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PERFORMANCE-BASED SEISMIC DESIGN AND ASSESSMENT OF IRREGULAR-PLAN RC BUILDING STRUCTURES-A CASE STUDY

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Abstract- Many buildings nowadays have irregular forms in both elevation and plan. Past seismic studies show that buildings suffer severe damage during earthquakes due to torsional irregularity. Provisions in different earthquake codes about torsional irregularity are based on a simplified analysis by the use of expected parameters that can reflect the effect of torsion on the dynamic behavior. This paper was introduced to investigate the torsional behavior of RC asymmetric structures designed for earthquake using Capacity Spectrum Method (CSM) based on performance, in which a modal pushover analysis is performed under the action of inertial forces describing the variation of the moment-rotation of the structure (pushover in torsion). The results obtained in terms of story drifts and rotations are compared to the Nonlinear Response History Analysis (NL-RHA). The obtained results show the benefit of the capacity spectrum method for estimating the seismic demands of the structure and the effectiveness of this method seems to be bearing fruit if when taking into account the contribution of the higher modes to the response by adopting adaptive lateral load pattern.

Keywords: Capacity spectral, Torsion, Pushover, Inertial forces, response history analysis.

1-Introduction

It is customarily acknowledged that the nonlinear time history analysis (NL-RHA) is the most accurate structural analysis method for seismic evaluation and design of buildings. Despite this significant advantage, due to the complexities of this method such as large number of results and large amount of time to perform the analysis, professionals prefer to use an alternative method. In fact, Pushover analysis has currently become the preferred analysis procedure for performance based design and evaluation of buildings, the procedure is relatively simple and takes into account the post-elastic behavior. It provides sufficient information about the seismic stresses imposed by the specific ground motion on the structural system and its components [7, 10].

In the context of seismic action, several cases of building collapse due primarily to torsion have been observed following major earthquakes. This torsion problem is created either by the irregular shape of the building, or by the offset of the center of gravity, compared to the center of rigidity, thus producing during an earthquake additional stresses to the horizontal forces. When the displacements thus generated exceed the deformation resistance of the structural elements, the latter break and, losing their bearing capacity, lead to the collapse of the building. The further the element is far away the shear center, the more the deformations as well as the displacements are amplified. When these displacements exceed the resistance to deformation of the structural elements, the latter break and, losing their bearing capacity, lead to the collapse of the building. However, even if the center of rigidity and the center of mass are theoretically coincident, the torsion must be considered because an accidental eccentricity, due to a variation of the characteristics (dimensions, masses, loads, etc.), cannot be excluded. For this reason, it is advisable to impart a high torsional rigidity to the structure.

Currently, the Algerian seismic rules [3] consider at each level of the structure an eccentricity with respect to the center of torsion to counter the effect of torsion on the dynamic behavior. Current seismic standards [6] also suggest the use of static non-linear (or pushover) methods similar to temporal dynamic methods, but where the difficulties of time-step calculation are avoided. These approaches combine a non-linear static analysis and a response spectrum analysis [7]. In this work, we propose a new simplified approach for the analysis of the non-linear dynamic behavior of asymmetric reinforced concrete structures [17] into three steps. First, a pushover analysis is carried out thanks to OpenSees software [13], under a distributed lateral action describing the variation of the lateral displacement of the structure according to the base reaction. The next step is to perform a response spectrum analysis that represents the seismic demand. Finally, by an iterative process, one seeks the intersection between the capacity diagram obtained by the pushover analysis and the inelastic response spectrum converted into acceleration-displacement format.

The aim of this work is therefore to determine the response of an asymmetric spatial structure by this new capacity approach. The modeling adopted consists of a semi-local discretization using multifiber beam elements [12], and the use of constitutive laws based on the theory of damage and plasticity for the concrete and steel respectively. The results obtained in terms of moments-rotation, displacements and inter-story rotations are then compared with the results obtained by the temporal dynamic analysis

2- Structure modelling and material behavior

The structure studied in this work is a RC frame reinforced concrete building of 6 floors, designed according to the CBA93 regulations [4].

A three-dimensional (3D) finite element model of a RC structure is performed and implemented in OpenSees [13].

The plan view of the building is an L-shaped; its total height is 18.87 m. The geometric characteristics of the building and the reinforcement assigned to the cross-section of the columns and beams are shown in figure 1.

