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REDUNDANCY AND RELIABILITY OF R/C BUILDINGS IN MEDIUM SEISMICITY REGIONS

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ABSTRACT

This paper presents results of inelastic pushover analyses of eight and twelve-story R/C buildings designed and detailed according to current seismic codes for the construction in medium seismicity areas. Two inelastic finite element packages were used in the analyses, namely Zeus-NL and DRAIN-2D. The former employs a detailed fiber modeling, while DRAIN-2D adopts the lumped plasticity modeling approach with member hysteretic rules simulating numerous experimental results of various structural members. The objective is to evaluate the redundancy and reliability of typical R/C buildings complying with current seismic provisions. The investigation employs different reliability factors and redundancy indices from the IBC-2003 code and from prior investigations. Differences between the seismic response from the two modeling approaches adopted in this study are highlighted. DRAIN-2D predictions of the ultimate strength of the eight-story building was found to be 10% lower than that of ZEUS-NL. DRAIN-2D results also indicated a three-story sway mechanism that was not detected by the refined fiber modeling of the eight-story building. Finally, a rational reformulation of reliability/redundancy factor is suggested. The study concluded that buildings adequately design and detailed to current seismic codes for medium seismicity regions have acceptable levels of reliability and redundancy.

Keywords: redundancy, reliability, medium seismicity regions, R/C buildings, nonlinear analysis.

INTRODUCTION

Reliability is the preferable measure of safety for structures in fuzzy conditions of loading and resistance (O'Conner, 2002). As evident of the continuous changes of seismic codes allover the globe, prediction of seismic loads and seismic building resistance are ever fuzzier. Therefore, structural seismic assessment and design is best approached by reliability methods. The aim of the current study is to assess the reliability of R/C framed structures in medium seismicity regions. This is carried out by investigating the seismic reliability of two R/C buildings designed and detailed according to current seismic design provision.

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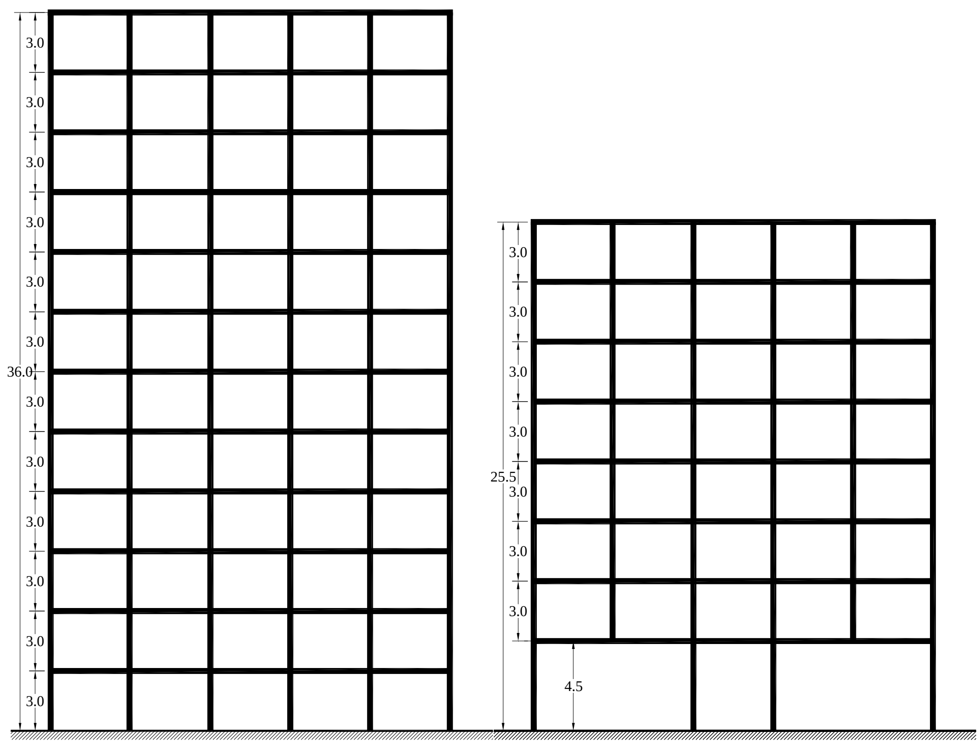
INVESTIGATED BUILDINGS

