Sensitivity of Reinforced Concrete Frames to Uncertain Component Capacity

Tae-Hyung Lee[1], Hak-Eun Lee[2], Chang Soo Lee[3], and K. M. Mosalam[4]

Abstract

Identifying significant structural components under seismic loading, in particular, in a probabilistic approach is of interest to many structural engineers. The first-order second moment method can be used to achieve this goal by estimating uncertainty in the seismic demand of a structural system induced by capacity uncertainties of each structural component. Significant structural components are those to which the seismic demand of the structure is more sensitive than it is sensitive to other ones. The developed procedure demonstrated by a ductile reinforced concrete frame shows that it is computationally effective and robust in terms of identifying significant structural components.

Introduction

Identifying the significant structural components to a specific seismic demand of the structural system (referred to as engineering demand parameter, EDP) is an important step of a performance-based earthquake engineering (PBEE) methodology. The quantification of the importance of structural components should consider the location of each individual component in the system, the stiffness contribution of each component, and the probabilistic distribution of the strength and deformation capacities of each structural component. This identification can be also useful for the decision-making process, in particular, for the rehabilitation of an existing structure within the framework of PBEE.

In spite of a large number of publications on probabilistic evaluation of structural systems, e.g. (Chryssanthopoulos et al. 2000), effort of assessing the importance of structural components on the system performance is very rare. In this study, the propagation of uncertainty in the strength and deformation capacities of structural components to their structural system with respect to its EDP is investigated using the first-order second moment (FOSM) method. The procedure of evaluating EDP sensitivity to individual components is demonstrated using a ductile reinforced concrete (RC) frame. EDP uncertainty induced by uncertainty in each structural component is used to identify significant structural components of the case study RC frame to a specific EDP. Significance of a structural component is defined in terms of the EDP sensitivity where a more significant component corresponds to a higher EDP sensitivity to this particular component.

Procedure of Identifying Significant Components

Uncertainties in material properties and the geometry are the major source of capacity uncertainties of the structural component that partly causes EDP uncertainty of a structural system. In this study, the strength and deformation capacities of a structural component are defined in terms of the moment-curvature relationship at critical cross-sections of the component, namely at both ends for beams

[1] Assistant Professor, Dept. of Civil Engineering, Konkuk University, Seoul, Korea.
[2] Professor, Dept. of Civil, Environmental, and Architectural Engineering, Korea University, Seoul, Korea.
[3] Professor, Dept. of Civil Engineering, University of Seoul, Seoul, Korea.
[4] Professor, Dept. of Civil and Environmental Engineering, University of California, Berkeley, CA, USA.

and columns in a typical RC frame structure. The stochastic fiber element model (Lee and Mosalam 2004) and OpenSees (McKenna and Fenves 2001) are combined to develop probabilistic section models of structural components. The computational model of the structural system is developed by a plastic hinge model whose behavior is dictated by the probabilistic section model. The FOSM method is used to compute EDP uncertainty of the structural system. Fig. 1 illustrates the procedure of the system evaluation using probabilistic section models in the context of the FOSM method to estimate EDP uncertainty. In this procedure, EDP uncertainty induced by uncertainty in one of the structural components is a measure of sensitivity of EDP to the corresponding component. From this measure, relative significance of each component to the system EDP can be identified and ranked accordingly.

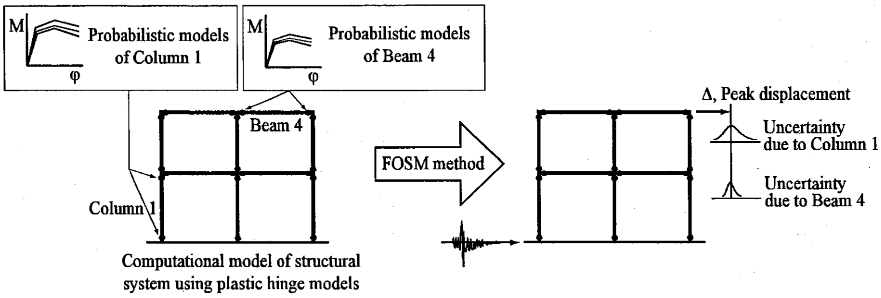


Figure 1. System evaluation procedure using probabilistic section models and FOSM method.

