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Redundancy of Dual and Steel Moment Frame Systems under Earthquakes

S.H. Song and Y.K. Wen[†]

Sargent & Lundy LLC, Chicago, IL, USA
University of Illinois at Urbana-Champaign, Urbana, IL, USA

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ABSTRACT

The reliability/redundancy of structural system has become a serious concern among engineers and researchers after structural failures in Northridge and Kobe earthquakes. The reliability/redundancy factor, ρ, in current codes considers only member force and floor area and has received much criticism from dissatisfied engineers. Within a reliability framework, the redundancy is investigated for dual systems of primary shear walls and secondary moment frames and steel moment frame systems. Probabilistic performance analyses are carried out based on nonlinear responses under SAC ground motions. The effects of structural configuration, ductility capacity, 3-D motion, and uncertainty of demand versus capacity are investigated. Important redundancy-contributing factors are identified and a uniform-risk redundancy factor is developed for design. The results are compared with the ρ factor and its inconsistency is pointed out.

Keywords: reliability, dual systems, steel moment frame systems, earthquakes, design

1. Introduction

Most studies on reliability/redundancy in the past have been limited to ideal simple systems. Structural redundancy under stochastic loads such as earthquakes has not been thoroughly investigated and, as a result, the factors affecting redundancy under such loads have not been well understood. Recent studies of simple parallel systems under static loads show that besides structural configuration such as the number and layout of components, member ductility capacity, uncertainty in load versus resistance, and the correlation of component strength, also contribute to the reliability/redundancy (Gollwitzer and Rackwitz, 1990; De *et al.*, 1989).

Recently, UBC (ICBO, 1997), NEHRP (BSSC, 1997), and IBC 2000 (1998), adopted a reliability/redundancy factor, ρ, which is a multiplier for calculating design lateral earthquake force. The ρ factor is given by:

$$\rho = 2 - \frac{20}{r_{max}\sqrt{A_B}} \text{ in US customary,}$$

or

$$\rho = 2 - \frac{6.1}{r_{max}\sqrt{A_B}} \text{ in SI units,} \tag{1}$$

$$E = \rho E_h + E_v$$

$$1 \leq \rho \leq 1.5$$

ρ =Reliability/Redundancy Factor
$r_{\max}$ =Maximum element-story shear ratio
A_B =Ground floor area of the structure, ft^2 (m^2)
E =Earthquake load on an element of the structure
E_h =Earthquarke load due to the base shear, V
E_v =Load effect resulting from the vertical component of the earthquake ground motion

The factor is, therefore, basically a function of the system configuration. There has been widespread dissatisfaction with this factor by engineers (e.g. Whittaker, *et al.*, 1999). It may produce questionable designs since many important factors affecting redundancy have not been considered in the formulation, such as ductility capacity and uncertainty in demand versus capacity.

Wang and Wen (2000) introduced a uniform-risk redundancy factor, R_R, based on consideration of system reliability using uniform hazard spectra. It is defined as the ratio of spectral acceleration causing incipient collapse of

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[†] Corresponding author
Tel.: +1-217-333-1328 ; Fax: +1-217-333-9464
E-mail address: y-wen@uiuc.edu

the structure to the spectral acceleration corresponding to an allowable probability of incipient collapse. The redundancy factor is unity if the incipient collapse probability is less than the allowable value. The R_R factor is given by the following equation:

$$R_R = \begin{cases} 1 & \text{when } P_{ip} \leq P_{ip}^{all} \\ \dfrac{S_a^{ip}}{S_a^{all}} & \text{when } P_{ip} \leq P_{ip}^{all} \end{cases} \tag{2}$$

$$R' = R \cdot R_R$$

P_{ip} =Probability of incipient collapse.
P_{ip}^{all} =Allowable probability of incipient collapse.
S_a^{ip} =Spectral acceleration corresponding to P_{ip}.
S_a^{all} =Spectral acceleration corresponding to P_{ip}^{all}
S_a^{des} =Spectral accel. corresponding to design prob. level.
R =Response modification factor
R' =Revised response modification factor=$R \cdot R_R$

The R_R factor is then applied to the Response Modification Factor, R, commonly used in building codes and standards. Its function is to adjust the required design force to achieve the same reliability for building systems with different redundancies. The R_R is based on the results of nonlinear dynamic analysis in which most of the above important redundancy-contributing factors are considered. The method of investigation set forth in Wang and Wen (2000) is followed in this study.