A representative sample of buildings was selected: a twelve-story regular building and an eight-story R/C irregular one. The two configurations represent common structural systems employed in moderate seismicity regions. Beam and column cross-sections are identical throughout the buildings, except for the ground story beams of the 8-story structure. All beam cross-sectional dimensions are 0.3×0.6 m, while they are 0.3×0.8 m in the ground floor of the 8-story building. The floor system comprises of a 0.14 m thickness solid slabs. The building layouts are shown in Figure 1.

The design seismic action was estimated using ECL (2003) for Cairo. This version of the code follows the provisions of the 2003 version of the Eurocode 8, which is a typical modern seismic code applicable to more than one country with various levels of seismicity and soil conditions. The design PGA is 0.15g and the soil is medium class (C). The importance factor is taken equal to 1.0. The permanent and live loads are 5.5 kN/m^2 and 2.0 kN/m^2, respectively. The concrete and steel strengths are 25 N/mm^2 and 400 N/mm^2, respectively. The two structures were designed and detailed for the purpose of the current investigation using the seismic provisions for ductile frames adopted by ECCS 203 (2001). All detailing and ductility provisions of ECCS 203 were taken into consideration, including the capacity design provision for columns. Figures 2 and 3 show column and beam sizes and reinforcement details of the two buildings.



