

## **Probabilistic Seismic Response Sensitivity of Nonlinear Frame Bending-Shear and Infill Model Parameters for an Existing Infilled Reinforced Concrete Structure**

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### **Abstract**

The seismic performance of older infilled frame reinforced concrete structures is influenced by the interaction of different components and mechanisms and is highly sensitive to several modelling parameters. A probabilistic response sensitivity analysis is performed on a case study consisting of an infilled frame structure incorporating state-of the art models of most significant sources of nonlinear behaviour: 1) axial-moment interaction in the frame components, 2) cracking and crushing of infill panels, and 3) infill-frame interaction induced shear failure of columns. Nonlinear fiber section beam column elements are assembled with eccentric ASCE41/FEMA356 infill strut models, hysteretic shear models of captive columns based on EC8 shear strength, and are processed through pushover-based tornado analyses. Probabilistic sensitivity to material parameters at operation, damage, life safety and collapse limit states indicates that modelling parameters of infill and mass source have a key impact on the system response.

**Keywords:** performance-based earthquake assessment, existing buildings, reinforced concrete, infill-frame interaction, shear failure, modelling uncertainty, probabilistic sensitivity, tornado diagrams.

## **1 Introduction**

There are several complex aspects associated with the stock of older infilled frame reinforced concrete structures such as interaction of frame and infill panels [1], [2], presence of unreinforced joints [3], bond-slip and anchorage slip near the joints [4], axial-flexural interaction and flexure-shear interactions in frame components [5],[6], etc. These effects can significantly affect the local and global response and are captured by accurate nonlinear models of structures and components. In general, it is difficult to predict the response of infilled RC frames since their behaviour is

extremely nonlinear and several of the input parameters of the structural models are uncertain.

This research work deals with probabilistic earthquake response sensitivity of infilled frame structures with particular emphasis on randomness in infill-frame interaction, axial-flexural interaction, shear flexure interaction in frame components and focusing on uncertainty [7] associated with modelling parameters at different earthquake intensity levels. Since available methods for analyzing the effects of randomness on structural response require different amounts of computation time, it is important to select an appropriate combination of the method for the treatment of uncertainty in seismic assessment. Some authors carried out studies which combine Monte Carlo simulations with nonlinear dynamic analysis [8], [9], or with pushover analyses [10]. The pushover-based procedures provide a simple yet effective approach for evaluating the seismic response of structures with the consideration of modelling uncertainties. Sensitivity is computed based on the response from a deterministic model, where all the random variables are set to their median values, and on the response obtained setting each random variable to 10<sup>th</sup> and 90<sup>th</sup> fractiles, while simultaneously holding the rest of the random variables to their median values. Studies of this type focused mainly on frame bending and infills nonlinearities, however the possibility that columns fail in shear is very high in the case of older infilled frame structures [11], [12], [13].

The pushover-based sensitivity analysis procedure provides a relatively simple yet effective approach for evaluating the seismic response of structures with the consideration of modelling uncertainties [10]. The results are presented by means of tornado diagrams [8], [9], which are commonly used in decision analysis [14], [15].

## 2 Methodology

The approach described herein is based on the so-called TORNADO plots from nonlinear static analysis carried out on a uniformly infilled frame structure from serviceability to ultimate limit states (O-D-L-C) [16].

<i>RV</i>	<i>Mass</i>	<i>f<sub>y</sub></i>	<i>f<sub>c</sub></i>	<i>E<sub>s</sub></i>	<i>E<sub>c</sub></i>	<i>Fi</i>		<i>Di</i>	
	(factor)	(MPa)	(MPa)	(MPa)	(MPa)	F <sub>y</sub> (KN)	F <sub>max</sub> (KN)	D <sub>y</sub> (mm)	D <sub>max</sub> (mm)
<b>Distribution</b>	normal	lognormal	normal	normal	normal	lognormal		lognormal	
<b>XM</b>	1	340	20.75	210000	20000	48.6	48.6	5	23
<b>COV %</b>	10	10	6.4	3.3	8	30	30	30	70
<b>X10%</b>	0.865	297.5	19.05	201120	18000	32	32	3.29	8.4
<b>X50%</b>	1	338.325	20.75	210000	20000	46.55	46.55	4.79	18.84
<b>X90%</b>	1.125	385	22.45	218880	22000	67.75	67.75	6.975	42.325

Table 01: Random variables (RV) and fractiles for TORNADO sensitivity analyses.

To perform these types of sensitivity analyses it is important to determine 10%, 50%, and 90% fractiles of all considered random variables. The considered material modelling parameters and their distributions are listed in Table 01.

