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A Nonlinear Dynamic Based Redundancy Index For Reinforced Concrete Frames

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Abstract: In almost all codes of practice for seismic resistant design of buildings, a behavior factor is used to reduce design base shear. The behavior factor is affected by several parameters such as ductility, overstrength and redundancy reduction factors. There are two common approaches to assess the effects of redundancy on the strength of a structural system, which are as follows: static pushover analysis and incremental dynamic analysis. The two indices: redundancy strength coefficient and redundancy variation coefficient have been introduced to measure these effects. Simplified methods are developed and presented to calculate these parameters. In this study, the redundancy strength and the redundancy variation parameters are evaluated for the reinforced concrete plane frames with different number of stories, bays and ductility capacities. The investigations indicate that these two parameters are mainly the results of redundancy reduction factors.

Key words: Redundancy, behavior factor, ductility, concrete frames, redundancy strength index, redundancy variation index

INTRODUCTION

Although behavior factor (R) has been an important subject in structural engineering studies in recent years but most important studies in this field get back to the last two decade. Among the researchers in this field. According to this method, to compute the quantity of R by an analytical method, it can be formulated as follows:

$$R = R_A \times R_B \times R_C \times \ldots \times R_N \qquad (1)$$

where, R_A, R_B, R_C,...R_N are parameters such as arrangement of frames, type of structural system, composition of loads, degree of uncertainty, damping, characteristics of nonlinear behavior in structure, characteristics of materials, ratio of building dimensions, failure mechanism and other effective parameters. The range of effective factors in determining R is such that it would almost be impossible to find two buildings with identical behavior factors. In other words, each building has its own unique features. Therefore, instead of adding all effective factors, as mentioned in the behavior factor relation, usually only the factors having more determinant role in the behavior factor are studied. In this study, two main coefficients namely the structural capacity and the force resulting from earthquake are primarily considered and the factors that help increase the capacity and reduce the seismic forces are determined in the following steps.

Separate researches on behavior factor, also known as Uang plasticity coefficient method were accomplished by Uang (1991). Pandy and Barai (1997) studied the structural sensitivity response to uncertainty. They assumed that for every structure subjected to a given loading, the general uncertainty is proportional to the reverse structural sensitivity response; thus, the structural response sensitivity reduces with increasing uncertainty.

Bertero and Bertero (1999) studied uncertainty in the seismic resistant design. In this study, they explained the main concepts of seismic uncertainty and defined the probabilistic effect of uncertainty on structural failure.

Wen and Song (2003) studied the reliability of structural behavior under earthquakes. They believed that when more elements are involved in resistance against lateral load, the probability for collapse of all elements, at the some time, is lower than the case when le elements with equal resistance are involved.

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Husain and Tsopelas (2004a, b) tried to determine structural uncertainty in reinforced concrete buildings. In that, they studied r_s (uncertainty resistance coefficient) and r_v (uncertainty variation coefficient) and their relation with the component's plastic rotation ductility factor (μ_θ). The effects of number of stories and bays, the length of bays and story height were studied as well. They then studied the effect of uncertainty on behavior factor (R_R). Here, the effect of number of stories and bays, bays' length, story height and also the effect of gravity loads on uncertainty coefficient are studied. Even the effect of number of frames present at each lateral load direction has been considered and finally, the procedure to compute uncertainty coefficient using uncertainty resistance and uncertainty change coefficients were studied.

REDUNDANCY

The redundancy concept has been considered by engineers, especially after Kobe, Northridge and Turkey earthquakes, during which many buildings with low redundancy degree were damaged. Therefore, the redundancy topic was introduced seriously and the degree of redundancy in structural systems was considered for seismic design.

There is some information about the useful effects of redundancy in structural resistance, but the efficient methods measurement methods are not available as yet. The effects of three parameters are usually considered to measure redundancy degree, which include:

- Static redundancy degree of system
- The ratio of probability in system failure to parts failure
- Involvement of additional capacity which was not necessary for design

Some researchers studied the effects of redundancy degree with deterministic method; that is, use of nonlinear static analysis. There are few studies in which probabilistic method is applied to determine the effects of redundancy degree using structural reliability.

Seismic redundancy degree (n) for a structural system is actually the number of critical areas (plastic hinges) in a structural system which continue to yield until the structure exceeds the allowable limit leading to emergency disasters like plastic displacement or complete collapse. In engineering problems of earthquake, it is assumed that if all critical points (plastic hinges) yield simultaneously, the structure would fail under earthquake shaking. The redundancy degree is defined using the parallel and serial structural system reliability theory, determining the probability of failure in serial systems by weakest connection model and setting the probability of failure in parallel systems through secure decay model.