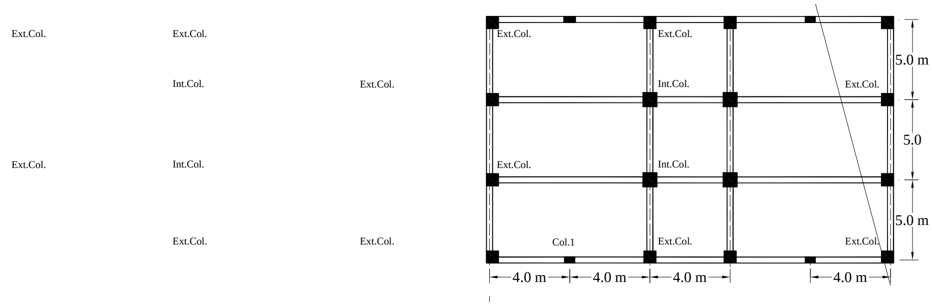


Figure 1. Plan and elevation of the two buildings

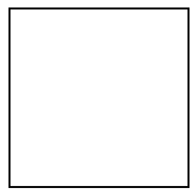


Figure 2: Typical reinforcement details of the 12-story building

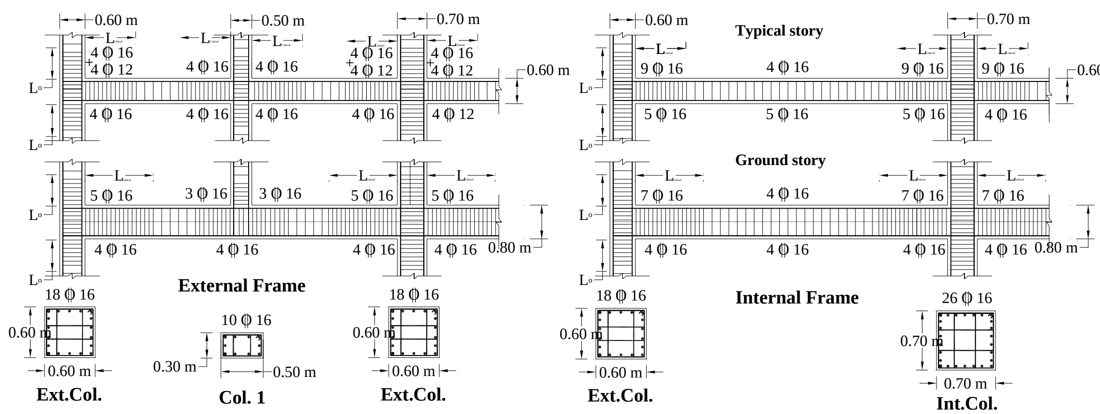


Figure 3: Typical reinforcement details of the 8-story building

ANALYTICAL TOOLS AND MODELING

The first finite element program employed in this study is a PC version of the program ZEUS-NL (Elnashai et al., 2004). The program was developed at Imperial College, UK, and University of Illinois at Urbana-Champaign, USA, for the inelastic analysis of reinforced concrete structures, taking into account the effects of geometric nonlinearities and material inelasticity. The program employs the fiber approach, whereby the spread of inelasticity is efficiently represented. The stress-strain response at each fiber is monitored during the entire analysis. The program has been extensively verified at leading universities is UK and the USA.

A uniaxial constant confinement concrete model is employed in the present work. This is based on the model of Mander et al. (1988), which has a good balance between simplicity and accuracy. The ultimate compressive strength of unconfined concrete, tensile strength, crushing strain and the confinement factor (K) are required parameters for this model. A bilinear elasto-plastic model is used to represent the reinforcement steel. In this simple model, loading and unloading in the elastic range follow a linear function throughout various loading stages with constant stiffness represented by the Young's modulus of steel. In the post-elastic range, a kinematic hardening rule for the yield surface defined by a linear relationship is assumed. Elasto-plastic elements are utilized to model all beams and column members. A cubic shape function is employed in this element to calculate the transverse displacement. This formulation is intended for representing the inelastic cyclic response of R/C members, accounting for material and geometrical nonlinearities. The integration of the governing equations are typically performed over two Gauss points.

The entire buildings are idealized for inelastic analysis. Sections are discretized in steel, unconfined and confined concrete fibers. Lengths of elements are determined according to the distribution of reinforcements. Lumped mass elements are employed to represent the concentrated inertia forces at nodes. The analysis was undertaken in the longitudinal direction where the critical response was expected.

The second analytical tool used in this investigation is DRAIN-2D (Prakash et al., 1993). Since inelasticity in framed structures under seismic excitation is concentrated at beam-column ends, the program adopts the lumped plasticity modeling approach with member hysteretic rules simulating available experimental results of structural members. In this approach, the element response is represented through zero-length plastic hinges located at the end of member ends. These hinges are in the form of nonlinear springs that may be connected either in parallel or in series. This modeling has been implemented in several general purpose nonlinear dynamic analysis programs, including DRAIN-2D (Prakash et al., 1993).

Two performance parameters were selected to define yield on the member and structure levels. Local yield is assumed when the strain in the longitudinal reinforcement exceeds the yield strain of steel. An elasto–plastic idealization of the actual capacity envelope is employed to define the global yield limit state. Since no degradation in lateral strength or a sidesway collapse mechanism were observed from the inelastic pushover analysis, as subsequently discussed, only two criteria are employed to describe local and global structural failure. These are exceeding the ultimate strain (curvature) in any structural member and reaching the interstory drift collapse limit state. Following the EC8 (2003) recommendations, the latter is considered equal to 2.5%.

SEISMIC LOADS

EC8 (2003) and ECL (2003) employ two different elastic spectra for design. The selection of the shape of the elastic response spectrum is based on the magnitude of earthquakes that contribute most to the seismic hazard rather than on the maximum credible earthquake. If the earthquakes that contribute most to the seismic hazard have a surface-wave magnitude, Ms, not greater than 5.5, the design code recommends that the Type (I) spectrum is adopted. When the earthquakes affecting a site are generated by differing sources, two shapes of the spectrum, Type (I) and (II), should be employed to adequately represent the design seismic action.