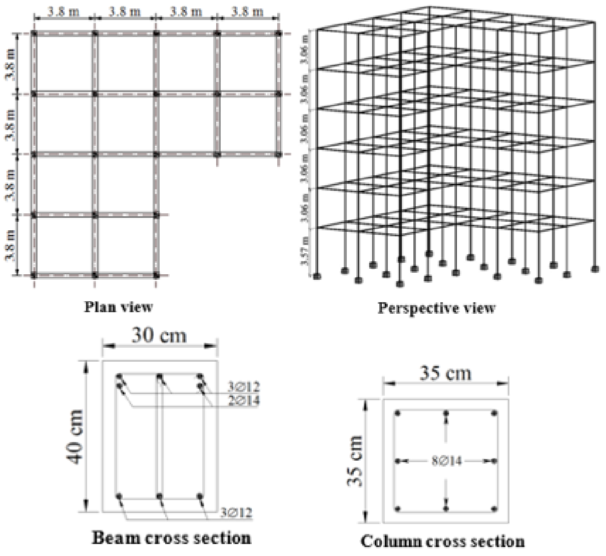

Figure 1: Plan of the designed structure

A simplified modeling strategy based on Euler-Bernoulli multi-fiber beam elements is adopted [12] whose deformation mode is uniaxial as presented in Figure 2.

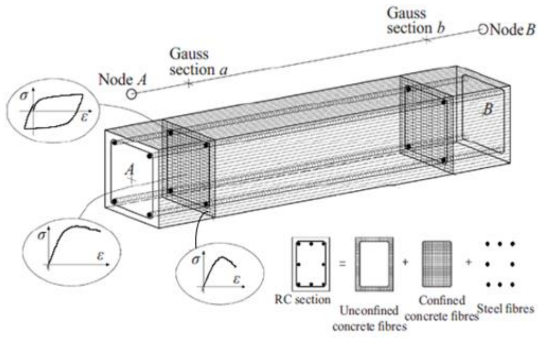

Figure 2: Multi-fiber beam element principle [14].

The constitutive laws used for the concrete and the steel are based on the mechanics of the damage and the plasticity respectively. The concrete model used is that adopted by Priestley [15]. Whereas the behavior of steel is simulated by the uniaxial elasto-plastic model with linear kinematic work hardening. The stress-strain relationships of the two models are shown in Figure 3

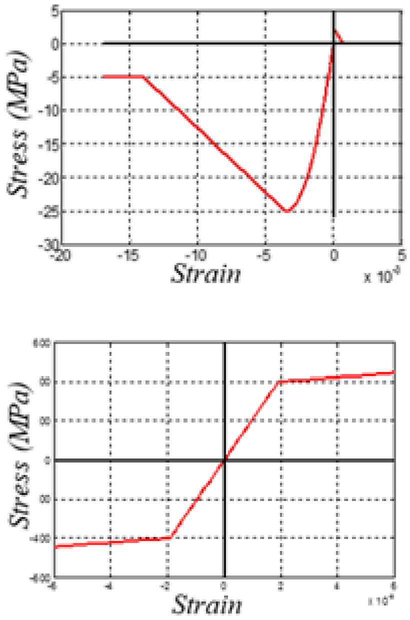

Figure 3: Behavioral laws of concrete and steel

The main characteristics defining the behavior of concrete and steel are summarized in table 1.

Table 1: Main characteristic of concrete and steels

Material	Parameter		
Concrete	Compressive strength	f_{bc} (MPa)	25
	Young's modulus	E_c (MPa)	32000
	Tensile strength	F_{bt} (MPa)	2.1
	Tensile limit deformation	ε_t	1.3x10-3
Steel	Young's modulus	E_s (MPa)	210000
	Yielding stress	f_y (MPa)	400
	Hardening coefficient	α	0.02

The constitutive models are implemented into the OpenSees computational framework [13], known as Concrete02 and Steel02 to model the behavior of concrete and steel respectively.

3- Dynamic analysis

Representative synthetic ground motions were used in this study and in particular for the calculation of the displacement history. Figure 4 presents the generated ground motion, compatible with the spectrum of the horizontal component of the RPA [3] seismic code (corresponding to the firm site S2 set at ground acceleration equal to 0.3g.

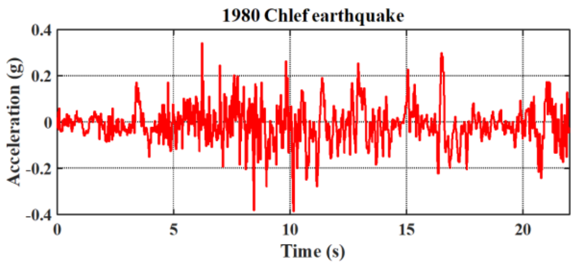

Figure 4: Earthquake recording used in the simulation

The results presented in figure 5 illustrate history response in terms of rotation at the top, for various values of the pic ground acceleration (PGA=0.5; 1.0; 1.75 and 3.0).