The following input parameters were identified as uncertain: the strength of the concrete ( $f_c$ ) and of the steel reinforcement ( $f_y$ ), the elastic moduli of concrete ( $E_c$ ) and steel ( $E_s$ ), the mass of the structure ( $m$ ), and the strength ( $F_i$ ) and displacement capacity ( $D_i$ ) of the infill panels, (Table 01). The dispersions for the random variables were taken from the literature [17]. The highest coefficient of variation (0.7) was adopted for the maximum displacement capacity of infill panels [18],[19], [20].

To plot the tornado diagrams a number of pushover analyses are performed, with performance point computed based on the N2 method [21]. The main steps to draw tornado plots are:

- i. Nonlinear static analysis is performed by fixing all modelling parameters to their best estimate value (median value) and response parameters such as interstory drift ratio, roof drift and base shear are calculated corresponding to all four limit states by using N2 method.
- ii. The same procedure is repeated and response parameters are calculated by considering one modelling parameter at the 10<sup>th</sup> and 90<sup>th</sup> fractile and all the remaining modelling parameters are set to their median value
- iii. After repeating step two for all considered random variables, the variation in each response parameter (swing) is arranged from increasing to decreasing order corresponding to the responsible random variable; these types of plots are referred to as tornado diagrams [8], [9] based on nonlinear static analysis.

### **3 Case study building and computational model**

Structures designed according to pre-1970s Italian codes commonly exhibit a number of deficiencies related to design for vertical loads only, inadequate confinement in the areas of potential formation of plastic hinges, insufficient transverse reinforcement in the members ends and nodal regions, and inadequate detailing of both longitudinal and transverse reinforcement. The prototype building used here is a 3-story non-ductile concrete frame with unreinforced infills designed according to engineering practice in Italy in the 1970's. An elevation view of the perimeter frames is shown in Figure 4. The building has three bays with masonry infill walls on the perimeter, and bare frames on the interior. More details on the structural design of the prototype building can be found in Gigliotti (2002) [22]. For the present case study we are considering a 2D infilled frame from this prototype structure (Figure 01).

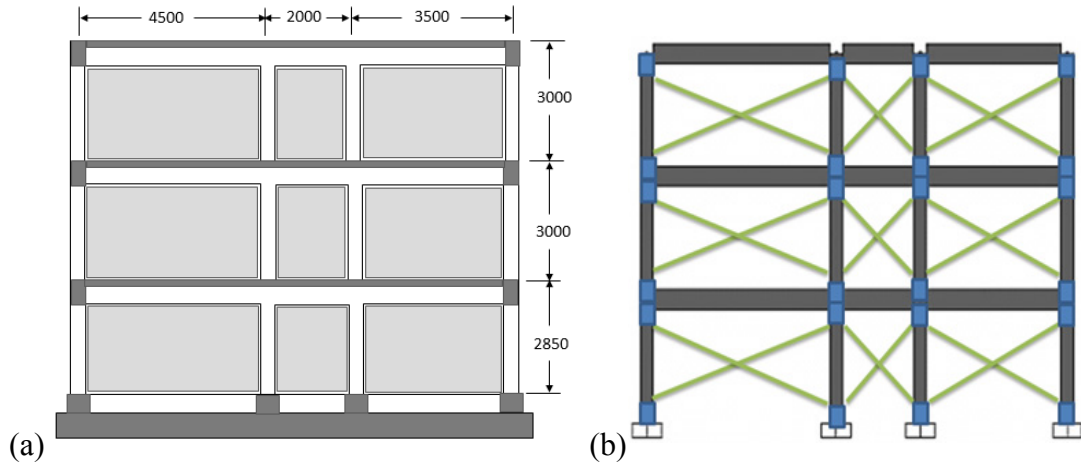


Figure 01: a) Base case 2D frame representative of pre-1970s Italian buildings, b) finite element model idealization.

A detailed nonlinear computational model of the 2D structure has been developed using OpenSees [23] and OpenSeesMP [24],[25], modelling the frame with nonlinear force-based fiber-section beam-column elements [5]. Each element has five integration points. Different model parameters are assigned to unconfined and confined concrete. In order to simulate the localized shear failure of a column, a nonlinear shear force-deformation constitutive model is used at the section level, to make it analogous to the Timoshenko beam [26]. Petrangeli et al. 1999 [27] extended the fiber section model originally developed for the section of an Euler-Bernoulli beam to the uniaxial bending section model of a Timoshenko beam, which is quite rational but computationally intensive. The simplified approach used here is based on the section aggregation (OpenSees [23]) of the phenomenological  $V-\gamma$  law, used by Martino & Spacone 2000 [28], and Marini and Spacone 2006 [6]. In this model bending forces become coupled at the element level because the equilibrium is imposed at the element level. However shear deformations are uncoupled from flexural and axial effects in the section stiffness.