The typical seismic scenario for medium seismicity regions, such as Cairo and nearby areas, is from shallow earthquakes of magnitude of 5.5. Therefore the elastic spectrum Type (I) is the most appropriate one for design, as recommended by ECL (2003). The seismic load of the investigated building may be represented by three records normalized to the code spectrum Type (I). El Centro 2 (USA, 1979), El Centro 11 (USA, 1979) and Hollister City Hall (USA, 1974) earthquakes may be therefore used. To account for possible earthquakes from other sources, an artificial accelerogram may be also employed to match the code spectrum Type (II). The elastic spectra of these records are depicted in Figure 4 along with the design code elastic spectra Type (I) and (II).

INELASTIC PUSHOVER RESULTS

Inelastic pushover analysis is a powerful tool to assess the inelastic lateral capacity and overstrength (Mwafy and Elnashai, 2002 and Mwafy, 2001). This refined analysis is conducted using the two FE programs employed in this study. Figure 5 shows the capacity curves of the two buildings obtained from Zeus-NL pushover analysis using an inverted triangular lateral load distribution. The two structures exhibit very high overstrength factors as a result of the higher contribution of gravity loads compared with the low seismic actions of medium seismicity regions. Although the lateral capacities of both buildings are comparable, the V/W ratio for the 12-storey regular frame is lower than that for the 8-story structure as a result of its higher gravity load. The total gravity loads used in seismic analysis are 36600 kN and 22680 kN for the 12 and the 8-story structure, respectively.

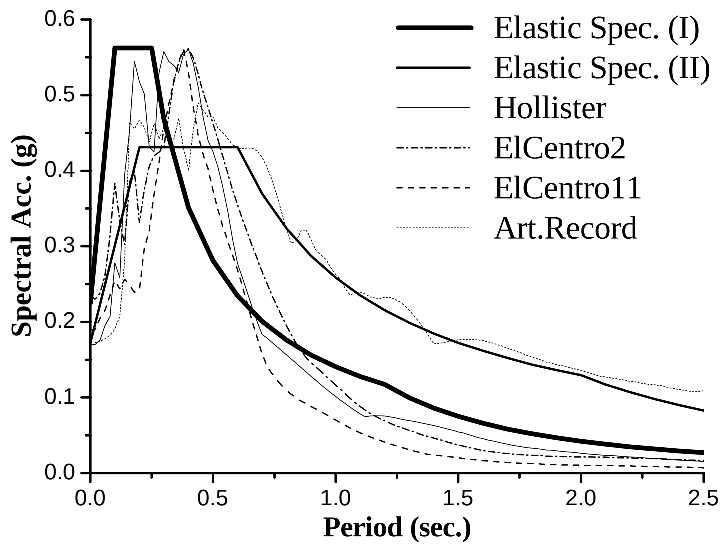
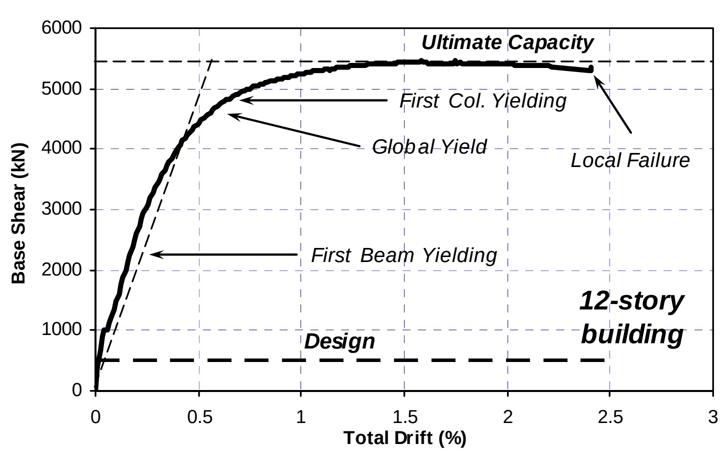