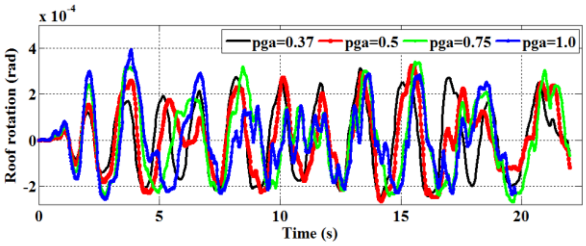

Figure 5: Time history response in displacement and rotation at the top for different values of PGA (0.37;0.5;0.75;1.0)

The proposed method is an approach that allows the evaluation of the seismic performance of structures. The method consists in combining between the Push-over analysis of a multi-degrees of freedom system, subjected to a distribution of lateral forces related to the choice of an appropriate deformation shape, and the analysis of the spectral response of an equivalent system with a single degree of freedom. This procedure therefore represents an extension of the capacity spectrum method developed by ATC-40 [1] and FEMA-273 [8]. Inelastic spectra, rather than elastic spectra with equivalent damping factor and natural period, are used [10].

The study consists in the first step in determining the characteristics of the structure at the elastic limit, in which the pushover curve, linked to the first mode (by assumption), is idealized into a bilinear curve using an iterative procedure based on the principle of equality of areas as shown in Figure 6. This curve is then transformed into a capacity curve corresponding to an equivalent simple oscillator by dividing the shear force at the base Vb by the equivalent mass M* and the displacement by the modal participation factor Γ1.

4- Spectral capacity method

The proposed method is an approach that allows the evaluation of the seismic performance of structures. The method consists in combining between the Push-over analysis of a multi-degrees of freedom system, subjected to a distribution of lateral forces related to the choice of an appropriate deformation shape, and the analysis of the spectral response of an equivalent system with a single degree of freedom. This procedure therefore represents an extension of the capacity spectrum method developed by ATC-40 [1] and FEMA-273 [8]. Inelastic spectra, rather than elastic spectra with equivalent damping factor and natural period, are used [10].

The study consists in the first step in determining the characteristics of the structure at the elastic limit, in which the pushover curve, linked to the first mode (by assumption), is idealized into a bilinear curve and then transformed into a capacity curve corresponding to an equivalent simple oscillator by dividing the shear force at the base V_b by the equivalent mass M* and the displacement by the modal participation factor Γ_1.

$$S_a = \frac{V_b}{M^*} \quad (1)$$

$$S_d = \frac{U_t}{\Gamma_1 \cdot \phi_{t,1}} \quad (2)$$

$$M_1^* = \frac{\left(\sum_{j=1}^{N} m_j \varphi_{j1}\right)^2}{\sum_{j=1}^{N} m_j \varphi_{j1}^2} \qquad \Gamma_1 = \frac{\sum_{j=1}^{N} m_j \varphi_{j1}}{\sum_{j=1}^{N} m_j \varphi_{j1}^2} \quad (3)$$

