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The effect of masonry infills on the seismic response of a four storey reinforced concrete frame—a probabilistic assessment

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ABSTRACT

A relatively simple probabilistic approach for the seismic performance assessment of building structures combines the SAC-FEMA method, which is part of the broader PEER probabilistic framework and permits probability assessment in closed form, with the N2 method. In this approach, the most demanding part of the PEER probabilistic framework, i.e. the Incremental Dynamic Analysis (IDA), is replaced by the much simpler Incremental N2 (IN2) analysis. Predetermined default values for dispersion measures are needed for the practical implementation of this approach. In the paper, the simplified approach is summarized and applied to the seismic performance assessment of three variants of a four storey reinforced concrete frame: a bare frame and two frames with masonry infill, one with openings and the other one without them. The probabilities of exceedance of selected limit states are estimated and discussed. The results of the analyses indicate that the probability of failure of the infilled frames with regularly distributed infill is smaller than that of the bare frame. The beneficial effect of the infill is more evident in the probabilistic analysis than in the deterministic analysis. Of the two infilled frames, the one with openings in the infill has a higher probability of failure.

1. Introduction

One of the methods developed for the seismic risk evaluation of structures is the SAC-FEMA method (SAC is a joint venture of the Structural Engineers Association of California, the Applied Technology Council, and California Universities for Research in Earthquake Engineering, FEMA is Federal Emergency Management Agency), which permits probability assessment in closed form [1], and represents a part of a broader PEER (Pacific Earthquake Engineering Research Center) probabilistic framework [2]. Within the framework of the SAC-FEMA method, the relationship between the seismic intensity measure and the engineering demand parameter is usually determined by Incremental Dynamic Analysis (IDA) developed by Vamvatsikos and Cornell [3]. IDA is a powerful tool for the estimation of seismic demand and capacity for multiple levels of intensity. However, it requires a large number of inelastic time-history analyses (and corresponding detailed data on the ground motion time-histories and hysteretic behaviour of structural elements), and is thus very time-consuming. It is often possible to create summarized IDA curves with less input data and less effort, but with still acceptable accuracy. One possible approach is to determine the seismic demand for multiple levels of seismic intensity using the N2 method [4] which is a practice-oriented nonlinear method based on pushover analysis and inelastic response spectrum. Such an approach yields the Incremental N2 (IN2) curve [5,6], which is intended to approximate a summarized IDA curve. In this paper, this simplified approach for probabilistic seismic performance assessment is summarized and applied to three variants of a four storey reinforced concrete (RC) frame: a bare frame and two infilled frames, one of them with openings and another one without them. The example structures are located at two different locations representing moderate and high seismic hazard. For the determination of an IN2 curve for an infilled frame, the extended N2 method, which is applicable to infilled RC frames, was used [7,8]. The results are compared with the results of the deterministic seismic assessment of the same structures, presented in the companion paper [9].

Despite the relatively large number of seismic reliability studies in the literature, few deal with infilled frames. One example of the seismic reliability of reinforced concrete frames with masonry infills is presented in [10].

2. Framework for probabilistic performance assessment

The simplified probabilistic performance assessment analysis combines two procedures, i.e. the N2 method [4], which is usually employed for a deterministic seismic performance assessment, and a probabilistic assessment in closed form, upon which the SAC-FEMA steel moment frame guidelines [1] are based. In this section the method used for the simplified probabilistic assessment

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is briefly explained. More detailed explanation can be found elsewhere, e.g. in [6].

The SAC-FEMA method is based on some simplifying assumptions, which permit the formulation of a probabilistic assessment in closed form [1]. An additional simplification is introduced by employing the N2 method instead of the IDA analysis for the determination of the relation between the seismic intensity measure and the engineering demand parameter. The curve which represents this relationship is usually called an IDA curve [3]. In the simplified procedure it is substituted by an IN2 curve [5,6]. An IN2 curve is intended to approximate a summarized IDA curve, and is not calculated for a single ground motion. The term "summarized", when related to IN2 curves, applies only to mean or median curves, since the proposed simplified approach is not intended for the determination of dispersion. Default values for the dispersion measures for randomness and uncertainty in displacement demand and capacity have therefore to be used in order to determine the probability of exceedance of a given limit state.

The N2 method is a relatively simple nonlinear analysis method for deterministic seismic assessment of buildings and bridges, which combines pushover analysis of a multi degree-of-freedom (MDOF) model with the response spectrum analysis of an equivalent single-degree-of-freedom model (SDOF). The N2 method has been mainly used for the seismic assessment of structures where the seismic demand (i.e. the engineering demand parameter) for a given seismic intensity is compared with the capacity corresponding to a given limit state. (Note that the expression "performance level" used in FEMA 350 [11] has basically the same meaning as "limit state" according to the Eurocode terminology.) In a probabilistic performance assessment the relationship between the seismic demand and the seismic intensity has to be determined for different values of the seismic intensity measure.