Bertero and Bertero (1999) studied the effect of redundancy and redistribution of internal forces in seismic design and stated that a part of behavior factor is originated from redundancy degree and can not be determined independent from overstrength and ductility. They also assumed that when the structure can not withstand gravity loads under the effect of earthquake forces, it would collapse. About structural resistance against displacement due to increasing lateral load, the resistance in the first yielding point is considered and the maximum resistance is predicted using the reliability of displacement capacity.

A structure takes advantage of the positive effects of redundancy degree when:

- Change coefficient in structural demand reduces in comparison to change coefficient in structural capacities
- Addition resistance increase
- Curvature capacity increases in plastic hinges
- A minimum rotation capacity is ensured in all elements of structural system

According to much uncertainty in structural capacity and demand, one of the methods in studying the redundancy of structural systems under seismic loads, is to use the reliability concept. In one kind of structural system without change in materials and configuration, the redundancy degree factor can only influence the reliability on structural stability against earthquake induced lateral loads and the structure behavior factor, seriously. It should be considered that the redundancy degree is different in similar frames. If the size of an element, its reinforcement and implementation details change, the failure mechanism may naturally change, but even for two completely similar frames, redundancy degree will be different for various lateral load models.

Behavior factor used in codes, which reduces the level of elastic forces in the design process and in its primary formulation, is defined in terms of ductility coefficient (R_μ) and the additional resistance coefficient (R_S). Ductility coefficient is computed considering nonlinear response of structural system. The relationships for computing functional ductility coefficient is formulated by some researchers by involving the natural period of structure and its ductility capacity, which are commonly based on nonlinear response change of a multi-story building relative to nonlinear response of a system with single degree of freedom.

The overstrength capacity show the actual lateral resistance in comparison to modeling resistance overstrength may be divided into two general parts. The first part is related to the overstrength resistance modeling until the first hinge yields in a structure and the second part is related to formation of the first hinge until a mechanism for total failure of a structure is developed.

In ATC-19 (1995), the formulation of behavior factor (R) is introduced. This coefficient includes an additional factor (R_R) used to account for the effect of redundancy degree in a structure. These effects include probability effects and others related to structural systems geometry either in a plan or at a point in height. Therefore, behavior factor (R) is equal to:

$$R = R_{\mu}.R_S.R_R \qquad (2)$$

Some effective parameters in redundancy and structural systems reliability are the ratio of demand to the capacity of structural systems, the kind of failure mechanism formed, building high, the number of stories, the length and the number of bays. This study computes the probabilistic and deterministic effects of redundancy through obtaining two redundancy resistance index (r_s) and redundancy variation index (r_v). These two indexes are used in measuring the resistance reduction coefficient from R_R redundancy for structural frames with two-dimensional reinforced concrete.

Redundancy indexes: Redundancy resistance index r_s represent the ability of a structural system in redistributing forces while failure and the capability of a structure in transferring the forces of elements yielded to the elements with higher resistance. This index is a function of static redundancy, ductility, strain hardening and the average resistance of elements in a structural system. Second index having probability nature is an r_v redundancy variations index. This index measures the probability effect of elements resistance on structural system resistance. It is also a function of static redundancy in a structural system and on the other hand is a function of statistical nature in ductility and structural elements resistance. Following variables are used in computing above indexes:

- Base shear in the beginning of yielding system
- Ultimate base shear
- The number of local failure or the number of plastic hinges caused during ultimate failure of structure
- The access of elements curvature to ultimate curvature

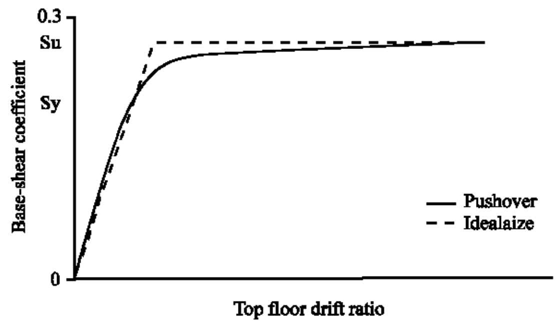

Fig. 1: Base-shear versus top-floor drift curve

Redundancy resistance index: Redundancy resistance index r_s are defined as the ratio of average ultimate resistance ($\bar{S}_u$) to yielding resistance ($\bar{S}_y$). In which $\bar{S}_y$ is the average system resistance non redundant system.

