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Building specific loss estimation for performance based design

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ABSTRACT: The main goal of performance-based design (PBD) is to design structures that will meet the performance expectations of their owners. This work describes research efforts of the Pacific Earthquake Engineering Research (PEER) Center aimed at describing the seismic performance of buildings as a continuum and in term of economic losses. Specifically this research provides three measures of performance expressed in terms of economic losses: (a) expected loss in the building as a function of ground motion intensity; (b) expected annual loss; (c) annual frequency of exceedance of a given loss level. These measures of performance provide quantitative information to help owners, lenders, insurers and other interested parties make informed decisions regarding their buildings. In the proposed approach the total loss in a building due to physical damage is treated as a random variable computed as the sum of the losses in individual structural and non-structural components. Economic losses are computed using a fully probabilistic approach that permits the explicit incorporation of uncertainties in the seismic hazard at the site, in the response of the structure, on the fragility of individual structural and non-structural components, and on the costs associated with the repairs or replacement of individual building components. Physical damage is estimated by combining building response parameters such as interstory drift ratio or peak floor acceleration computed with incremental dynamic analyses with component fragility functions. The latter functions describe the probability of individual building components of being in various damage states as a function of structural demand parameters. Results from an existing non-ductile seven-story reinforced concrete building are presented.

1 INTRODUCTION

The main goal in Performance Based Earthquake Engineering (PBEE) is to design facilities with predictable levels of performance. In order to predict the levels of performance of a facility, they need to be expressed in terms of quantifiable variables. One alternative is to express the performance levels in terms of the economic losses in the facility due to earthquakes with certain levels of intensity. The main advantage of considering economic losses as a measure of performance is that it can be estimated as a continuum.

Although many studies have been conducted in the past regarding loss estimation, the vast majority of them are devoted to very rough estimations of losses to a large number of structures. Studies of this type include the one of Steinbrugge et al. The study was conducted on a portfolio of dwellings in a specific region. A deterministic methodology was used to correlate Modified Mercalli Intensity as a measure of ground motion level of intensity to the damage in dwellings.

One of the most extensive portfolio-based loss estimations is the study accomplished by Applied Technology Council in 1985, ATC 13. The objective of the study was to estimate the loss and damage due to earthquakes in California in terms of selected earthquake shaking characterizations and identified facility classes. The methodology used in ATC 13, was based on developing damage probability matrices through an expert opinion procedure.

A small portion of loss estimation studies can be categorized as component-based loss estimation. The first type of loss estimation study of this type was done by Scholl et al. in 1980. The study was aimed at improving procedures to estimate dollar losses in high-rise structures as a function of ground motion and structural response parameters. Gunturi (1993) accomplished a building-specific monetary damage estimation based on mechanistic models that relates loadings to structural response. Porter and Kiremidjian (2001) introduced a building-specific seismic vulnerability procedure based on Monte Carlo simulations.

None of the previous studies provides an adequate platform to identify and propagate sources of uncertainty in loss evaluation. As part of this research study we are developing a step-by-step rational methodology to estimate losses in individual buildings. The sources of uncertainty in the methodology are clearly identified and their influence on different loss parameters is investigated.

Presented in this paper is a detailed description of the methodology to estimate the annual expected loss of the building. First we introduce a step-by-step procedure to estimate the annual expected loss for a single component. The proposed procedure is capable of providing useful outputs in the intermediate steps toward calculating the final loss parameter. In the next step a sensitivity analysis is performed on the influence of different sources of uncertainty on the annual expected loss of a single component. Finally the procedure to evaluate the annual expected loss for the building is presented and its applications in PBEE is presented. As an example the methodology is applied to a PEER testbed reinforced concrete structure. Specifically, the component loss estimation is exemplified for a slab-column connection located in the second story of the testbed building.

2 INTRODUCING THE TESTBED BUILDING

A seven - story reinforced concrete structure has been used as a testbed for the described methodology. The building was designed in 1965 and built in 1966. The structural system of the building consists of moment-resisting perimeter frames and interior gravity-resisting frames (flat slabs and columns). The structure is nominally symmetric with the exception of an infill wall in the first floor of the north frame of the building. A detailed description of the testbed building has been presented in Browning et al. (2000).

