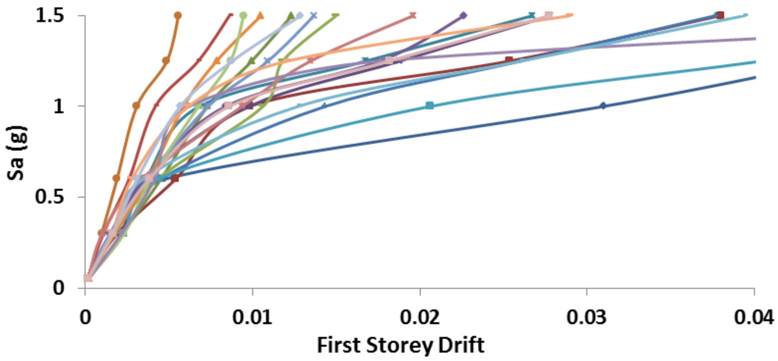

Figure 4: Result of IDA applied to reference building with seismic load applied in 45 degree

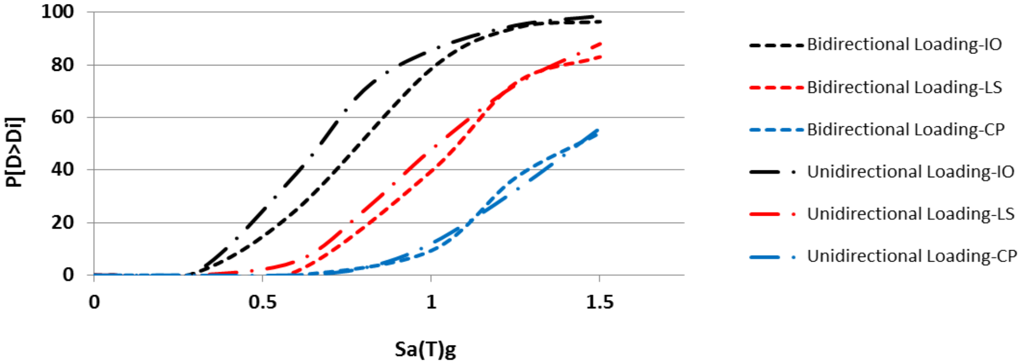

Figure 5: Comparison of fragility curves of reference shear wall building under time histories with different directions

6. Discussion and Conclusion

Seismic fragility analysis of existing buildings assesses the building performance trough probabilistic approach. In order to derive analytical fragility curves, detailed numerical simulation of the structure and applying numerous time history analyses are necessary. Therefore, parameters affecting the results require evaluation and some of them need to be eliminated before analysing different building categories and performing time consuming analyses. Herein, effect of site specific record selection for cities with western and eastern Canadian seismicity characteristics was assessed having both spectral acceleration and peak ground acceleration as seismic intensity measures.

The fragility curves derived for western and eastern seismicity based on spectral acceleration have similar shapes with a margin of 5% difference. This observation indicates that choosing spectral acceleration as the indicator of seismic hazard would give a normalized format of hazard and the results derived for one site can provide information for other sites having similar building design. However, this does not indicate similar seismic vulnerability of the building in western and eastern sites. To make a judgement on vulnerability of the building in each site, the fragility of the buildings under expected levels of seismic hazard for that site must be used. As an illustrative example, NBCC design spectral acceleration which is based on seismic hazard with 2% probability in 50 years for the 5-storey building located in Vancouver is twice the value for similar building in Ottawa.

When peak ground acceleration is chosen as seismic hazard intensity parameter, the difference in site specific records becomes more significant and obvious. Accordingly, at each PGA value the western time history records are indicators of an event with longer duration and possibly several ups and downs, while the eastern records represent events with significantly shorter durations enforcing less deformation on the structure.

The last investigation was performed on the direction of applied load with time history records applied parallel to one of principal axes and in a 45 degree angle with respect to both planar axes. When the same records are applied at 45 degree, each component has scalar value equal to 0.7 times the load magnitude. As a result, having the records at a degree initially imposed lower drift values. Moreover, the building nonlinear response is delayed at this case. However, at higher values of seismic hazard and especially for the collapse prevention limit state, more severe damage is possible when bidirectional records are applied with a margin of 5% difference in fragility results. The overall behaviour under unidirectional application of the seismic load was more severe and the conclusion is that for future investigation on fragility analysis, it is safe to apply the load parallel to the main axis.

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