2. Modeling and Design of Dual and Steel Moment Frame Systems

In designing a shear wall structure, the primary concern is accurate determination of the yield strength and the ultimate strength. For this purpose, an equivalent shear wall model is proposed, which is composed of multiple columns and rigid beams. The computer software DRAIN3DX is used to model the shear wall response behavior, in which a fiber beam column element is used to describe the global hys-teretic behavior of a concrete shear wall. For compu-tational efficiency, the bars are assumed to be elastic with end plastic connection hinges based on the assumption that the plasticity can be lumped at the ends of the bars. The proper pullout properties (skeleton curve) defined in DRAIN3DX for connection hinge fibers are selected to consider stiffness/strength degradation and pinching effect. The softening region, which allows more energy dissipation capacity, is incorporated into the system by a hysteretic model with stiffness and strength degradation. The load-carrying capacity of the dual systems is highly dependent on the slope of the negative stiffness. The material and geometric properties follow those of UBC-97 (ICBO, 1997).

Under the assumption of flexural deformation of shear wall, the top displacement at yielding and ultimate performance levels are calculated based on its curvature diagram. This is so-called "displacement-based design methodology". The accuracy of this methodology is dependent on the assumption for the curvature diagram. UBC 97 adopts a curvature diagram based on two assumptions: the plastic depth at the base of the shear wall is equal to one-half of wall length and the yield curvature is equal to 0.0025/wall length. Based on the curvature diagram, the ultimate top displacement is calculated as the sum of the yield displacement and the additional displacement developed through plastic rotation. The displacement ductility ratio (μ) is a function of ($\varepsilon_{c,\max}/\beta$) according to the curvature diagram under the assumption of constant wall aspect ratio. β is a ratio to account for neutral axis depth in terms of wall length and $\varepsilon_{c,\max}$ is a maximum concrete strain (Wallace, 1994).

The NEHRP-97 provisions stipulate that the moment frame in a dual system shall have a capacity of resisting at least 25% of the design forces. The total shear force resistance is to be provided by the combination of the moment frame and the shear walls or braced frames and in proportion to their rigidities. In order for the moment frames to contribute significantly to the resistance of the dual system, their stiffness and strength should be comparable to those of the shear walls. Under lateral force, both the shear walls and the moment frames resist the lateral force at the initial stages of loading. After the failure of the first shear wall, the lateral force can be redistributed through the damaged dual system according to the load-carrying capacity of the components.

The SMRF systems in the dual systems and steel moment frames are designed according to the requirements of NEHRP-97 for a strong-column and weak-beam (SCWB) system. Both ductile and brittle connection response behaviors are considered. Ductile component behavior is modeled by DRAIN3DX (1994). The brittle failure is described by the model of Wang and Wen (2000).

3. Response Analysis and Redundancy Evaluation

The performance of the system is described in terms of response thresholds corresponding to three levels of probability of exceedance, i.e., 2%, 10%, and 50% in 50 years. Shear Wall Drift Ratio (SWDR) and Maximum Column

Drift Ratio (MCDR) of SMRF system are used for this purpose. The median response under SAC-2 ground motions and coefficient of variation at each level are calculated and a log-normal distribution is then used to fit the results and obtain the performance curve, which is then used for calculation of the redundancy factor. The target (acceptable) incipient collapse probability is assumed to be 10% in 50 years for the shear walls and 2% in 50 years for the system. The SWDR capacity thresholds corresponding to the incipient collapse probability are from 1.6% to 3% depending on aspect ratio of the shear walls (Bertero *et al.*, 1991) and the MCDR capacities are from 5% or 8% for moment frames depending on connections being brittle or ductile (Foutch, 2000).