3 FRAMING EQUATION FOR COMPONENT - BASED LOSS ESTIMATION

The annual expected loss of single components can be evaluated using the total probability theorem as:

$$E[L_j] = \sum_{i=1}^{m} \int_0^{\infty}\int_0^{\infty} E[L_j \mid DS = ds_i]\, P(DS = ds_i \mid EDP_j = edp)\, P(EDP_j > edp \mid IM = im) \left| \frac{dn(IM)}{dIM} \right| dEDP\, dIM \qquad (1)$$

Where | d $\nu(IM)$ / d IM | is the derivative of the hazard curve as a function of the intensity measure, IM, at the site. P ($EDP_j > edp \mid IM = im$) is the probability of the Engineering Demand Parameter for component j , EDP_j , exceeding a certain limit , edp, conditioned on a given level of intensity. P($DS = ds_i \mid EDP_j = edp$) is the probability of being at a damage state, DS_i , conditioned on a given level of deformation. E [$L_j \mid DS = ds_i$] is the expected loss in the component ‘*j*’ at a given damage state.

Various approaches can be used in evaluating the annual expected loss of a component. For example, one can integrate the conditional probability of exceedance of the *EDP* over the intensity measure, *IM* at the first step to compute the annual probability of the *EDP* exceeding a certain limit. The next step then would be integration over all *EDP*’s to evaluate the probability of being at a damage state. In the last step one can evaluate the annual expected loss of a component summing over all possible damage states. In this study, however, we are proposing an approach that provides the most useful intermediate results. In the proposed approach first we do the summation over all damage states to estimate the component expected loss as a function of the *EDP*, E [$L_j \mid EDP$]. Then we integrate over a range of *EDP*’s to estimate the component expected loss as a function of the level of intensity, E [$L_j \mid IM$]. In the last step the integration over the levels of intensity will be performed to estimate the component annual expected loss, E [L_j].

From equation (1) it can be seen that four main ingredients are required to evaluate the annual expected loss for a single component: the seismic hazard curve at the site, the structural response that has the best correlation with the damage in the component, the vulnerability of the component and the cost required to repair or replace the damage in the component.

4 ESTIMATION OF THE FOUR INGREDIENTS

4.1 Estimation of the seismic hazard at the site

The estimation of the seismic hazard at the site can be accomplished via a Probabilistic Seismic Hazard Analysis (PSHA). The analysis evaluates the annual rate of exceedance of the spectral ordinates at the site by taking into account the uncertainties associated with different characteristics of all seismic sources affecting the site. Figure 1 shows the seismic hazard curve for the site, where the testbed building is located. The hazard curve has been obtained from information readily available from the United States Geological Survey (USGS), Frankel et al. (2000).

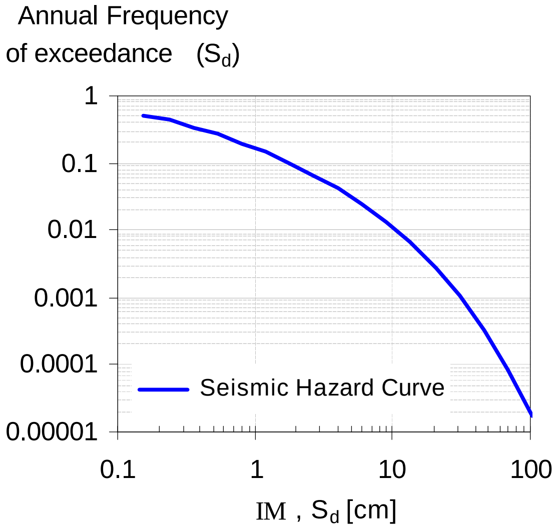

Figure 1. Seismic hazard curve at the site.

