ANALYTICAL SEISMIC VULNERABILITY ASSESSMENT OF LOWRISE STEEL MRFs

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1. ABSTRACT

The Global Earthquake Model (GEM; *http://www.globalquakemodel.org/*) is a grand effort to proffer a comprehensive open source tool for large scale loss assessment studies. For this to be accomplished, an analytical seismic vulnerability assessment methodology needs to be developed that links ground shaking with repair cost for a building class. The test bed for the present study is a set of low/mid-rise steel moment-resisting frames (SMRFs) designed for high seismicity US regions and selected appropriately so as to represent all important aspects within their class. The structural analysis was performed using Incremental Dynamic Analysis (IDA). On that premise, the selection of a single Intensity Measure (IM) to parameterize IDA results and, eventually, vulnerability curves needs to be tackled. It was demonstrated that scalar IMs can have an overall satisfactory performance. Once the uncertain structural response is defined in terms of interstory drifts and floor accelerations, across a wide range of intensities, the methodology proceeds to the vulnerability estimation and consequently to loss assessment. The end product of this study is a high-quality set of vulnerability curves whose weighted moments are taken as the uncertain vulnerability function of the investigated building class.

2. INTRODUCTION

Given the lack of sufficient historical data on the seismic performance of a broad range of building classes worldwide, the value of an analytical model to assess vulnerability and, consequently, loss becomes apparent. To this end, a set of guidelines was recently developed by Porter *et al*. [1] aiming to offer a practical analytical method for assessing the relationship between the ground shaking and the repair cost for a building class. The term ‘building class’ refers to a set of index structures [2] which are appropriately selected, so as to account for variations of their key features (e.g. height, construction era etc) that are the most influential to seismic performance.

For assessing the structural response from elasticity up to global collapse, Incremental Dynamic Analysis (IDA) [3] is employed. Furthermore, the important task of selecting a single Intensity Measure (IM) across the class will be addressed. Following the evaluation of the structural response, the study proceeds to the vulnerability and loss assessment of the low/mid-rise steel moment-resisting frame (SMRF) building class. This will be built upon the component-based FEMA-P-58-1 approach [4] but the latter will be simplified in such a manner so as to minimize the invested effort.

3. CLASS DESCRIPTION AND SAMPLING

The test bed of the present work is a set of six (6) low/mid-rise SMRFs, built in the US in high-seismicity regions. The analyzed structures were selected from a report issued by the National Institute of Standards and Technology (NIST) [5]. The main features differentiating the buildings within the class were considered to be: a. the building height, defined as the number of stories (parameter $X1$) and b. the design base shear, as determined by the code-based value of spectral acceleration at 1.0sec, termed $SD1$ in US codes (parameter $X2$). The first macroscopic characteristic was based on a sample of 3562 buildings in Memphis catalogued by Muthukumar [6]. For assessing the distribution of $SD1$ in high-seismicity zones a comprehensive catalogue of US highrise buildings has been extracted from the Emporis highrise building database and appropriately processed. To minimize the number of samples needed to represent the population of low/mid-rise SMRFs, a set of representative “index buildings” was selected using class partitioning [7]. The methodology results also to a certain weight to represent the contribution of each index building to the total sample (see Table 1).

Index	No of stories, $X1$	Code design level, $X2$	Weight
1ELF	1	0.6g*	0.5503
2ELF	2	0.6g*	0.1760
3ELF	4	0.6g*	0.0337
5ELF	1	0.2g*	0.1738
6ELF	2	0.2g*	0.0556
7ELF	4	0.2g*	0.0105

* $SD1$ for site class D

Table 1. Features $X1$, $X2$ and moment matching weights for the six index buildings

All archetype buildings have a rectangular floor plan that consists of a three-bay perimeter frame on each side. For both design and assessment these special perimeter SMRFs were assumed to withstand the seismic forces whilst the contribution of the gravity frames to the lateral strength and stiffness resistance capacity of the building was disregarded. All the beam-to-column connections were Reduced Beam Section (RBS) connections. The global destabilizing P-Δ effects are taken into account assuming that each SMRF apart from its tributary gravity loads also carries half the seismic mass of the building.