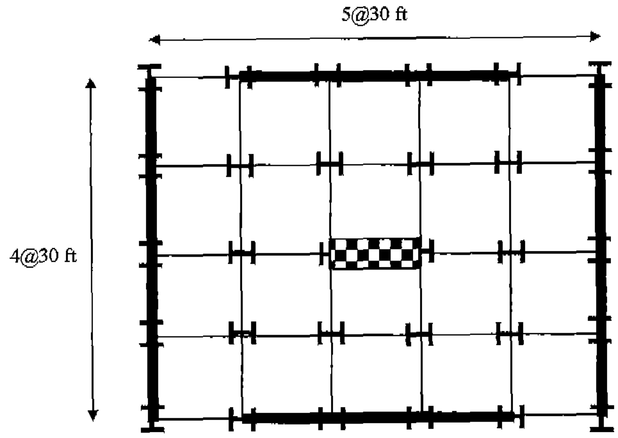

Fig. 1. 1-Shear Wall System.

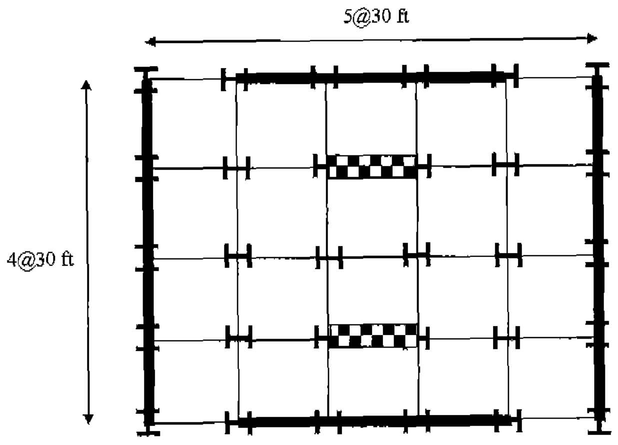

Fig. 2. 2-Shear Wall System.

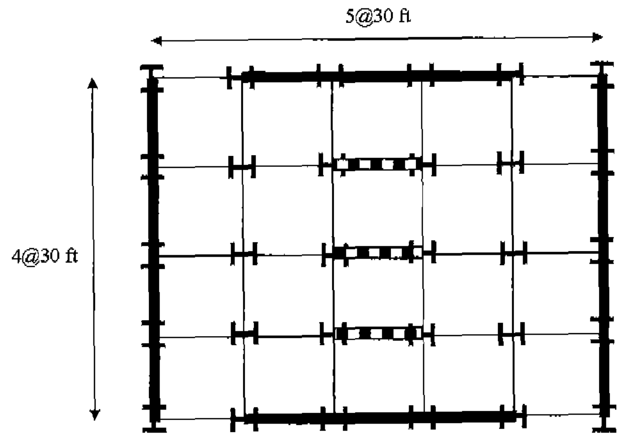

Fig. 3. 3-Shear Wall System.

3.1 Five-Story, One-Way Dual Systems

3.1.1 Effect of Number of Shear walls

The configurations of dual systems with different number of shear wall components and layouts are shown in Figs. 1, 2, and 3. The hysteretic restoring force of the shear wall under cyclic loading is also shown in Fig. 4 which compares well with experimental results. The design of the two- and three-shear wall systems follows the same procedure as that of the one-shear wall system except the dimension and stiffness of the shear walls are properly adjusted so that the lateral resistances of these systems are the same to have a consistent comparison of the performances. The SWDR responses are found to be moderately dependent on the number of shear walls. The SWDR are 2.52% for the one-shear wall system, 2.50% for the two-shear wall system, and 2.43% for the three-shear wall system showing a 3.7% reduction from one- to three-shear wall system.