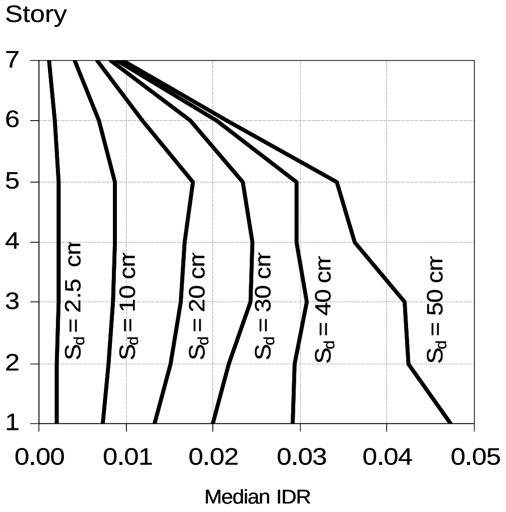

Figure 2. Changes in the median Interstory Drift Ratio, IDR, along the height of the testbed structure and at different levels of intensity.

4.2 Estimation of the structural response

The structural response due to seismic excitation can be estimated by performing a Probabilistic Seismic Structural Response Analysis (PSSRA) on a computer model of the structure. One possible approach in PSSRA is to apply a series of earthquake ground motion time histories to the building model and to estimate the peak responses at different levels along the building height. For the purpose of loss estimation the structural responses should be evaluated at all story levels of the structure along the height. Further, those structural responses should be evaluated that have the closest correlation with the damage in the components.

Damage in almost all structural components such as beams, columns and slab-column connections and most of the non-structural components such as partitions, masonry walls, doors and windows is closely correlated with the Interstory Drift Ratio, *IDR*. For some other non-structural elements such as fire sprinklers, parapets, suspended ceilings and building contents, however, the damage is closely correlated with peak floor acceleration.

The main output from PSSRA is the probability distribution of the structural response, namely interstory drift ratio or peak floor acceleration, at different locations and at different levels of intensity. Researchers have used a lognormal probability distribution for maximum drift response at a given level of intensity. Our studies verify that for both, the interstory drift ratio at all stories and peak floor acceleration at all floor levels, a lognormal probability distribution can be assumed for the structural response probability distribution. This important observation reduces the response estimation to estimating only two parameters, one measure of central tendency and one measure of dispersion to fully define the demand parameter probability distribution. Figure 2 depicts the variations of median interstory drift ratio, *IDR*, at all stories in the testbed building and at 6 different levels of intensity.

As described earlier associated with each location shown on Figure 2 and with each level of intensity is a probability distribution for the structural response. Figure 3 depicts the changes in the probability distribution of the interstory drift ratio at the second story, IDR_2, of the testbed building as a function of the level of intensity, *IM*.

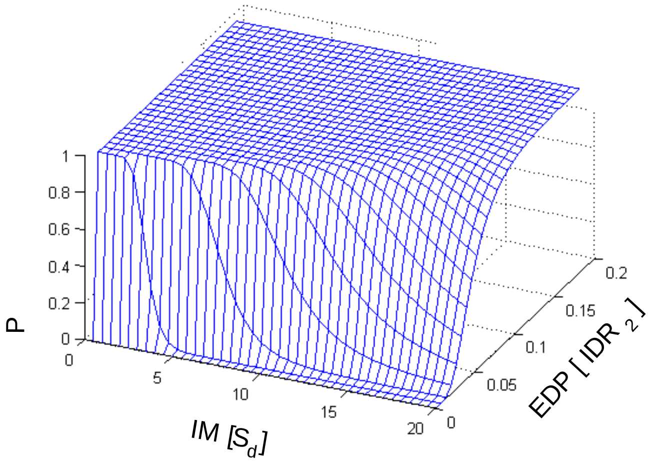

Figure 3.Changes in the probability distribution of the interstory drift ratio at the second story of the testbed building.