4. MODELING

The six index buildings were analyzed using 2D model idealizations of the MDOF structures. Regarding the structural members, their behavior was depicted using lumped plasticity elements with an elastic hardening backbone that is followed by a negative branch and a complete loss of strength at an ultimate ductility. The capping rotation θ_c (i.e. total rotation just before the loss of strength) was computed as the sum of the yield rotation θ_y and the pre-capping rotation θ_p, with the latter being evaluated from empirical equations recently proposed by Lignos and Krawinkler [8]. These equations were obtained by fitting a comprehensive database of structural tests using regression equations that incorporate the effect of material, section geometry and member dimensions. Results are offered separately for beams with RBS ends and beams other-than-RBS. The former will be employed for beams and the latter, for lack of better data, to model the columns.

5. IDA FUNDAMENTALS

For evaluating the seismic performance of the index buildings, Incremental Dynamic Analysis (IDA) [3] is adopted. IDA is a powerful tool of structural analysis that involves performing a series of nonlinear time-history analyses for a suite of ground motion records scaled at increasing intensity levels. To define the IDA curves, two scalars are needed, these being the Intensity Measure (IM) to represent the severity of the seismic input and an Engineering Demand Parameter (EDP) to monitor the structural response. For the present study, a number of different IMs were used for illustrating their efficiency, whereas only two classes of EDPs are needed: the peak Interstory Drift Ratio (IDR) at each story and the Peak Floor Acceleration (PFA) at each floor. The ground motion records needed for the IDAs come from the far-field record set from FEMA P695 [9] that contains 22 records with two horizontal components (i.e. 44 individual accelerograms in total).

6. IM SELECTION

The selection of an appropriate IM is an important task towards the development of analytical seismic vulnerability functions, either for a single building or for a set of index structures. The IM essentially governs the bias and the variance inherent in evaluating the structural demand for given levels of intensity. Thus, the two most important properties of the IM are efficiency and sufficiency. Sufficient is an IM that renders the structural response independent of any other seismological or ground motion characteristic. Efficient is an IM that is highly correlated to the structural response, thus reducing its variability from record to record.

Considering a set of structures, as opposed to a single building, increases the requirements placed on the IM. In that case, the selected single IM should remain efficient and sufficient for the entire class, a prerequisite that is not easily met. $S_a(T_1)$ is often considered to be a relatively sufficient and efficient IM. Nevertheless, it does not satisfy the requirement for a common IM for all buildings within the class, as it is structure specific. A simple remedy is to choose a single common period T that can be considered representative of the class. Two potential candidates are S_a(1sec) and $S_a(T_{1m})$, where T_{1m} is the mean (or median) of the first mode period of all index buildings. On account of single buildings, Cordova *et al*. [10] introduced S_{agm} that was initially defined as the geometric mean of the two spectral acceleration components evaluated at two period levels, these being the fundamental period T_1 and a period that is two times the fundamental period, $2T_1$. On that premise, a second class of IMs was considered, this being the $S_{agm}(T_i)$, which are defined as the geometric mean of spectral acceleration values $S_a(T_i)$ estimated at several periods T_i that may span the following ranges:

a) Five logarithmically spaced T_i periods over the $[T_{2m}, 1.5T_{1m}]$ range, where T_{2m} and T_{1m} are the mean T_2 and T_1 periods,
b) Seven logarithmically spaced T_i periods over the $[\min T_2, 1.5\max T_1]$ range,
c) Five linearly spaced T_i periods over the $[T_{2m}, 1.5T_{1m}]$ range,
d) Four T_i periods defined as $[T_{2m}, \min[(T_{2m}+T_{1m})/2, 1.5T_{2m}], \mathrm{T}_{1m}, 1.5T_{1m}]$,
e) Five T_i periods defined as $[T_{2m}, \min[(T_{2m}+T_{1m})/2, 1.5T_{2m}], T_{1m}, 1.5T_{1m}, 2T_{1m}]$,