$$r_s = \frac{\bar{S}_u}{\bar{S}_{nr}} = \frac{\bar{S}_u}{\bar{S}_y} \qquad (3)$$

So, in Eq. 3, both parameters $\bar{S}_u$ and $\bar{S}_y$ can be defined with respect to nonlinear static analysis curve (Fig. 1). In a method suggested for this study in studying the effects of redundancy using nonlinear dynamic analysis with increased acceleration, the base shear during failure and yielding is considered. In earlier studies, this method is applied for studying the effects of overstrength. In this study, the system failure standards that will be considered in nonlinear static and dynamic analysis with increased acceleration are as follows:

- Limitations related to storey drift which according to Iran 2800 standard for buildings which period lower than 0.7 sec are limited to 2.5% and for structures with period more than 0.7 sec are limited to 2%
- The index of structure stability which in a structure with high ductility is limited to 0.125 and in a structure with low ductility is limited to 0.25
- The formation of failure mechanism in a structure and collapsing structure
- The access of structure failure index to a number one according to Park and Ang (1985) criterion

In pushover static analyses performed in this study, it is assumed that lateral loads with reverse triangular distribution are inserted into a structure which is proportional to Iran 2800 standard earthquake force. In nonlinear dynamic analysis with increased acceleration, the maximum acceleration of any record is coordinated to a primary number (here, it is considered to be 0.02 g) and in one stage in increased to 0.02 g and the structure is analyzed in every step until when one of the four above-mentioned criteria's is occurred. In this stage, the analysis is stopped and base shear is used during yielding and maximum base shear is used for measuring r_s redundancy resistance index.

Redundancy variation index: The relation between resistance of a structural system and the resistance of its composing elements is obtained using plastic analysis of structure. In this relation, the selection of failure mechanism is important because it can result in non-actual estimates from redundancy variation index. For simplify computations, one sway mechanism according to Fig. 2 is considered. This mechanism is based on the strong column and weak beam assumption which column resistance is at least 20% more than the resistance of beams.

The frame strength (base shear strength) for any failure mode could be represented by the following expression:

$$S = \sum_{i=1}^{n} C_i . M_i \qquad (4)$$

Where:
S = Frame strength (base shear)
n = No. of plastic hinges in the frame resulting from the particular failure mode or collapse mechanism considered
M_i = Yield moment of the structural element where plastic hinge i is formed
C_i = Coefficient with units radians length that is a function of the plastic rotation and geometry of the structure. Equation 4 is of the form of the strength equation of a parallel system type

The mean value of the frame strength can be derived from the fallowing expression:

$$\bar{S} = \sum_{i=1}^{n} C_i . \bar{M}_i \qquad (5)$$

Where:
Mi = Mean value of the strength of the structural element where plastic hinge i is formed

Accordingly the standard deviation of the frame strength σ_f can be obtained from:

$$\sigma_f = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} C_i C_j \rho_{ij} \sigma_{Mi} \sigma_{Mj}} \qquad (6)$$

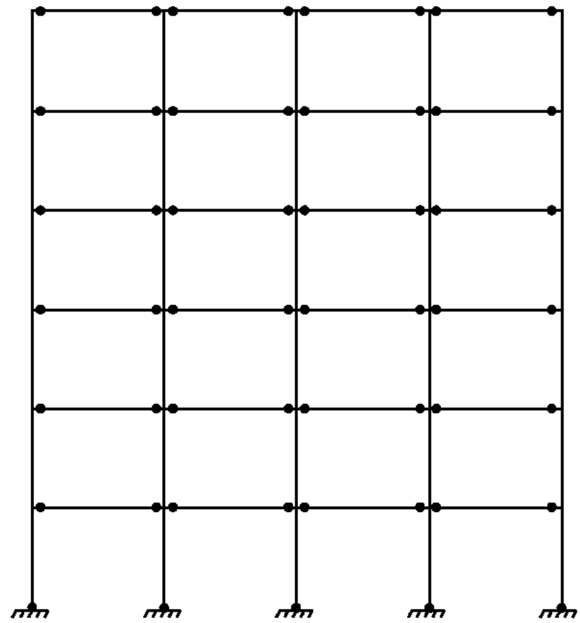

Fig. 2: Sway type failure mode of a generic plane frame

Where:
ρ_{ij} = Correlation coefficient between the strengths M_i and M_j
σ_{Mi} = Standard deviation of the yield moment M_i
ρ_{ij} = 1 for i = j

To further simplify the deviation, a regular multistory multi-bay frame with the following properties is considered:

- The frame is composed of elements with identical normally distributed strengths:

$$\bar{M}_i = \bar{M}_j = \bar{M}_e \qquad (7)$$

$$\sigma_{Mi} = \sigma_{Mj} = \sigma_e \qquad (8)$$

- The correlation coefficient between the strength of any two pairs of elements is the same:

$$\rho_{ij} = \rho_e \qquad (9)$$

- The bays of the frame have identical spans and the stories identical high which result in:

$$C_i = C_j = C \qquad (10)$$

Equation 5 and 6 now become:

$$\bar{S} = n.c.\bar{M}_e \qquad (11)$$

$$\sigma_f = C\sigma_e\sqrt{n + n(n-1)\rho_e} \tag{12}$$

The following relationship between the Coefficient of Variation (CV) of the frame strength υ_f and the CV of the element strength v_e is calculated by dividing Eq. 12 to 11:

$$v_f = \frac{\sigma_f}{\bar{S}} = \frac{\sigma_e}{M_e}\sqrt{\frac{1+(n-1)\rho_e}{n}} = v_e\sqrt{\frac{1+(n-1)\rho_e}{n}} \tag{13}$$

The redundancy variation index r_v is defined as the ratio between υ_f and v_e:

$$r_v = \frac{v_f}{v_e} = \sqrt{\frac{1+(n-1)\rho_e}{n}} \tag{14}$$

For a parallel system with unequally correlated elements, ρ_e could be substituted with the average correlation coefficient $\bar{\rho}$ defined as:

$$\bar{\rho} = \frac{1}{n(n-1)}\sum_{\substack{i,j=1\\ i\neq j}}^{n}\rho_{ij} \tag{15}$$

Therefore, Eq. 14 can be modified using the average correlation coefficient of the strengths of the plastic hinges as fallows:

$$r_v = \sqrt{\frac{1+(n-1)\bar{\rho}}{n}} \tag{16}$$

Hence, the redundancy variation index r_v is a function of the number of plastic hinges n and their average correlation coefficient between their strengths and represents a measure of the probabilistic effects of redundancy on the system strength, its values range between 0 and 1.

For a building structure where a single plastic hinge causes collapse (n = 1), r_v = 1 and the structure under consideration in non redundant. The other extreme value r_v = 0 indicates an infinitely redundant structural system and is reached either when an infinite number of plastic hinges are required to cause collapse (practically n attains large values) or when element strengths in a structure are uncorrelated (the average correlation coefficient in Eq. 6 is zero).

Using Eq. 16 r_v can be estimated from a pushover or dynamic analysis and for a particular value of the average correlation coefficient of the structural member strength.

Redundancy factor R_R: The deterministic effect captured by the redundancy strength index r_s (mainly structural indeterminacy effects) shifts the probabilistic density function of the non-redundant system strength towards higher values to the right, without any shape changes. On the other hand, the probabilistic effects accordingly change the shape of the probabilistic density curve without changing its average value (Fig. 3).

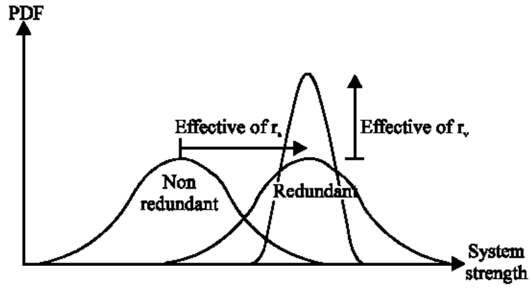

Fig. 3: Effects of redundancy indices r_s and r_v on structural system strength

The overall effects of redundancy on the structural strength may be completely described by the ratio of the ultimate strength of a structural system to the ultimate strength of non-redundant structure. Thus:

$$R_R = \frac{S_u}{S_{nr}} \tag{17}$$

Where:

S_u = Structural system strength which includes all the effects of redundancy

S_{nr} = The same strength but for non-redundant structural system

Assuming that the strength of a structure is distributed normally, the characteristic or design strength of a structural system, its standard deviation, the coefficient k is formed. Therefore, both S_u and S_{nr} may be written as follows:

$$S_u = \bar{S}_u - k\sigma_f \tag{18}$$

$$S_{nr} = \bar{S}_{nr} - k\sigma_{nr} \tag{19}$$

Where:

σ_f = SD of the frame strength

σ_f = SD of the non-redundant frame strength

$\bar{S}_u$ = Average of the ultimate frame strength

$\bar{S}_{nr}$ = Average of the non-redundant frame strength

An expression for σ_f could be obtained as follows:

$$r_v = \frac{\sigma_f}{v_e}\frac{1}{r_s\bar{S}_{nr}} \Rightarrow \sigma_f = r_v r_s v_e \bar{S}_{nr} \tag{20}$$