The evaluation of reliability/redundancy of 5-story, one-way dual systems under biaxial motions is then carried out based on the above response statistics and the seismic hazard at the site. The uniform-risk redundancy factor, R_R, as defined above is calculated and the required design forces are compared with those based on the reliability/redundancy factor, ρ in Table 1. The ρ factor requires a 50%

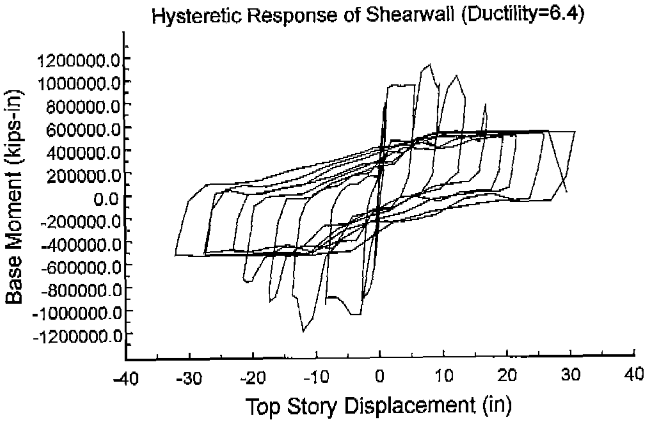

Fig. 4. Hysteretic Response of Shear Wall.

Table 1. Comparison of Required Design Force Based on Uniform-Risk and r Factor (5-Story, One-Way Dual Systems)

System		R_R	ρ
Number of Shear Walls	1	1.20	1.50
	2	1.17	1.02
	3	1.03	1.00
Ductility of Shear Walls	5.4	1.14	1.00
	6.4	1.03	1.00
	7.4	1.00	1.00
Correlation of Shear Walls	0	1.17	1.02
	0.2	1.17	1.02
	0.6	1.17	1.02
	1.0	1.17	1.02
Ratio of EQ Load to Strength Variability	2.67	1.03	1.00
	3.56	1.03	1.00
	5.33	1.03	1.00

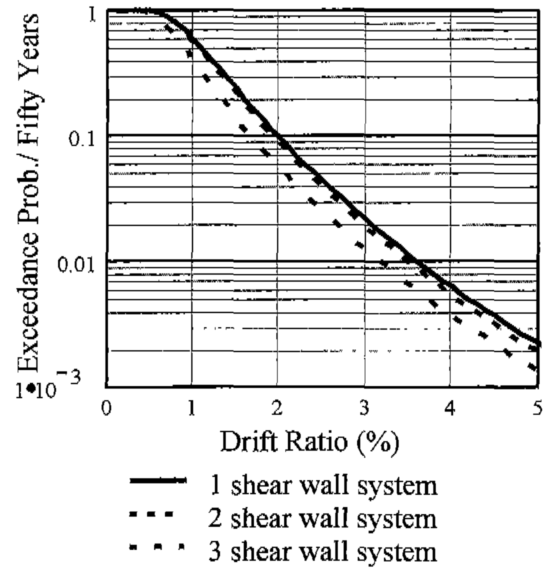

Fig. 5. Probabilistic Performance Curves.

increase in design force for the one-shear system whereas the uniform-risk factor requires only 20%. The probabilistic performance curves of the dual systems of different shear walls are given in Fig. 5. It is noted that the 50% increase in design earthquake force according to the ρ factor grossly overestimates the lack of redundancy of the one-shear wall system.

3.1.2 Effect of Ductility Capacity of Shear Walls

The effect of different ultimate drift ratios ranging from 0.8 to 1.1% is investigated for the three-shear wall system having a ductility capacity of 5.4, 6.4, and 7.4 designed according to the displacement-based method. The drop of ductility capacity from 7.4 to 5.4 leads to a 14% increase in the design earthquake force according to the uniform-risk factor. On the other hand, the ultimate drift capacity is not considered in the ρ factor, therefore, the design earthquake force remains the same.

3.1.3 Effect of Correlation of Shear Wall Strength

The two-shear wall system with a ductility capacity of 6.4 is considered. Resistance random variables with a correlation coefficient ranging from 0.0, 0.2, 0.6, to 1.0, among the shear walls are generated by Monte Carlo method. The SWDR responses are beyond the elastic limit under 2% in 50 years earthquakes. It is found that the strength correlation has no significant effects on the system redundancy. The results can be attributed to the dominance of the uncertainty in the excitation and the interaction between the shear walls and the SMRF systems that absorbs some of the impact of shear wall strength variability. As a result, the differences in correlation in the capacity become inconsequential.