Figure 4. 5% critical damping response spectra of input ground motions



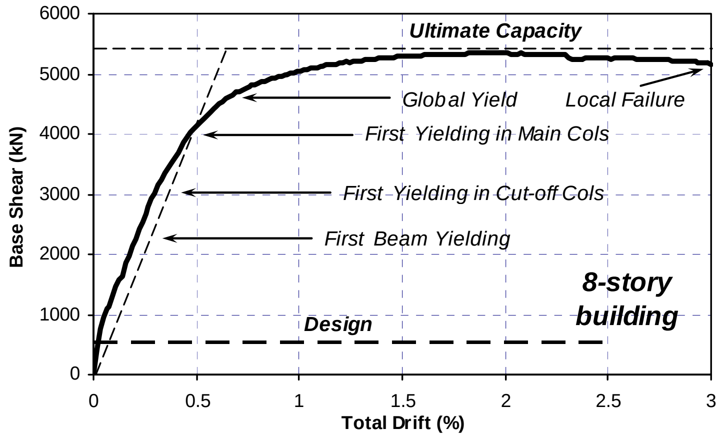


Figure 5. Base shear versus top displacement response of the two buildings obtained from Zeus-NL inelastic pushover analysis

Sequence of first yielding in beams and columns as well as the global yield and collapse limit states are highlighted on the capacity curves depicted in Figure 5. Formation of plastic hinges in columns of external frames is also depicted in Fig. 6. These frames are more vulnerable than internal systems as a result of the higher stiffness of their beams, which attract higher seismic forces. First yield is observed in beams in both structures. However, the unfavorable concentration of plastic hinges in the planted columns of the irregular building is alarming.

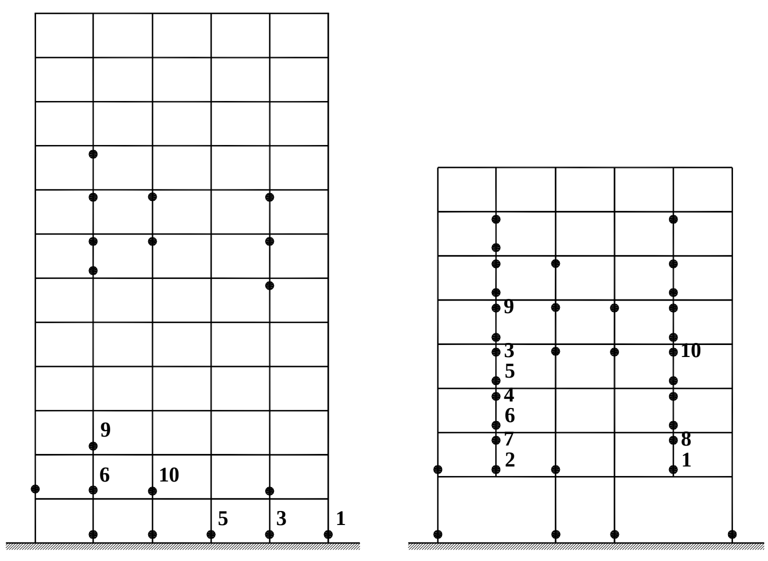


Figure 6: Plastic hinge formation in columns of external frames from Zeus-NL

RELIABILITY AND REDUNDANCY

The seismic design process is not deterministic but rather probabilistic one, because of the uncertainties and fussiness involving load and strength predictions. Uncertainties in determining the highest seismic forces occurring during the lifetime of a structure are obviously high. Moreover, there exist wide variations in lateral strength predictions from different analytical models. This is clear from Figure 7 where different predictions of lateral strengths are obtained for the eight-story building for different modeling appraches (Zeus-NL and DRAIN-2D). In such circumstances, seismic reliability provides an accurate measure of the building safety against earthquakes in terms of the probability of surviving a seismic event, P_s, as defined by Eqn.(1).

$$P_s = 1.0 - P_f \tag{1}$$

where: P_s is the reliability of the structure,
and P_f is the probability of failure of the structure.