By virtue of $\bar{S}_u = r_s.\bar{S}_{nr}$; Eq. 19 results into:

$$S_u = r_s\bar{S}_{nr} - kr_v r_s v_e \bar{S}_{nr} = r_s(1 - kr_v v_e)\bar{S}_{nr} \tag{21}$$

Where:

r_v = Redundancy variation index
r_s = Redundancy strength index
v_e = CV of the strength of the structural system elements

Using Eq. 19, 21 and 17 becomes:

$$R_R = \frac{r_s(1 - kr_v v_e)\bar{S}_{nr}}{\bar{S}_{nr} - k\sigma_{nr}} = r_s\left(\frac{1 - kv_e r_v}{1 - kv_{nr}}\right) \tag{22}$$

where, v_{nr} is the CV (coefficient of variation) for non-redundant frame strength.

A non-redundant frame structure could be modeled as a parallel system consisting of ideal elastic-brittle elements. Such a system behaves like a series system, where failure of one element results in the system collapse and that the safety index of the system is equal to that of the element. For a non-redundant system, (n = 1) $v_{nr} = v_e$. Therefore, the redundancy factor (R_R) can be expressed as follows:

$$R_R = r_s\left(\frac{1 - kv_e r_v}{1 - kv_e}\right) \tag{23}$$

For a normally distributed strength not being exceeded 95% of the time, k ranges between 1.5 and 2.5. Without any loss of generality the following values of the CV of the element strength could be used, v_e = 0.08 -0.14. Whence, an average value of 0.2 , for the product kv_e could be used with reasonable accuracy in evaluating the effect of r_s and r_v on R_R (Fig. 4).

$$R_R = r_s\left(\frac{1 - .2r_v}{0.8}\right) = 1.25r_s(1 - 0.2r_v) \tag{24}$$

The expression for r_s =1.0 corresponds to a non-redundant system or a system consisting of ideal elastic-brittle elements. For kv_e = 0.2, probabilistic effect of redundancy on the strength of a system could not exceed 25%. That is for a system with r_v = 0 and accordingly the highest value for R_R = 1.25. On the other hand, given a structure with minimal probabilistic redundancy effect, R_R is proportional to r_s.

Case study about the effects of redundancy on two-dimensional concrete frames: In order to compute redundancy indices, 16 frame samples from 2 to 5 bay and with two, four, six and ten stories were designated. SAP2000 software and the IDARC software are used for nonlinear dynamic and nonlinear static analysis.

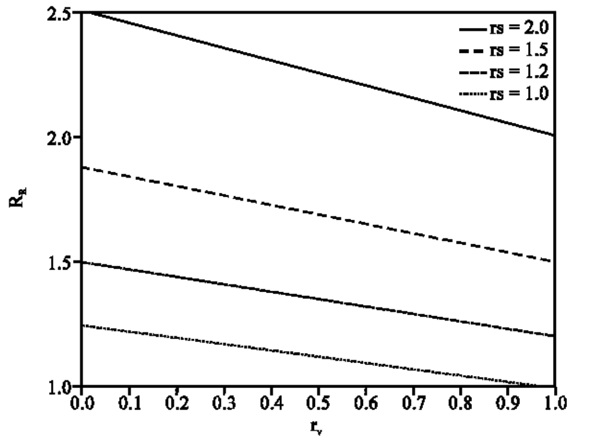

Fig. 4: Variation of R_R with respect to r_s and r_v for structural systems with kv_e = 0.2