The Giuffrè-Menegotto-Pinto [29], stress-strain model is used for the steel reinforcement. The modified Kent and Park [30], stress-strain relationship is used for both confined and unconfined concrete fibers (with zero tensile strength). Infill panels are modelled using truss elements, the backbone curve is determined according to the ASCE-41 provisions [31] and this law is assigned to bi-diagonal truss elements by using a uniaxial trilinear hysteretic material.

The mass of the structure is modelled using lumped masses at the nodes. Model masses are directly computed from the total dead load including the self-weight and the superimposed dead load. The seismic live loads are accounted for with a 30% contribution in the model mass.

P-Delta geometric transformation is used, and the nonlinear equilibrium equations are solved through the Newton-Raphson solution algorithm with a displacement control integrator. Additional algorithms are used depending on the convergence of the solution.

## 4 Numerical results

Figure 02 shows the probabilistic pushover curves obtained assuming one variable as random, while the remaining modelling parameters are set at their median value. For comparison of results the pushover analysis is also performed considering all variables at their median values.

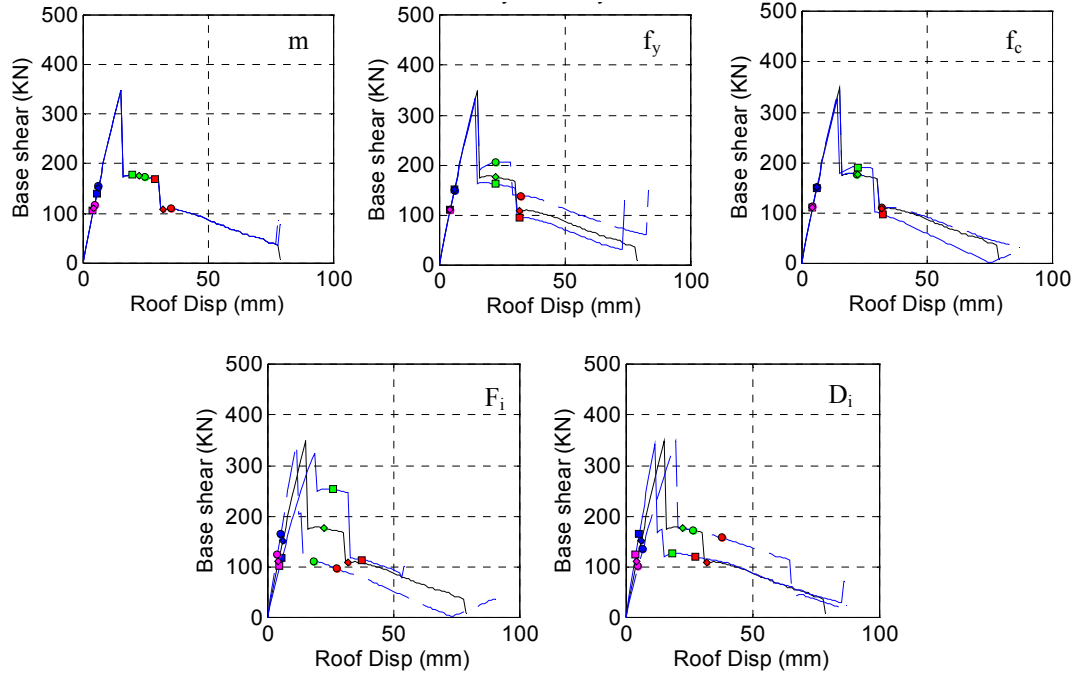


Figure 02: Pushover curves with O, D, L, C limit states demands for the infilled frame, for the base-case model and for the models where each random variable is set to their 10<sup>th</sup> and 90<sup>th</sup> fractiles.

Tornado diagrams are represented for each of the selected engineering demand parameters (EDPs) considered here (roof displacement, maximum interstory drift ratio and base shear). The EDPs are evaluated at code mandated serviceability and ultimate limit states by using the N2 method (Figure 03).

For almost all response parameters and at all limit states, the infill characteristics and mass source show larger uncertainty swing as compared to other modelling parameters. For base shear at L and C limit states in addition to infill characteristics the yield strength of steel also produces larger swings.

The maximum variation observed in the fundamental period of the structure is around 13% while the variation in maximum capacity of the frame is around 7%. Similarly base shear and roof displacement variation at different limit states showed that the maximum swing is observed at L and C limit states when the system becomes highly nonlinear.