Another method for calculating reliability, termed the Second Order Reliability Method (SORM), is used here (Melchers, 1987; Christensen and Murotsu, 1986; and O'Conner, 2002). The SORM method is suitable for cases of limited availability of statistical information about applied loads and building strength. In this method a reliability (or safety) index, β, is used to calculate the structural reliability as shown by Eqn. (2) below:

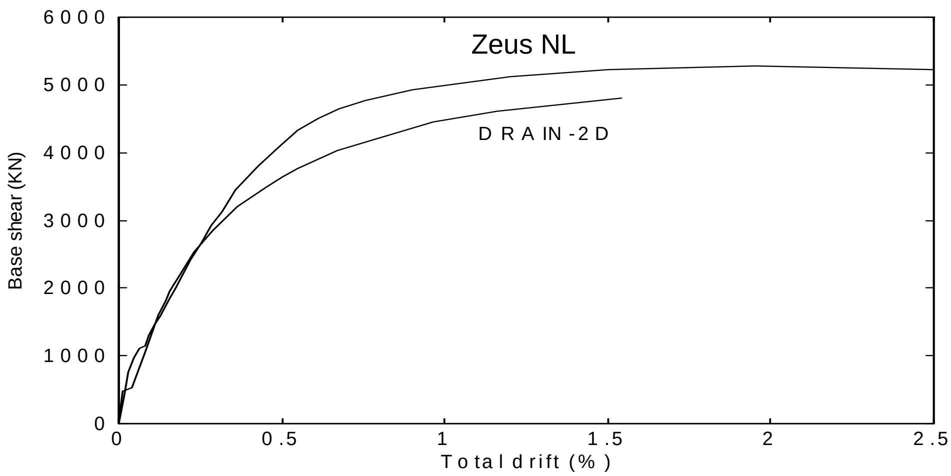


Figure 7. Base shear versus top displacement response of the eight-story building obtained by ZEUS-NL and DRAIN-2D

$$P_s = 1.0 - \varphi(-\beta) \tag{2}$$

where: $\varphi(\,.\,)$ is the cumulative value of standard normal distribution function.
The building codes level of reliability (safety) has been found to corresponds to values of β between 3.5 and 3.7, which gives probability of failure around 0.0001, (Malchers, 1988; O'Connor, 2002).
Redundancy is a characteristic of the statically indeterminate structures with structural members failing in ductile manner. Such structures are capable of withstanding the failures of many of their components before reaching the overall collapse. As current design codes define the system strength as the capacity at the instance of first member yield, redundant structures, which have higher strength, will possess more safety than the irredundant ones. Therefore, and to have a uniform level of safety (reliability) among structures, UBC (1997) and its successors IBC (2000 and 2003) have penalized the less redundant structures by increasing their design forces by as high as 50%, through multiplying the design base shear by a reliability/redundancy factor, ρ, as given by Eqn. (3), with two limiting values between 1.0 and 1.5.

$$\rho = 2 - \frac{6.10}{r_{\max}\sqrt{A_B}} \tag{3}$$

Where r_{max} is the ratio of the highest shear in any bay of the frame to the total story shear, and A_B is the area of the building at base.

In framed structures, the higher the number of ductile frames, the lower the ratio r_{max}; also the higher the number of bays in a frame, the lower the ratio r_{max}. Therefore, buildings with high degree of indeterminacy, yields lower values of ρ; hence lower seismic design forces. Husain and Tsopelas (2004) have introduced two redundancy indices to measure seismic redundancy of framed structures. Namely, the redundancy strength index, r_s, as given in Eqn. (4), and the redundancy variation index, r_v , as shown in Eqn. (5) below:

$$r_s = \frac{S_u}{S_y} \tag{4}$$

$$r_v = \frac{1.0}{\sqrt{n\ (m-1)}} \tag{5}$$

These two equations are to be used in the context of the pushover analysis of the seismic resistance system. Where, S_u and S_y are the ultimate capacity and the capacity at the point of first yield of the system; n is the number of plastic hinges (yielded locations) in one line of resistance (frame) that brought the system to the overall collapse; and finally m is the number of lines of resistance. The values of r_s are larger than 1.0 and could be as high as 4.0. The larger the r_s value, the more redundant the structure. On the other hand, values of r_v vary between 1.0 and zero, with lower values representing redundant structures.