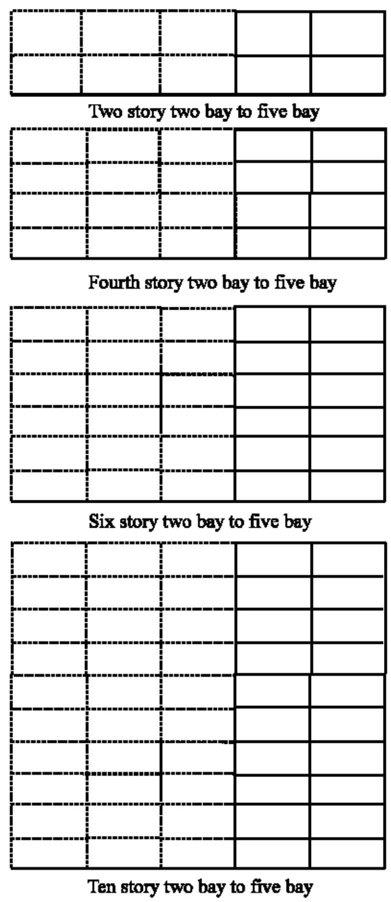

Fig. 5: Reinforced concrete frames with two story two bay to ten story five bay

For nonlinear static analysis, 16 frame samples with high ductility and 16 frame samples with low ductility are selected (Fig. 5). The lateral load pattern applied to the structure is reverse triangular, which is approximately in accordance with lateral force criteria of the earthquake standard 2800 of Iran. Four different cases of design and analysis are considered for comparison. In the first case, the bay length is 4 m and the story height is 3 m and in the second case, the story height is increased from 3 to 4 m. In the third case, the bay length is increase to 5 m and finally in the forth case, the gravity loading intensity is increased to 30%. Therefore, in static nonlinear analysis, one hundred twenty eight frames are designed with SAP2000 and then analyzed by the IDARC. Response curves are computed in terms of displacement at the top of structure (Δtar) with respect to base shear divided by structure weight (C_b). Two values, base shear coefficient during yielding and also maximum base shear coefficient are important over curve. The r_s index is obtained by dividing maximum base shear coefficient to the base shear coefficient when yielding.

RESULTS AND DISCUSSION

Using maximum number of plastic hinges formed in nonlinear static analysis, one can obtain r_v index. As a result of having these two indices, resistance reduction coefficient can be obtained from redundancy according to relations in the third part. Figure 6 shows the r_s changes with respect to number of bays and stories for high ductility. Accordingly, Fig. 7 show r_v changes for the first case. Finally, Fig. 8 shows R_R changes for high ductility.

As it is clear from results, redundancy resistance coefficient is not much sensitive, at both high and low ductility, to number of bays, but it is increased by adding the number of stories. Also by increasing the number of bays and stories, redundancy change coefficient is reduced. As a result, redundancy factor is increased by adding the number of stories and is not sensitive to the number of bays. Thus for computing redundancy factor, five bays are averaged.

In order to carry out nonlinear dynamic analysis with increased acceleration by the IDARC software, a special software is developed to do these operations automatically. This software begins to analyze with a primary PGA value in any stage and it continues the operation with 0.02 g increase relative to the earlier measure, until one of the failure conditions is reached. In this case, the value of base shear coefficient is applied for computing r_s and also for computing r_v index. The number of plastic hinges formed while failure is used to compute 16 frames with high ductility and 16 frames with low ductility. Eight seismic records are applied, equally, for both linear and nonlinear static analysis methods, for 4 different cases. Finally, 1024 frames were analyzed with

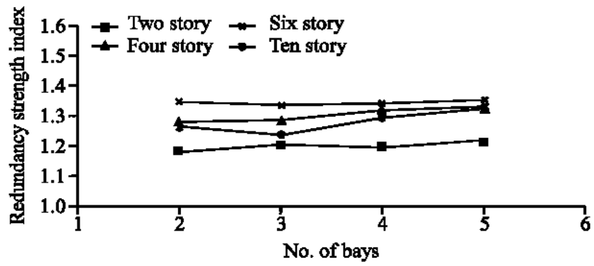

Fig. 6: Variation of redundancy-strength index with respect to No. of bays and stories

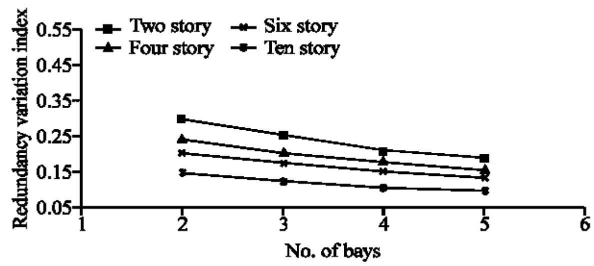

Fig. 7: Variation of redundancy variation index with respect to No. of bays and stories (correlation coefficient = 0)

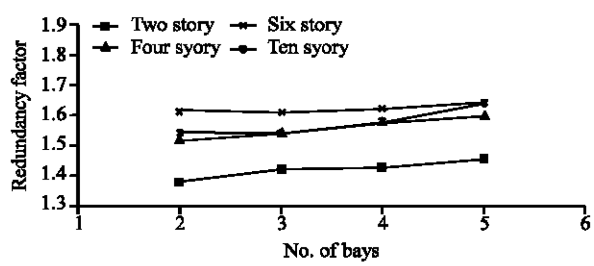

Fig. 8: Variation of redundancy factor with respect to No. of bays and stories (correlation coefficient = 0)

different cases and the values of base shear coefficient while forming the first plastic hinge. Maximum base shear coefficient and the number of plastic hinges when failing are used as parameters required for computing r_s, r_v and R_R indices. It is necessary to note that the average values obtained from eight records is the basis for computing above indices.