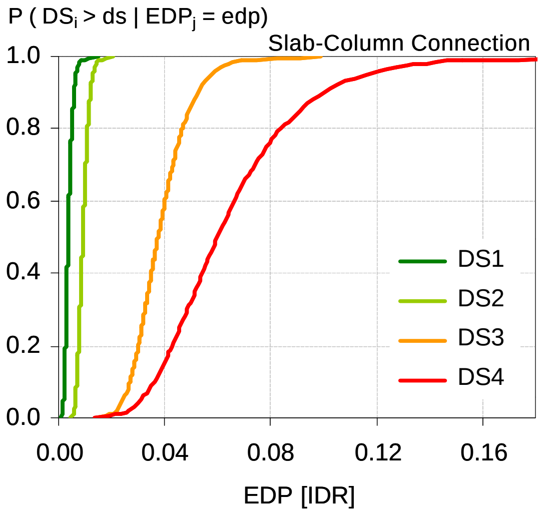

Figure 4. Vulnerability functions for a slab – column connection located in the second story of the testbed building.

4.3 Estimation of the component vulnerability

The vulnerability of a component can be estimated by using fragility functions. Fragility functions estimate the probability that a particular building components will be or exceed different damage states as a function of the engineering demand parameters evaluated in the previous step, section 4.2. Evaluation of fragility functions can be summarized in three steps. The first step is to define the damage states associated with the component. Definition of damage states is based on the courses of action that need to be taken after observing that damage state in the component.

The next step is to gather information that relates different damage states of the component to the motion in the component. Various sources of information are available for motion-damage pairs of a component. One source of information is the experimental tests that have been done on the component in previous research studies. Motion-damage pairs can also be gathered from the observed damage in buildings in previous earthquakes. Based on the gathered motion-damage database for the component, fragility functions associated with each damage state can then be developed in the last step.

The above procedure is exemplified to estimate the vulnerability of a slab-column connection in the testbed building. Four damage states have been defined for this component; First visible damage, wide cracks, punching shear failure and loss of vertical carrying capacity. First visible damage state is the damage state at which small cracks can be observed in the connection. Wide cracks is the damage state at which significant cracking can be observed in the connection. The punching shear failure damage state is the damage state at which a significant degradation can be observed in the connection strength. A main characteristic of connections failed in punching shear failure is a round crack around the column. The last damage state is the damage state at which the connection is not capable of carrying any vertical load. There is not many information available for this damage state.

Results from 7 experimental research studies are used to develop the motion-damage pairs database. Based on this database fragility functions for different damage states of a slab-column connection have been developed. Our studies verify that the fragility functions for each of the damage states for this component can be assumed as a lognormal cumulative function. Figure 4 shows the fragility functions derived for a slab-column connection located in the second story of the testbed building.

4.4 Punching shear failure damage state

The third damage state for a slab-column connection is defined when the punching shear failure occurs in the connection. Previous research studies, Pan et al. (1988), Robertson et al. (1990), have shown that the drift level at which shear failure occurs in a connection is mainly a function of the gravity shear ratio, V_g/V_0 in the connection. The value V_g is the vertical shear acting at failure on the slab critical section defined at a distance $d/2$ from the column face in which d is the average slab effective depth. V_0 is the punching shear strength of the connection that can be calculated based on code recommendations, Pan et al. (1988). This important observation can be implemented in developing fragility functions with smaller dispersion for this damage state.

Introducing the gravity shear ratio as a parameter in defining fragility functions will provide a family of fragility curves instead of one single fragility function as can be seen in Figure 5. As illustrated in this figure fragility functions for punching shear failure damage state vary as a function of the demand parameter, *EDP*, and the gravity shear ratio, V_g / V_0.