FOSM Method

Let's consider $Y = g(\mathbf{X})$ of a random vector $\mathbf{X} = [X_1, X_2, \ldots, X_n]^T$ having the mean vector $\boldsymbol{\mu}_\mathbf{X} = [\mu_1, \mu_2, \ldots, \mu_n]^T$ and variance-covariance matrix VC[**X**]. The first and second moment approximations of Y by the FOSM method are $\mu_Y \approx g(\boldsymbol{\mu}_\mathbf{X})$ and $\sigma_Y^2 \approx \nabla^T g(\mathbf{X}) \mathrm{VC}(\mathbf{X}) \nabla g(\mathbf{X})$ where $\nabla g(\mathbf{X}) = [\partial g/\partial x_1, \partial g/\partial x_2, \ldots, \partial g/\partial x_n]^T$ is the gradient of $g(\mathbf{X})$ with respect to **X**. In this study, the σ_Y^2 is selected as the sensitivity measure of Y with respect to **X**. In this way, dispersions of the random variables can be considered, as well as the gradients of the function with respect to those random variables. Note that the correlations of **X** are considered in estimating σ_Y^2. In this study, a finite element model (FEM) is used as the method to develop the function g in the above derivation. Moreover, the gradients of g are numerically obtained using the finite difference approach. More details of the FOSM method and its application to EDP sensitivity can be found in (Lee and Mosalam 2005).

Case Study: Ductile RC Frame

The selected ductile RC frame, referred to as VE, was tested by Vecchio and Emara (1992). This frame is a two-story, one-bay RC frame which consists of beams and columns with rectangular cross-sections, as shown in Fig. 2. Nominal material properties are listed in Table 1 as well as corresponding probability distribution properties adopted from various literatures, e.g. (Mirza et al. 1979).

Probabilistic Section Models of Structural Components

Force boundary conditions of typical structural components are identified according to the load setup consisting of the gravity load and monotonic lateral load as shown in Fig. 3(a). These boundary conditions are the constant axial load, monotonic lateral load, and monotonic axial load, i.e. P_a, P_l, and αP_l, respectively, as shown in Fig. 3(b). It is decided that three typical structural components can be considered for VE frame with analysis parameters listed in Table 2.

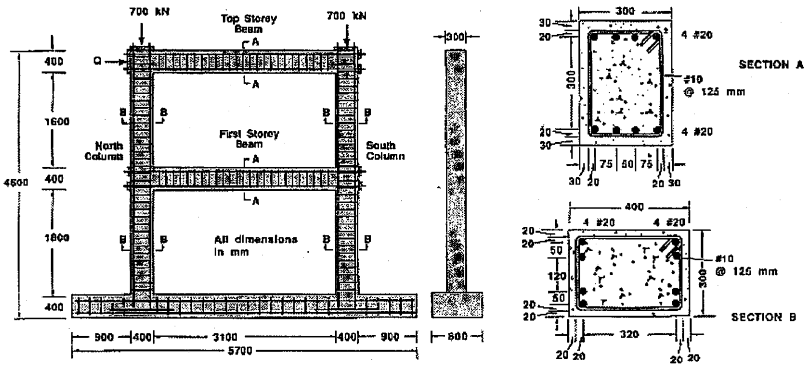
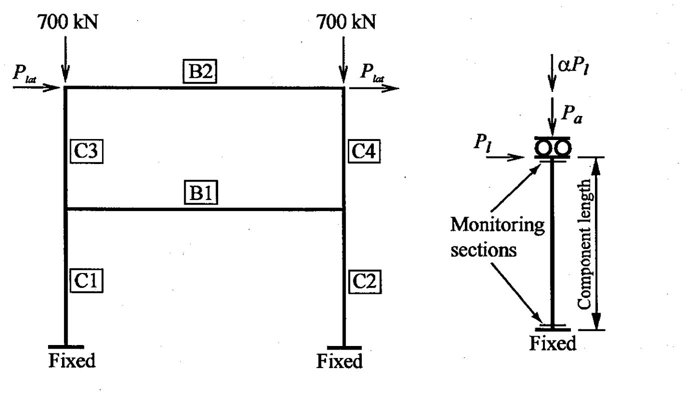


Figure 2. Design details of VE frame (Vecchio and Emara 1992) (1 in = 25.4 mm).