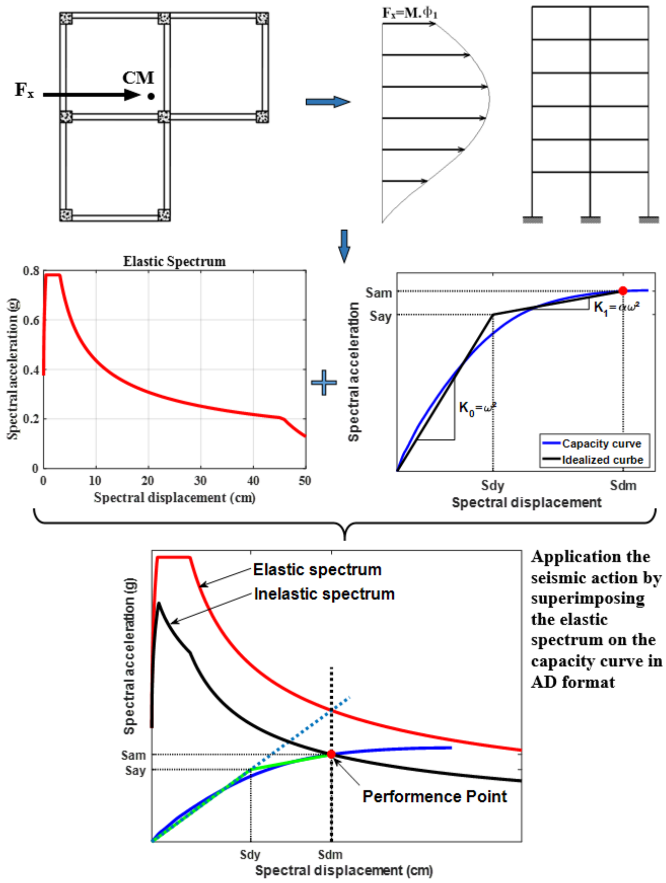

Figure 6: Flow Chart of the used approach

Where Sa is the acceleration imposed on the structure from the earthquake, Ut is the displacement at the level of the roof and ϕt,1 is the amplitude of the first mode of vibration, at the level of the roof.

The seismic performance of the structure is graphically represented by the intersection of the capacity curve and the reduced response spectrum (seismic stress). The elastic period of the system T*=0.62s is greater than the characteristic period of the ground Tc=0.4s. Thus, the principle of equal displacements in the range of the average periods is applied [7]. Knowing that the maximum displacement of the system equivalent to a single degree of freedom is 14.58 cm (Figure 7), the performance point corresponding to the maximum displacement Ut of the structure is estimated at 20.01 cm witch is calculated as follow:

$$U_t = \Gamma_1 \cdot S_{d,perf} \cdot \phi_{t,1} = 1.38 \cdot 14.58 \cdot 1 = 20.01\text{cm}$$

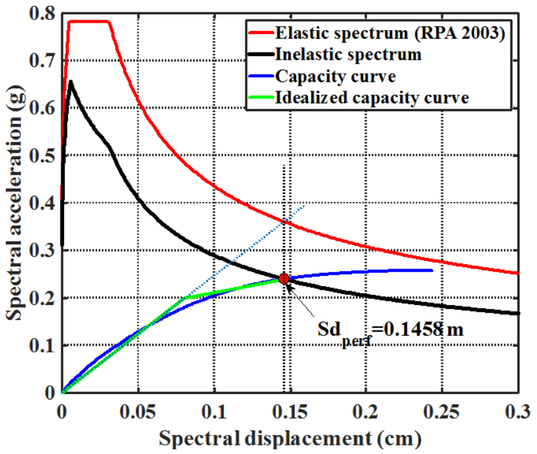

Figure 7: Capacity curve and Performance point

5- Qualification of the method

Generally, the results of the analysis, presented in Figure 8, show that the application of the capacity spectral method in torsion leads, compared to the time history analysis method, to a slight overestimation of the drifts at all the levels, which tends to decrease in the intermediate stages (close to temporal dynamic analysis). This observation comes mainly from the fact that the first mode is privileged. The results show, however, an underestimation of floor rotations and inter-floor rotations, but the envelope of the estimated values is more or less conservative

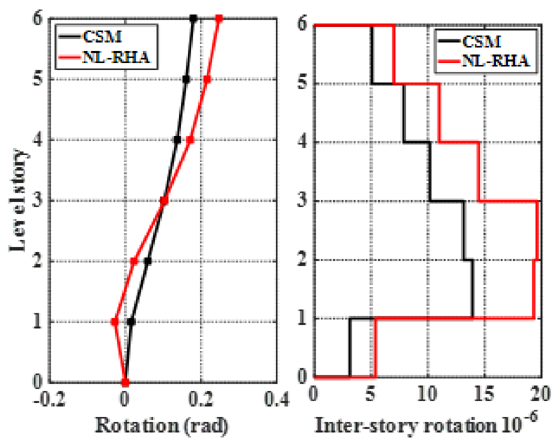

Figure 7: Response in terms of rotation and inter-story rotations at floor level

6-Conclusion

This paper focuses on a non-linear capacity spectrum method to improve the response of irregular plan reinforced concrete structures whose behavior is described using the variation of inter-story rotation of the structure (pushover in torsion).

The Method is based on the assumption that the response is fundamentally controlled by the first mode of vibration and that the shape of this mode remains constant throughout the duration of the seismic excitation. This assumption can sometimes be insufficient, in particular after the yielding of the structure. It is therefore essential, for a better estimation of the seismic response of the structure, to take into account the contribution of the higher modes to the response by adopting adaptive load distributions, which try to follow the redistribution of the forces of inertia related to the effects of variation of the dynamic characteristics during the inelastic response.

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