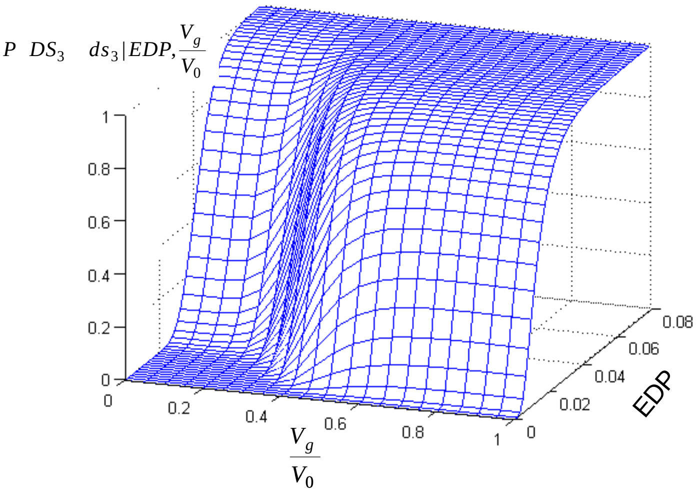

Figure 5. Changes in the fragility function of the third damage state with the gravity shear ratio and the Engineering Demand Parameter, EDP.

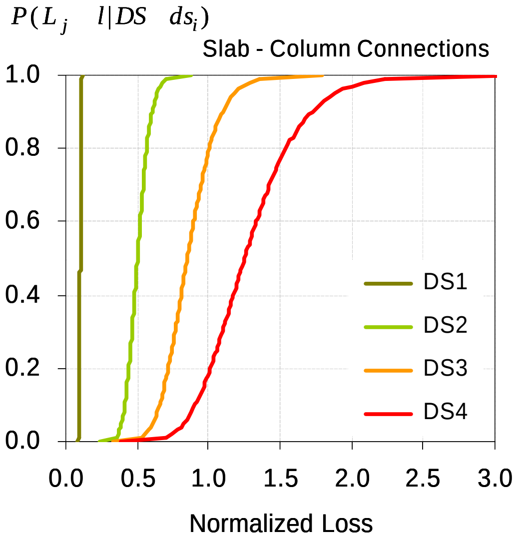

Figure 6. Cost functions of a slab-column connection

4.5 Estimation of the component repair or replacement cost

The repair or replacement cost of a component can be estimated by itemizing the tasks that need to be accomplished after the occurrence of each of the damage states. For example, the repair and replacement actions that can be taken for a slab – column connection after the occurrence of each damage state is explained. For the first damage state, first visible damage, one possible course of action that can be taken is to fill the cracks with grout and do some painting. To repair the connection after the occurrence of second damage state, wide cracking, epoxy injection, grouting and painting need to be accomplished. When a punching shear failure occurs, third damage state, the concrete needs to be removed from the cracked area, additional reinforcement needs to be placed in the cracked area and new concrete should be poured. For the last damage state, loss of vertical carrying capacity, the tasks are pretty much similar to building a new slab-column connection besides the removal cost for the old connection.

The cost associated with each of the itemized tasks can then be estimated from different construction cost databases. Two sources of uncertainty exists for the estimated cost for each damage state. One source of uncertainty stems from different costs for each of the itemized tasks based on different sources of information. Another source of uncertainty stems from different techniques to repair or replace a component. Figure 6 depicts the schematic cost functions developed for the slab – column connection example, assuming that the cost distribution is lognormal.

5 PROCEDURE TO EVALUATE THE ANNUAL EXPECTED LOSS

The variations of the expected loss for a component as a function of the changes in the *EDP* can be calculated using the estimated vulnerability and cost functions for the component.

$$E[L_j | EDP] = \int_0^{\infty} E[L_j \mid DS = ds_i]\, P(DS = ds_i \mid EDP_j = edp)\, dEDP \tag{2}$$

in which the integrand terms have been defined earlier in equation (1). Figure 7 shows the changes in the expected loss for a slab-column connection in the second story of the testbed building as a function of the interstory drift ratio. As can be seen from the figure the expected loss increases with the increase in the level of drift. The variation, however, can not be approximated as an “S” function as can be understood from this figure.