Table 1. Nominal material properties and assumed probability distributions of VE frame.

Property	Nominal value	Mean	COV[g] (%)	Distribution
(a) Concrete				
Compressive strength[a]	4,350 psi	4,036 psi	15	Normal
Initial modulus of elasticity[b]	3,984 ksi	3,984 ksi	8	Normal
(b) Longitudinal reinforcing steel				
Yield strength[c]	61 ksi	60.61 ksi	9	Lognormal
Ultimate strength[d]	86 ksi	86.42 ksi	9	Lognormal
Young's modulus	27,900 ksi	27,900 ksi	3.3	Normal
Ultimate strain	0.07	0.07	20	Normal
(c) Transverse reinforcing steel				
Yield strength[e]	66 ksi	65.83 ksi	9	Lognormal
Ultimate strength[f]	93 ksi	93.86 ksi	9	Lognormal
Young's modulus	27,900 ksi	27,900 ksi	3.3	Normal
Ultimate strain	0.07	0.07	20	Normal

Correlation coefficient of [a] and [b], [c] and [d], and [e] and [f] are 0.8, -0.5, and -0.55, respectively. [g] Coefficient of variation.



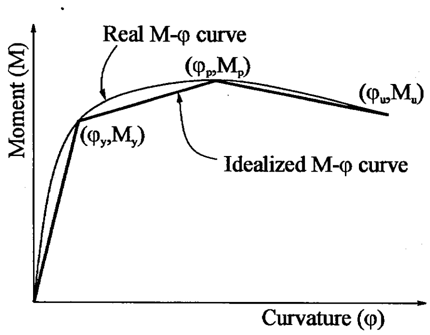
(a) Structural system model of VE (b) Structural component model

Figure 3. Identifying the typical structural components by a linear elastic analysis.

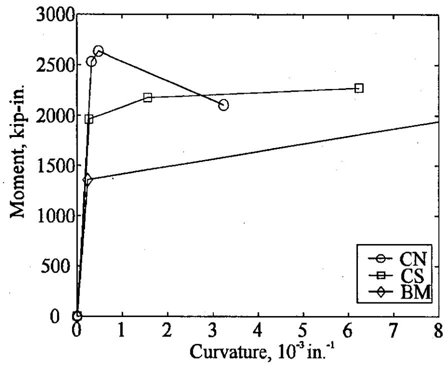
Table 2. Analysis parameters for typical structural components of VE frame.

Component	P_a (kips)	α	Length (in)	Remarks
CN	157.5	1.0 (compression)	78.7	Represents C2 and C4
CS	157.5	-1.0 (tension)	78.7	Represents C1 and C3
BM	0.0	0.0	137.8	Represents B1 and B2

A series of pushover analyses is performed to develop probabilistic moment-curvature relationships at critical cross-sections of each typical structural component using OpenSees and the stochastic fiber element model used to generate OpenSees inputs for Monte Carlo simulation. A set of moment-curvature relationships are generated and idealized by trilinear models (Fig. 4(a)). Fig. 4(b) shows the means of the idealized moment-curvature relationships of the three typical structural components. Means, standard deviations (SD), and correlation coefficients of parameters defining the moment-curvature relationships are obtained. COV's of the moments (M_y, M_p, and M_u) range from 5% to 10%, while those of the curvatures (φ_y, φ_p, and φ_u) range from 9% to 20%.



(a) Idealization



(b) Mean relationships

Figure 4. Probabilistic moment-curvature relationships at critical cross-sections of VE frame.