Figure 9 shows r_s values for frames with different number of bays and stories for high ductility. Therefore, Fig. 10 shows r_v values for high ductility cases. Figure 11 shows R_R values in terms of the number of different bays and stories for high ductility.

For the first case, redundancy resistance coefficient in nonlinear dynamic method like in nonlinear static

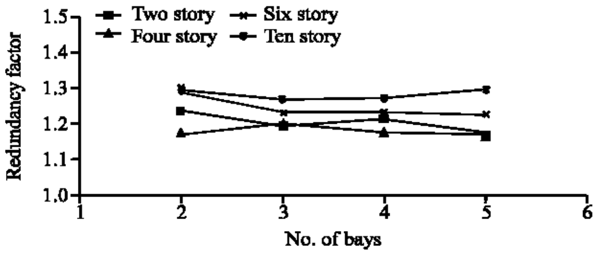

Fig. 9: Variation of redundancy-strength index with respect to No. of bays and stories

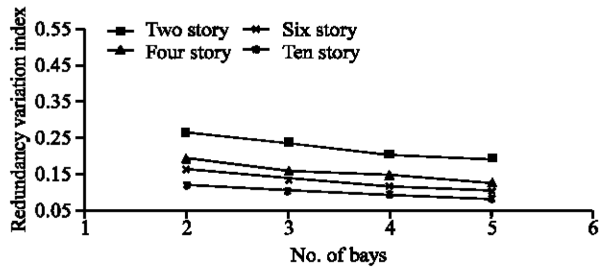

Fig. 10: Variation of redundancy-variation index with respect to No. of bays and stories (correlation coefficient = 0)

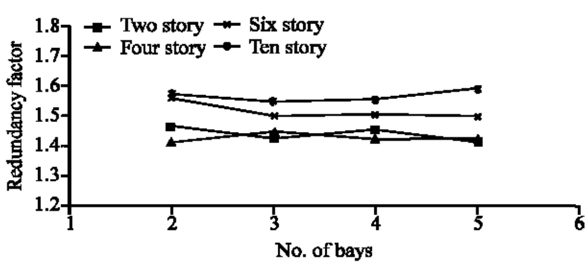

Fig. 11: Variation of redundancy factor with respect to No. of bays and stories (correlation coefficient = 0)

method, is not much sensitive, in both high and low ductility, to the number of bays but with increasing the number of stories, this coefficient would rise. Accordingly, redundancy change coefficient is also reduced by increasing storey and bay numbers and as a result, redundancy factor increases with adding the number of stories, but is not sensitive to the number of bays. Thus for computing redundancy factor, four bays are averaged.

Figure 12 and 13 show redundancy factor changes, respectively for nonlinear dynamic and static methods and for both high and low ductility. Figure 14 and 15 show the redundancy factor coefficient changes, respectively for nonlinear dynamic and static methods in four different conditions and high ductility. Figure 16 shows redundancy coefficient changes for nonlinear dynamic and static method with high ductility.

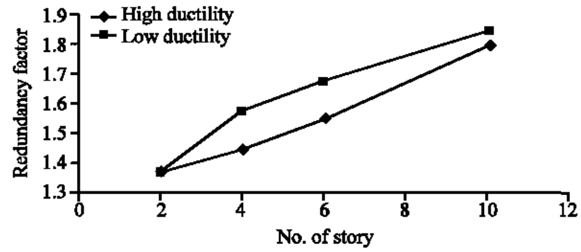

Fig. 12: Variation of redundancy factor with respect to No. of stories and dynamic analysis (case 1)

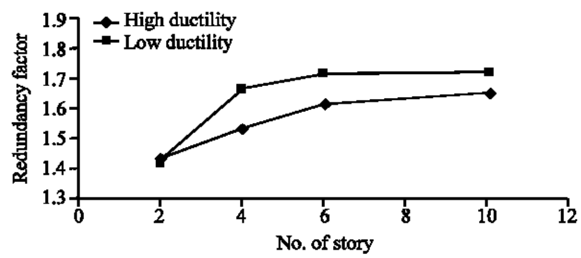

Fig. 13: Variation of redundancy factor with respect to No. of story for pushover analysis (case 1)