The IN2 curve represents the relation between an engineering demand parameter and a seismic intensity measure. The top displacement is usually used as the engineering demand parameter, and the spectral acceleration, i.e. the value in the elastic acceleration spectrum at the period of the idealized system, represents the intensity measure. The engineering demand parameter and the corresponding seismic intensity measure will be denoted as $\tilde{C}$ and $s_a^{\tilde{C}}$, respectively. The whole IN2 curve can be determined by repeating the N2 approach for increasing ground motion intensity until "failure" occurs. In the simplest but very common case the "equal displacement rule" applies, i.e. the inelastic displacement is assumed to be equal to the elastic displacement of the system with the same stiffness and mass, but with unlimited strength. In such a case the IN2 curve is a straight line (with its origin at the point $(0, 0)$) until "failure" occurs. It is necessary to determine only the point corresponding to "failure". In general, the shape of the IN2 curve depends on the relation between the reduction factor, ductility and period (the R–μ–T relation), which defines the inelastic spectra to be used in the N2 method for the determination of seismic demand. For example, in the case of infilled RC frames, the IN2 curve consists of straight lines, as presented in Fig. 1, for which three points have to be evaluated by the N2 method [7,8] (in Fig. 1, these are the points at the top displacements *a*, *b* and *c*). The idealized capacity diagram with indicated yield and near collapse points is also shown. It is conservatively assumed that the structure fails after the NC limit state is attained. Thus the IN2 line after the NC limit state is horizontal. Knowing the IN2 curve, the engineering demand parameter can be easily linked to the corresponding seismic intensity measures.

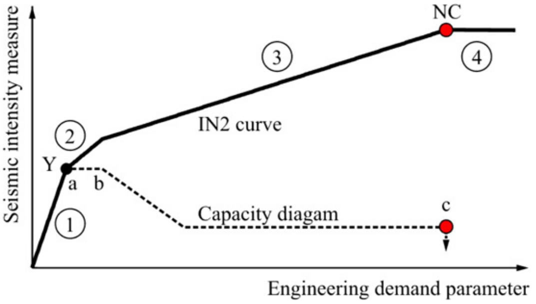

Fig. 1. A typical IN2 curve for an infilled RC frame building. Y and NC indicate the yield and near collapse points.

Once the seismic intensity $s_a^{\tilde{C}}$, which causes a selected limit state, has been determined from the IN2 curve, the x confidence level estimate of the annual probability (mean annual frequency) of the exceedance of a given limit state $P_{LS,x}$ can be determined as [1]

$$P_{LS,x} = \tilde{H}\left(s_a^{\tilde{C}}\right) C_H C_f C_x \qquad (1)$$

$$C_H = \exp\left[\frac{1}{2}\beta_H^2\right], \qquad C_f = \exp\left[\frac{k^2}{2b^2}\left(\beta_{DR}^2 + \beta_{CR}^2\right)\right],$$
$$C_x = \exp\left[K_x\sqrt{\frac{k^2}{b^2}\left(\beta_{DU}^2 + \beta_{CU}^2\right)}\right]. \qquad (2)$$

$\tilde{H}\left(s_a^{\tilde{C}}\right)$ is the median value of the hazard function at the seismic intensity $s_a^{\tilde{C}}$. It provides a median estimate of the annual probability that the seismic intensity will be equal to or exceed the level $s_a^{\tilde{C}}$, i.e. the seismic intensity "corresponding" to the median displacement capacity $\tilde{C}$. k is a parameter of the hazard function, idealized in the form $\tilde{H}(s_a) = k_o \cdot (s_a)^{-k}$, and b is a parameter of the function relating the engineering demand parameter to the intensity measure, i.e. of the so-called IDA curve, or, in the case of the simplified method, of the IN2 curve. IDA or IN2 curve is idealized in the form $\tilde{D}(s_a) = a \cdot (s_a)^b$. K_x is the standardized normal variate associated with the probability x of not being exceeded. For example, the values $K_x = 0$, 1 and 1.28 are associated with 50%, 84% and 90% confidence levels, respectively. β_H is the dispersion measure for hazard. The product $\tilde{H}\left(s_a^{\tilde{C}}\right) C_H$ represents the mean value of the hazard function $\bar{H}\left(s_a^{\tilde{C}}\right)$. Other β parameters represent the dispersion of the engineering demand parameter (i.e. the top displacement) due to ground motion variability (randomness) and due to variability related to structural modeling and analysis (uncertainty). β_{DR} and β_{CR} are the dispersion measures for randomness in the top displacement demand and capacity, and β_{DU} and β_{CU} are the dispersion measures for uncertainty in the top displacement demand and capacity. For practical applications, predetermined default values for dispersion measures, based on statistical studies of typical structural systems, will be needed. In the example shown in this paper, some rough preliminary estimates were used.

3. Probabilistic performance assessment of example structures

3.1. Description of the example structures and the mathematical modeling

The example structures are the same as in the companion paper [9]. A bare and two infilled four-storey plane RC frames have been studied (Fig. 2). The buildings had been designed to reproduce the design practice in European and Mediterranean countries about forty to fifty years ago [12]. The elements of the RC frame were modelled by one-component lumped plasticity elements, consisting of an elastic beam and two inelastic rotational hinges. The infills were modelled by means of two diagonal strut