EDP Sensitivity to Structural Component Uncertainty

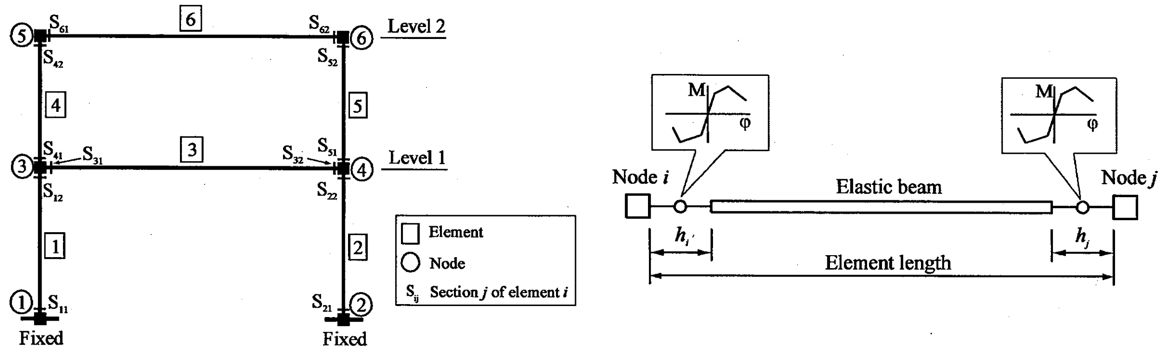
The FOSM method is used to estimate the mean and standard deviation of an. COV of EDP is used as a measure of sensitivity of EDP to individual structural components. A structural component with larger corresponding COV of EDP is considered as more significant than that with smaller corresponding COV of EDP. Based on nonlinear time history analyses under the effect of ensemble of earthquake records, the peak absolute floor acceleration (PFA), the peak absolute floor displacement (PFD), and the peak interstory drift ratio (IDR) are selected as EDPs.

Structural Modeling

The 2D computational model of VE frame is developed using OpenSees as illustrated in Fig. 5(a). All structural components are modeled by a plastic hinge as shown in Fig. 5(b). The behavior of each plastic hinge is dictated by assigned moment-curvature relationship. A set of 20 ground motion profiles are used for nonlinear time history analyses.

Significant Cross-Sections

The significance of each cross-section to the EDPs at various IM levels is investigated. Each cross-section is considered as a random variable and COVs of an EDP induced by each random variable are compared to identify relative significance of each cross-section. The relative significance of a cross-section is expressed as the ratio of its contribution to EDP uncertainty to the contribution of all components. Mathematically, the contribution of i^{th} cross-section is σ_i^2 / σ_T^2 where $\sigma_T^2 = \Sigma_{j=1}^{n} \sigma_j^2$ for n cross-section.



(a) Overview of the model (b) *beamWithHinges* model

Figure 5. OpenSees model of VE frame.

Figure 6 shows mean relative contributions of cross-sections to EDP uncertainties. From Fig. 6(a), it is observed that S11 and S21 are the most significant cross-sections to PFA_1 for $S_a \leq 0.39g$. The significance of S61 and S62 increases as the IM level increases, while that of S31 and S32 stays at relatively low level as the IM level increases. From Fig. 6(b), it is observed that S11 and S21 are the most significant cross-sections to PFA_2 for S_a=0.25g. Similar to PFA_1, significance of S61 and S62 increases as the IM level increases. Unlike PFA_1, the significance of S31 and S32 PFA_2 is not negligible and varies with the IM level. Overall observations of Figs. 6(c) and (d) are almost identical. For all IM levels, S11 and S21 are the most significant cross-sections to PFD uncertainty, while S31 and S32 are the next significant ones, except for the case for S_a=0.48g where S61 and S62 are equally significant as S31 and S32. From Figs. 6(e) and (f), it is observed that S11 and S21 are the most significant cross-sections to IDR uncertainty for all IM levels. The significance of S31 and S32 to IDR uncertainty does not change appreciably as the IM level increases. Moreover, S31 and S32 are the second significant cross-sections to IDR_1 for all IM levels. The significance of S61 and S62 to IDR uncertainty increases as the IM level increases up to S_a=0.48g and then decreases thereafter.