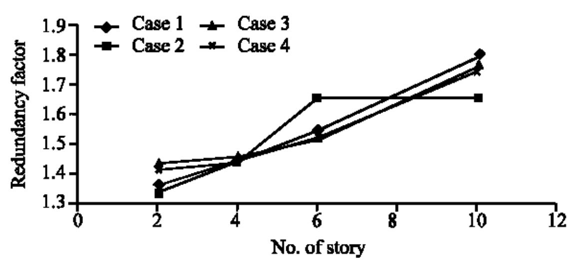

Fig. 14: Variation of redundancy factor with respect to No. of story (high ductility and dynamic analysis)

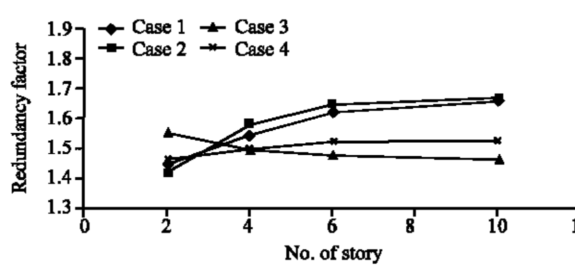

Fig. 15: Variation of redundancy factor with respect to No. of story (high ductility and pushover analysis)

In this study, we propose two measures, which can be used to quantify the effects of redundancy on structural systems.

The proposed indices are the redundancy strength index r_s and the variation strength index r_v. Redundancy

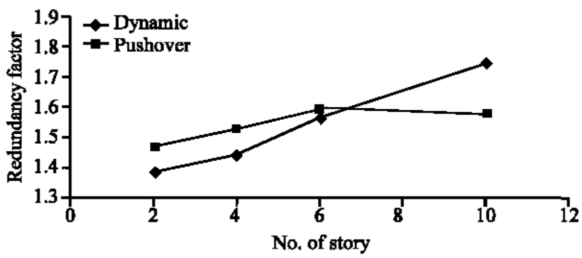

Fig. 16: Average of redundancy factor with respect to No. of story (low reduction)

strength index captures the deterministic effects of redundancy and redundancy variation index is captures the probabilistic effects of redundancy on strength of structural systems. These two indices seem to be better indicators as measures of redundancy effects in structural systems than the number of plastic hinges at failure. They depend on the number of members within the structure, on the ductility capacity of structural members, and on the distribution of strength and stiffness among members of the structure .

The results relate previous finding in support on the number of plastic hinges at failure. The redundancy variation index r_v decreases (probabilistic effects of redundancy increases) as the number of bays and floors increases. The probabilistic effects of redundancy are smaller in frames with fewer stories (The redundancy variation index r_v values are higher). Note that the r_v values are inversely proportional to the numbers of plastic hinges at failure and it is expected that the number of plastic hinges formed in frames with more stories will be larger than in frames with less stories.

On the other hand results relate previous finding in contradiction on the deterministic effect captured by the redundancy strength index r_s (mainly effects due to structural redundancy). It can be observed that the redundancy strength index r_s values and in this case the effects of redundancy are lower for frames with fewer stories, because r_s is ratio of ultimate to yield strength and its value is affected by the number of stories and bays, span to depth ratio of beams, story height and gravity loads.

CONCLUSION

Comparing the values obtained from analysis to compute resistance reduction factor resulting from R_R redundancy, the following results are obtained:

- In nonlinear dynamic analysis method with increased acceleration (IDA), the R_R coefficient is increased in most conditions with reducing ductility and show that, structures designed with low ductility have higher R_R than high ductility. In the Static Pushover Analysis method (SPO), similar to Incremental Dynamic Analysis method (IDA), the valve of R_R is increased in most conditions with lowering ductility
- As observed in Incremental Dynamic analysis (IDA), R_R coefficient in most conditions is increased with adding the number of stories for elements having high ductility but in Static Pushover Analysis method (SPO), R_R coefficient increases with adding the number of stories for first and second conditions but is not much different for third and forth conditions
- Comparing the responses obtained from Static Pushover Analysis method (SPO) with Incremental Dynamic Analysis (IDA), it is concluded that in most conditions, R_R coefficients obtained from static method are larger than dynamic method, but this difference is maximally 10%. According to results from figure, we can conclude that the results obtained from nonlinear static method are in good agreement with results obtained by nonlinear time history method and may be used as a reliable method

Finally, it should be emphasized that these results are only for frames modeled in this study and might not hold true for all other structural models.

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