In the next step the component loss can be computed as a function of the level of intensity, using the expected loss as a function of *EDP* and the probability of exceedance of *EDP* conditioned on IM.

$$E[L_j | IM] = \int_0^{\infty} E[L_j \mid EDP_j = edp]\, P(EDP_j > edp \mid IM = im)\, dIM \tag{3}$$

in which, the E [L_j | $EDP_j = edp$] can be computed from equation (3) and P($EDP_j > edp \mid IM = im$) has been defined earlier in equation (1). Figure 8 depicts the changes in expected loss for a slab-column connection in the second story of the testbed building. As can be understood from the figure the expected loss in the component increases as the level of intensity increases. The rate of increase, however, decreases at higher levels of intensity.

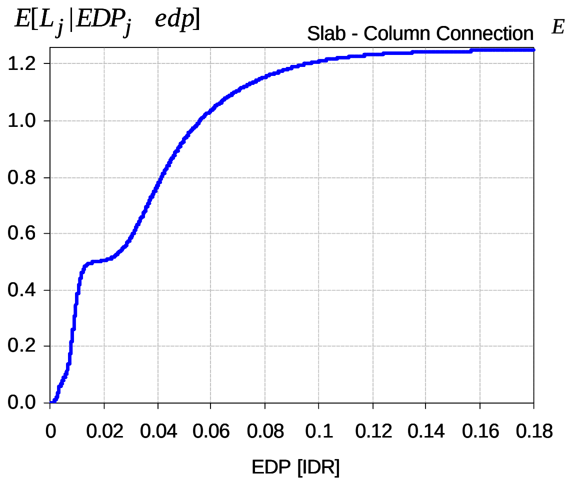

Figure 7. Changes in the expected loss of the slab – column connection conditioned on the Engineering Demand Parameter, EDP, with the changes in the EDP.

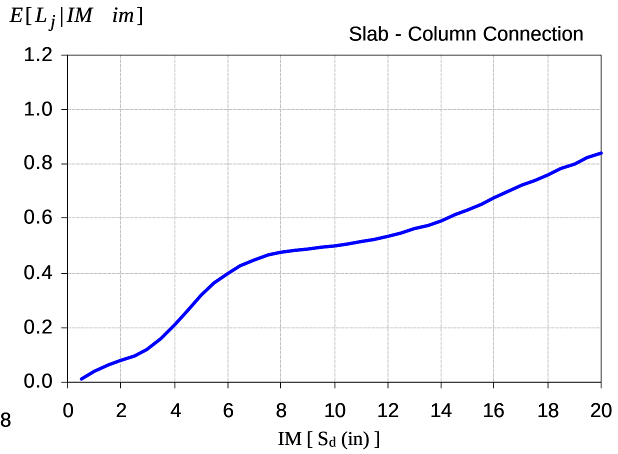

Figure 8. Changes in the expected loss of the slab – column connection conditioned on the intensity measure with the changes in the level of intensity.

To evaluate the annual expected loss the conditional expected loss on *IM*, E [L_j | *IM*], will be integrated over all possible seismic rates of exceedance:

$$E[L_j] = \int_0^\infty E[L_j \mid IM] \left| \frac{dn\,(IM)}{d\,IM} \right| d\,IM \qquad (4)$$

in which, the E [L_j | *IM*] can be computed from equation (4) and | d ν(*IM*) / d *IM* | is the derivative of the hazard curve at the site.

6 SENSITIVITY ANALYSIS ON SOURCES OF UNCERTAINTY

Three main sources of uncertainty influence the expected loss of a component; the uncertainty in the seismic hazard at the site, the uncertainty in the demand parameter and the uncertainty in the damage states. It should be noted that the uncertainty in cost only influences the estimation of the rate of exceedance of the loss and not the component expected loss. Given that the major portion of the uncertainty in the seismic hazard has already been included in the hazard curve, a sensitivity analysis on the other two sources of uncertainty has been accomplished. In the analysis, first we consider that the dispersion in the damage is assumed constant and the dispersion in the demand ranges from half of the original dispersion to twice of that amount. In another sensitivity analysis, the dispersion in demand is constant and the dispersion in the damage ranges from half of the original dispersion to twice of that value.