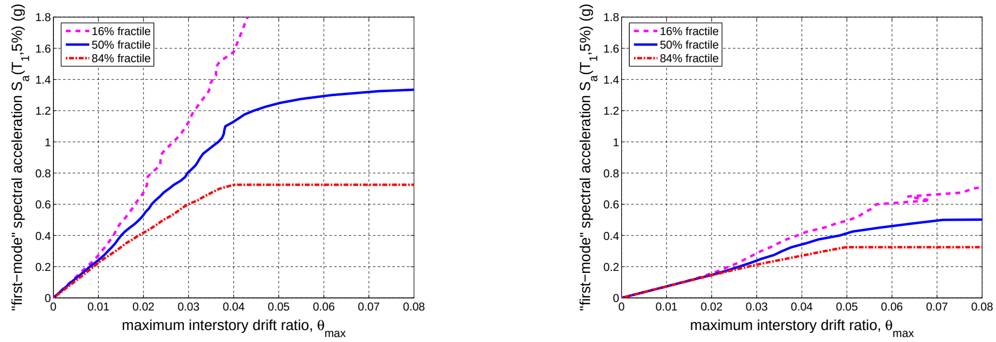
7. IDA ANALYSIS RESULTS

IDA was applied to each of the six index buildings for the 44 accelerograms using the hunt&fill algorithm to achieve a consistent number of 12 nonlinear dynamic analyses per record. In each case the analysis was run up to global dynamic instability. Figure 1 presents the results in the form of 16,50,84% fractile IDA curves for the maximum IDR and two characteristic index buildings. The results presented in Figure 1 are not directly comparable due to the use of a different $S_a(T_1)$ for each building. It is for this reason that we should transform the results to a common IM that can be used for defining the vulnerability function of the class.

8. COMPARISON OF DIFFERENT IMs

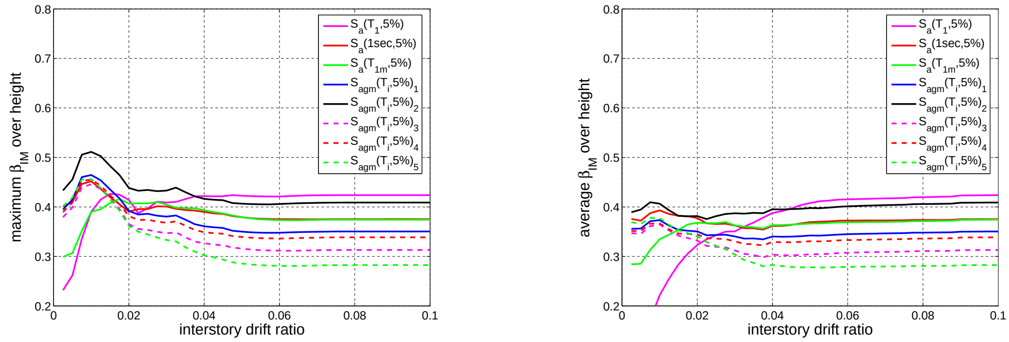
The testing of candidate IMs for efficiency can be performed *a posteriori* and for any number of IMs without incurring any additional computational cost: The same IDA results are simply reused and reprocessed. The proposed methodology differs from similar studies that have appeared before in the literature (e.g.[11]), in two important aspects, namely (a) using an IM given EDP (IM|EDP) basis and (b) employing all IDR and PFA values at each story, rather than just the maximum IDR over all stories. Working on an IM|EDP basis essentially translates to using vertical stripes of points in Figure 1, produced as cross sections of the 44 IDA curves with a vertical line signifying a given EDP value. This has the obvious advantage of allowing a detailed view of efficiency that can reach all the way up to global collapse.

Efficiency is tested by evaluating the dispersion β_{IM} of the IM|EDP values, i.e. the standard deviation of the log of the IM capacities for a range of EDP values. Lower dispersions mean higher efficiency. The ensemble results are shown for the 3ELF 4-story in Figure 2, for the interstory drift EDP. The IM ranking across all IDR values reveals that $S_a(T_{1m})$ possesses the best performance in the elastic region whereas $S_{agm}(T_i,5\%)_5$ has an advantage in regions where the spread of inelasticity results in substantially elongated periods, but also when considering the PFA response, which is not presented here for brevity.



(a) 3ELF 4-story ($SD1_{max}$) (b) 5ELF 1-story ($SD1_{min}$)

Fig. 1. Summarization of the IDA curves into 16,50,84% fractile curves of the maximum IDR for two index buildings



(a) maximum dispersion of IDR given IM (3ELF) (b) average dispersion of IDR given IM (3ELF)

Fig. 2. Maximum and average dispersions of the IM for given values of the IDR response of the 3ELF 4-story index building considering eight IMs

9. VULNERABILITY ESTIMATION

When estimating seismic losses, in order to inject the needed variability, one should define three variants of each index building: one variant with relatively rugged components, one with typical components, and one with relatively fragile components. Only the top 6 or so nonstructural/content component types and the top 1 or 2 structural component types are considered. By “top components” is meant the components that contribute most to construction cost new.