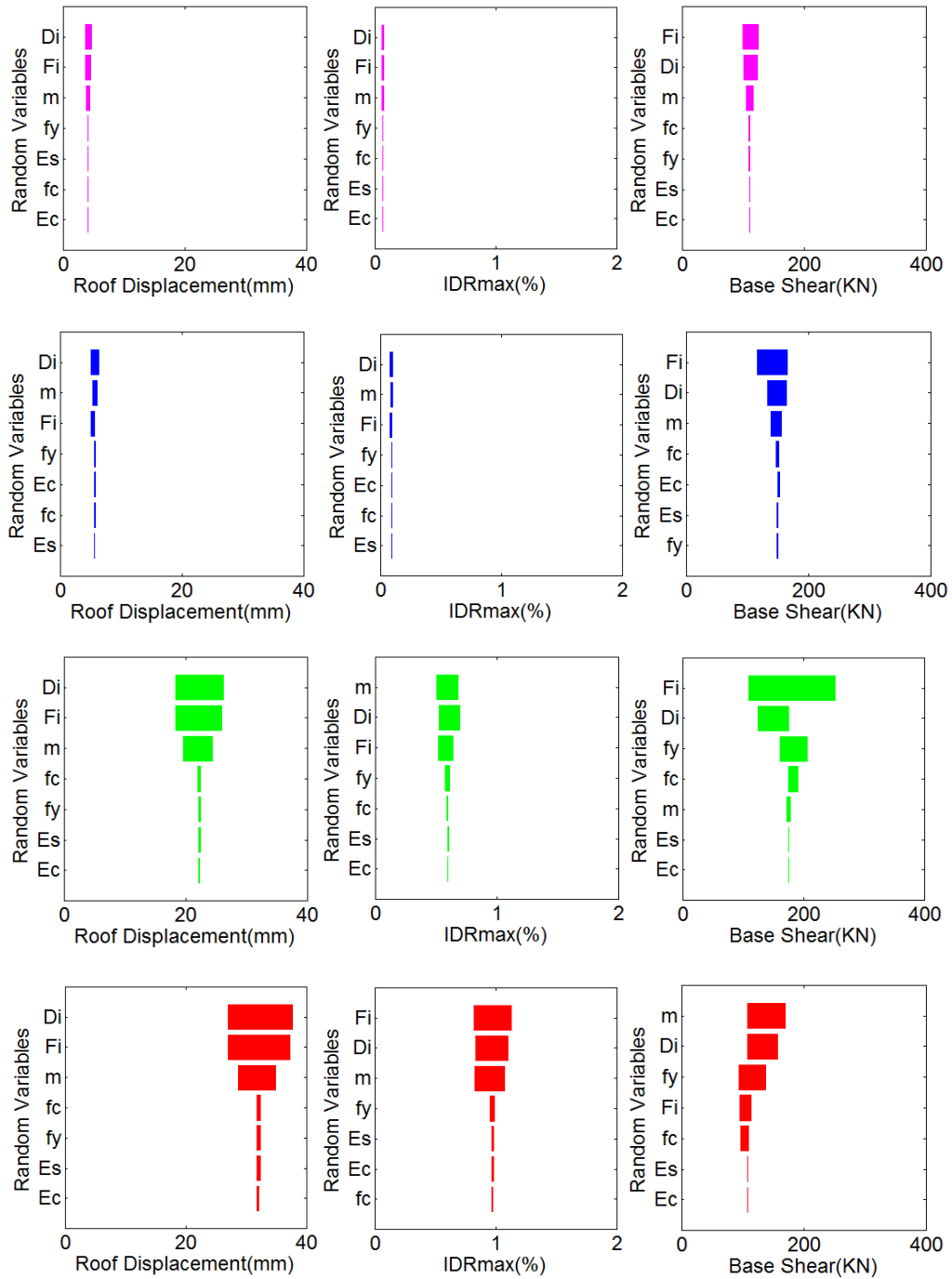


Figure 03: Tornado plots at O (pink), D (blue), L (green) and C (red) limit states from nonlinear static analysis.

## 5 Conclusions

This paper presented seismic response sensitivity analyses for a case study of an older infilled frame structure incorporating state-of the art models of most significant sources of nonlinear behaviour: 1) axial-moment interaction in frame components, 2) cracking and crushing of infill panel and 3) infill-frame interaction induced shear failure of column. Probabilistic sensitivity of the response through tornado plots at reference limit states (operational, damage, life safety and collapse) point out that the infill characteristics (such as infill stiffness, maximum strength and displacement capacity) and the mass source have the greatest impact on the seismic response parameters.

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