Table 1 shows the changes in the expected loss of the slab-column connection due to either of the described sensitivity analyses. As can be seen from the table, for this component and for the types of uncertainties considered in the estimation of demand parameters and of vulnerability functions, the uncertainty associated with the vulnerability functions plays a significantly more important role in the component annual expected loss. For example, over estimating the uncertainty in the demand by 100 % changes the expected loss by only 12 %, the value in row 3 column 4 of table 1, whereas overestimating the uncertainty in the damage by 100 % changes the annual expected loss by 76 %, the value in row 4 column 3.

7 ANNUAL EXPECTED LOSS OF THE BUILDING

The annual expected loss for the building can be computed summing over all the losses from structural, non-structural and content components in the building:

$$E[L_{Bldg.}] = \sum_j \sum_{i=1}^{m} \int_0^\infty \int_0^\infty E[L_j \mid DS = ds_i]\, P(DS = ds_i \mid EDP_j = edp)\, P(EDP_j > edp \mid IM = im) \left| \frac{dn(IM)}{dIM} \right| dEDP\, dIM \qquad (5)$$

The summation can be performed at any of the steps described earlier. For example, the summation can be done over component expected loss, conditioned on the intensity measure:

$$E[L_{Bldg.} \mid IM] = \sum_j E[L_j \mid IM] \qquad (6)$$

in which, E [L_j | *IM*] is the component expected loss, conditioned on the intensity measure, and E [$L_{Bldg.}$ | *IM*] is the building expected loss conditioned on the *IM*.

Figure 9 depicts a schematic view of equation (6). Figure 9 can be compared to a pushover curve, which is the current state of practice in performance-based design. In a pushover curve a measure of global response, such as roof displacement will be plotted against a measure of ground intensity, such as the base shear of the structure. The structural engineer attempts to relate such a graph to what will actually happen in a facility due to earthquakes with certain credible levels of intensity. Using a graph such as the one presented in Figure 9, however, will produce a better platform for the facility stakeholders to understand what will actually happen in the building due to earthquakes with certain levels of intensity and to make informed decisions about their facilities.

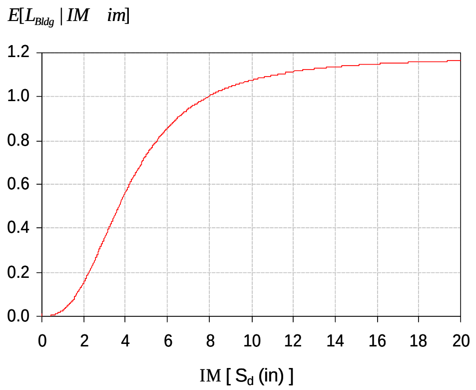

Figure 9.Changes of the building expected loss conditioned on the intensity measure with changes in the level of intensity.

Table 1. Summary of the results of the senisitivity analyses.

X DM | EDP X EDP | IM	0^*	0.5	1	2
0^*	0.54	-	0.57	-
0.5	-	0.60	0.62	-
1	0.95	0.97	1.00	1.12
2	-	-	1.76	1.83

* The values presented are the factors to multiply the orignal dispersion.

** The values are the ratio of the component loss with new dispersions to the ones computed with original dispersions.

8 SUMMARY AND CONCLUSIONS

A methodology is presented to evaluate the annual expected loss for buildings. The methodology is based on estimating the expected loss for individual components. A step-by-step procedure is proposed, which is capable of producing useful intermediate results along the way of evaluating the annual expected loss. The procedure is applied to a PEER testbed structure. Specifically, the annual expected loss associated with a typical slab - column connection located in the second story of the testbed structure is evaluated.

One important advantage of the proposed methodology is that the sources of uncertainty influencing the final result can clearly be identified and investigated. A sensitivity analysis is performed on the influence of the uncertainty associated with the demand parameter and the one associated with the vulnerability functions on the annual expected loss of the slab-column connection. Results show that for the sources of uncertainty considered in this study and for the case of a slab-column connection, the uncertainty in the vulnerability functions has a more significant effect than the one in the demand parameter.

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