The values of peak floor accelerations at each floor or roof diaphragm and peak transient drift ratios at each story, captured via IDA, are input to fragility functions for each component at each floor (for acceleration-sensitive components) or story (for drift-sensitive components). One uses Monte Carlo methods to simulate ground motion time history, damage for each component, and repair costs per damaged component type and damage state. Total damage factor (*DF*, repair cost as a fraction of replacement cost new) in any simulation is given by Equation 1, in which V denotes the replacement cost new of the building, f denotes the fraction of V represented by the component types in the inventory, a is an index to floor level, N_a is the number of diaphragms, c is an index to component types, N_c is the number of component types considered, d is an index to damage states for a given component type, N_d is the number of possible damage states,

$n(a,c,d)$ is the number of damaged components at floor a, type c, in damage state d, and $u(c,d)$ is the unit cost to repair a component of type c from damage state d.

$$DF = \frac{1}{V \cdot f} \sum_{a}^{N_a} \sum_{c}^{N_c} \sum_{d}^{N_d} n(a,c,d) \cdot u(c,d) \qquad (1)$$

One calculates DF for each of many simulations for each combination of structural model and component set at each level of ground motion intensity, and captures mean damage factor (MDF) and coefficient of variation (COV) as a function of ground motion intensity. One equally weights the poor, typical, and superior-quality variants to estimate the MDF and COV for each index building and applies the class partitioning weights to calculate the MDF and COV for the class as a whole.

10. CONCLUSIONS

A practical methodology has been presented for performing analytical vulnerability assessment for low/mid-rise steel building classes. Significant novel features of the proposed approach include: (a) Using class partitioning to select representative index buildings, (b) the use of simple structural models together with IDA for performing structural assessment, (c) the introduction of the geometric mean of spectral accelerations at adjacent periods as a sufficient and efficient intensity measure across an entire building class, (d) the use of a reduced list of "top components" that need to be taken into account for assessing the damage factor and (e) Monte Carlo simulation to propagate the uncertainty from different realizations of each index building to the class vulnerability results.

11. AKNOWLEDGEMENTS

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ΑΝΑΛΥΤΙΚΉ ΕΚΤΙΜΗΣΗ ΤΗΣ ΣΕΙΣΜΙΚΗΣ ΤΡΩΤΟΤΗΤΑΣ ΜΕΤΑΛΛΙΚΩΝ ΠΛΑΙΣΙΩΝ ΧΑΜΗΛΟΥ ΥΨΟΥΣ

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ΠΕΡΙΛΗΨΗ

Στόχος του Παγκόσμιου Σεισμικού Μοντέλου (*http://www.globalquakemodel.org/*) είναι η δημιουργία ενός εργαλείου ανοιχτού κώδικα για την εκτίμηση των απωλειών σε μελέτες ευρείας κλίμακας. Για την επίτευξη του εν λόγω στόχου, απαιτείται η ανάπτυξη μίας αναλυτικής μεθοδολογίας εκτίμησης της σεισμικής τρωτότητας η οποία θα συνδέει για μία δεδομένη κλάση κτιρίων την ένταση της εδαφικής κίνησης με το κόστος αποκατάστασης των ζημιών. Στην παρούσα έρευνα χρησιμοποιήθηκε ένα σύνολο μεταλλικών πλαισίων, χαμηλού και μέσου ύψους, τα οποία έχουν σχεδιαστεί για περιοχές υψηλής σεισμικής επικινδυνότητας των ΗΠΑ. Τα κτίρια επιλέχθηκαν έτσι ώστε οι ιδιότητες τους να είναι αντιπροσωπευτικές της συγκεκριμένης κλάσης. Για την εκτίμηση της σεισμικής συμπεριφοράς των κτιρίων χρησιμοποιήθηκαν Αναλύσεις Δυναμικής Αντίστασης (ΑΔΑ). Στο πλαίσιο αυτό απαιτήθηκε η επιλογή ενός χαρακτηριστικού, για ολόκληρη την κλάση, Μέτρου Έντασης (ΜΕ) προκειμένου να παραμετροποιηθούν τα αποτελέσματα των ΑΔΑ αλλά και εκείνα των καμπυλών τρωτότητας. Προέκυψε ότι τα βαθμωτά ΜΕ έχουν ικανοποιητική συμπεριφορά. Ακολούθως της εκτίμησης της σεισμικής συμπεριφοράς υπολογίστηκε η σεισμική τρωτότητα των κτιρίων. Το τελικό προϊόν της παρούσας έρευνας είναι ένα σύνολο καμπυλών τρωτότητας, από τις (στατιστικά) σταθμισμένες ροπές των οποίων προκύπτει η τρωτότητα του υπό ανάλυση κτιριακού συνόλου.