The redundancy of the two building of this work is evaluated according the prementioned procedure. The following table shows the values of ρ, r_s and r_v for the two buildings evaluated according to Eqns. (3), (4) and (5), respectively. The table also shows the values of the reliability index, β, and a redundancy related response modification factor, R_r introduced by Tsopelas and Husain (2004).

Table (1) Redundancy measures of the two buildings investigated

Building	**ρ factor**	**r_s index**	**r_v index**	**β index**	**R_r factor**
Eight-story	< 1.0	2.20	0.12	3.99	2.54
Twelve-story	< 1.0	2.40	0.09	4.66	2.79

The results of the pushover analysis performed by ZEUS-NL are used in these reliability and redundancy calculations. The reliability index, β, is a function of the redundancy indices r_s and r_v, as well as the coefficient of variation of both the element strength and the seismic loads. The coefficient of variations are given the values of 0.1 and 0.3, respectively.

The values of the reliability and redundancy factors and/or indices shown in Table (1) are indicative to the high level of redundancy inherent in the two buildings. They possess a degree of redundancy does not require increasing their design forces. Moreover, it allows even for seismic force reductions, if the code permits, as evidence of ρ values less than one (negative values of ρ factor are obtained for both buildings). The table values show also that the twelve-story building is more redundant than the eight-story one. Furthermore, the reliability level of both structures are satisfactory as their reliability index β values are larger than 3.7.

Reliability/redundancy factors, ρ, less than 1.0 are typically calculated for framed structures of relatively small or medium floor areas, which can be interpreted as a higher redundancy than the code-assume values in the lateral load system. However, negative values of ρ, that can't be rationally interpreted, may be obtained. Therefore, a formulation that omits this confusion would be well perceived. It is proposed in the current study to reformulate the ρ factor in a ratio format to obtain only positive values lower or greater than the unity. Moreover, the suggested formulation should be function of the redundancy response modification factor, *R*. The proposed reformulation takes the following form:

$$\rho^* = \frac{R_r^o}{R_r} \tag{6}$$

Where, ρ^* is the proposed reformulation of the IBC-2003 ρ factor, and $R^o{}_r$ is the R_r factor of a reference structure with the code least acceptable level of redundancy. From analyzing available numerical investigations on the R_r factor of R/C framed structures, Husain (2001) and Tsopelas and Husain (2004) concluded that a value of 1.75 looks reasonable for the reference redundancy force reduction factor, $R^o{}_r$. Using the new formulation, the reliability / redundancy factor of the two investigated buildings are 0.69 and 0.63 for the eight-story and the twelve-story, respectively.

CONCLUSION

This paper presented the results of inelastic pushover analyses of eight and twelve-story R/C buildings designed and detailed according to the current seismic codes for the construction in medium seismicity regions. Two inelastic FE tools were used in the analysis, namely ZEUS-NL and DRAIN-2D, employing the detailed fiber and the lumped plasticity modeling approaches, respectively. An investigation of the seismic reliability and redundancy of the two buildings was carried out to evaluate their seismic performance. Different reliability factors and redundancy indices from international seismic codes and from prior investigations were used. Based on the presented results and discussions, the following conclusions are drawn:

(1) Inelastic pushover results of ZEUS-NL and DRAIN-2D were not sufficiently correlated, where predictions of the ultimate strength of the eight-story structure using the latter was 10% lower than that of ZEUS-NL.
(2) DRAIN-2D results indicated a three-story sway mechanism that was not detected by the refined fiber modeling of the eight-story building. This clearly shows the wide variation and the uncertainty in strength predictions of R/C structures from different inelastic modeling approaches.
(3) The investigated buildings possessed a higher level of redundancy than the assumed code redundancy level, as observed from ρ values far less than the unity.
(4) The two buildings have high level of reliability (safety) as they have reliability index, β, of about 4.0 or more, which is higher than the code safety level of 3.7.

(5) The study suggested a rational reformulation of reliability/redundancy factor to adopt in seismic codes, as given in Eqn. (6).

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