Several remarks can be made from the observations related to the conditional sensitivity of EDPs to cross-sections of VE frame. These remarks can be summarized as follows: 1) The significance of structural components to all EDPs varies depending on the IM level. In particular, contributions of the top level beam to all EDPs vary within the widest range of all structural components; 2) at lower IM levels (i.e. $S_a \leq 0.2g$), only first story columns and first floor beam are significant to all EDPs implying that the first yielding may occur in one or some of these structural components; 3) both end-sections of the two beams and the bases of the first story columns are significant cross-sections to all EDPs at all IM levels. This agrees with the failure mechanism observed in the experiment; and 4) the bases of the first story columns are the most significant cross-sections to all EDPs at all IM levels except for PFA at higher IM levels where the contributions of the two cross-sections of the top level beam are also significant.

Concluding Remarks

A systematic approach of identifying significant structural component or cross-sections using the FOSM method is developed and demonstrated by a ductile RC frame (referred to as VE). Sensitivity of EDPs (i.e. the peak absolute floor acceleration and displacement, and the peak interstory drift ratio) to individual structural components is estimated using the FOSM method. Uncertainty in the strength and deformation capacities of the component is expressed as probabilistic moment-curvature relationships at critical cross-sections of the component located at its ends. EDP uncertainty induced by each structural component is used to determine which components are most significant to the corresponding EDP. To consider the effect of uncertainty in the ground motion profile, a set of 20 ground motion records are selected and scaled according to specified IM levels.

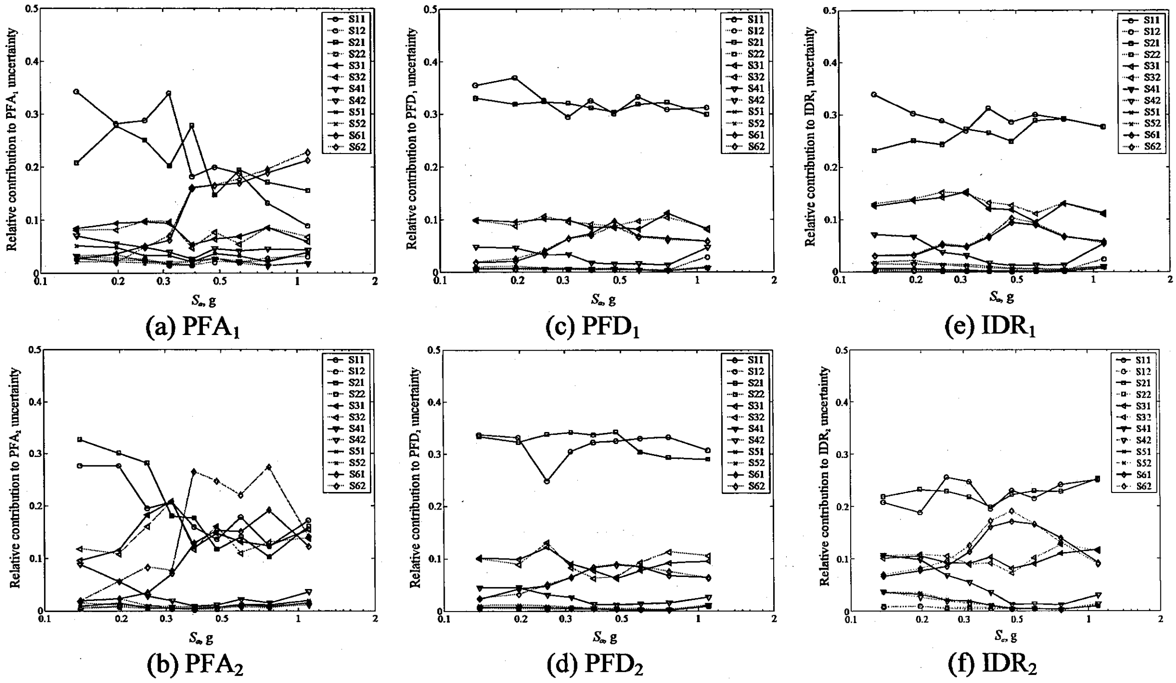


Figure 6. Mean contributions of cross-sections of VE frame to various EDPs.

For VE frame, the two beams and the two first story columns are significant to EDPs at almost all IM levels. In particular, the beam at Level 1 and the two first story columns are more significant than any other structural component to all EDPs at lower IM levels implying that the first yielding may occur in one or more of these three components. Both end-sections of the two beams and the first story column bases are significant cross-sections to all EDPs at all IM levels.

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