3.1.4 Effect of the Ratio of Earthquake Load to Shear Wall Resistance Variability

The three-shear wall system with an aspect ratio 1.68 is studied. The shear wall resistance uncertainty (coefficient of variation) is assumed to be 10%, 15%, or 20%. The 2% in 50 years median shear wall drift ratios are found to be 2.40%, 2.42%, and 2.43% showing almost no differences, largely due to the dominance of uncertainty in the earthquake excitation.

The one-shear wall system is then redesigned according to the uniform-risk redundancy factor and its performance evaluated. The performance is very close to that of the three-shear wall system and satisfies the 2% in 50 years performance requirement. The investigation has been extended to 5-story, and 10-story two-way dual systems with similar results (Song and Wen, 2000).

3.2 SMRF Systems

Three 3-story moment frames of 1×1 bay, 2×2 bay, and 3×3 bay are designed (Fig. 6). To model the irregularity of mass and stiffness distribution of the diaphragm, a 5% offset recommended by NEHRP is used in this study. The systems are designed such that these three frames have the same lateral resistance but allow brittle connection failures. The connection fracture hysteresis model of Wang and Wen (2000) is used which reproduce well the test results by Anderson, *et al.* (1995) as shown in Fig. 7. Nonlinear dynamic analyses are performed under SAC-2 motions. The median drift ratio of the 1×1 bay SMRF under 2/50 earthquakes is 6.63% and that of the 3×3 bay SMRF is 5.14% when ductile connections are assumed for

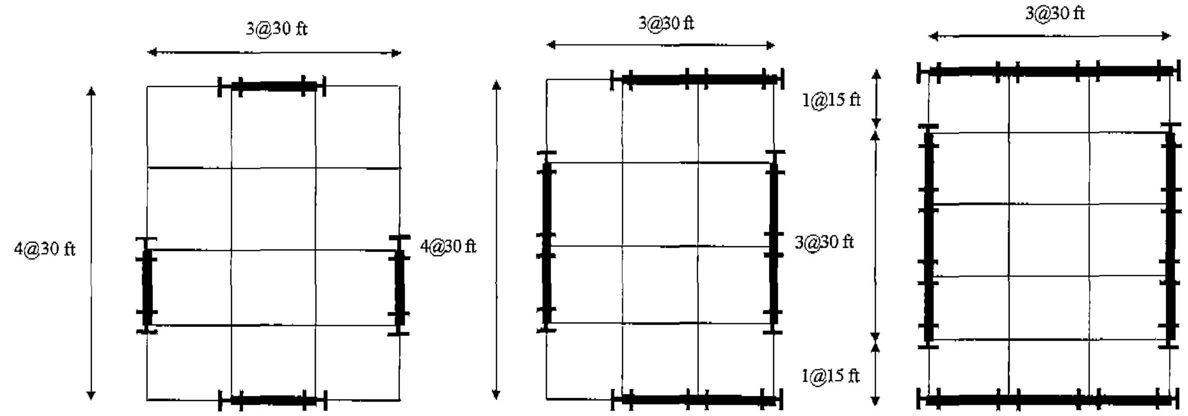

Fig. 6. 3-Story SMRF Systems of Different Configurations (1× 1 Bay, 2x2 Bay, and 3x3 Bay).

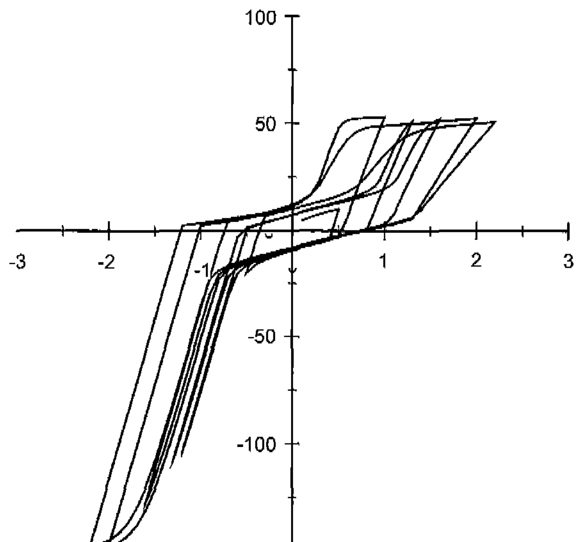

Fig. 7. Brittle Fracture Model.

Table 2. Comparison of Required Design Force based on Uniform-Risk Factor and ρ Factor (3-Story SMRF Systems with 5% Torsion)

	System	R_R	ρ
1x1 Bay	Ductile Connection	1.06	1.25
	Brittle Connection	1.58	1.25
2x2 Bay	Ductile Connection	1.08	1.25
	Brittle Connection	1.56	1.25
3x3 Bay	Ductile Connection	1.08	1.24
	Brittle Connection	1.45	1.24

both systems. A 22.5% response reduction is observed. The median response of the systems with brittle fracture connections is higher than that of the systems with ductile connections. The median response reduction at 2/50 hazard level in the 3x3 bay system compared with the 1x1 bay system, however, is only 10.4%. It can be, therefore, concluded that, when torsional motions are included into the consideration, the response is reduced effectively by using larger number of bays and smaller member sizes if the components are ductile. The effectiveness is significantly reduced if the components are brittle.

The required design forces according to the uniform-risk factor and ρ are compared in Table 2. According to the uniform-risk factor, for systems with ductile connections, there is adequacy reliability/redundancy for the 2x2 bay and 3x3 bay systems and no increase in force is required while an increase of 6% is required for the 1x1 bay system. On the other hand, for systems with brittle connections, the required increase in design force is 58% for the 1x1 bay, 56% for the 2x2 bay systems, and 45% for the 3x3 bay system. In contrast, the ρ factor is calculated to be 1.25 for the 1x1 bay and 2x2 bay systems, and 1.24 for the 3x3 bay system, indicating an increase of about 25% required of all systems, regardless of connection ductility capacity, since connection response behavior is not considered. The probabilistic performance curves of the systems with ductile and brittle connections are given in Fig. 8. The benefit of redundancy is more evident for the moment frames with large drift capacity. Also, the benefit of large number of bays is more evident for the moment frames with ductile connections. There are only very small differences in probabilistic performances of the three systems when the connections are brittle.

The investigation is then extended to comparison of performances of 3-story 4x4 bay versus 6x6 bay SMRFs and 9-story 5x5 bay versus 8x8 bay SMRFs with ductile connections but no torsional motions. The systems are designed such that they have equal lateral resistances. The responses of two systems with different bays are found to be almost the same and all four systems satisfy the 2% in 50 years drift ratio performance requirements. Therefore

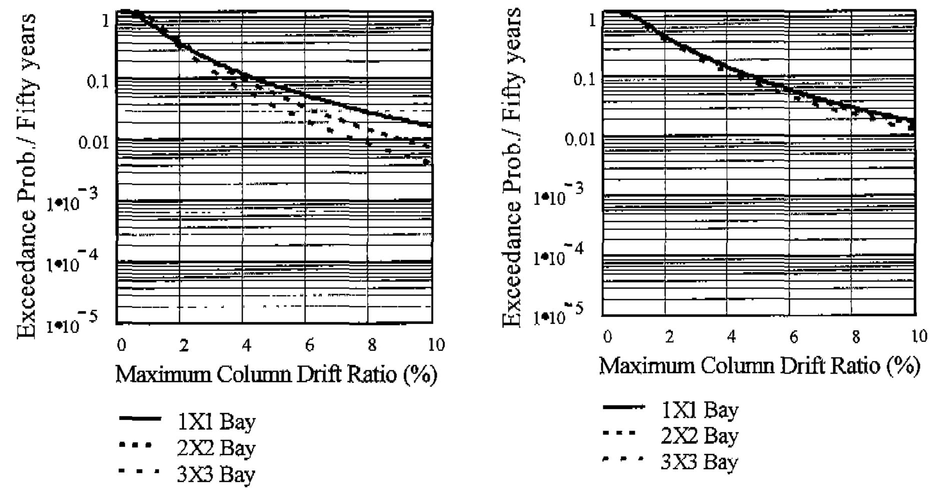

Fig. 8. Performance of 3-Story SMRF Systems with Torsio (Wang and Wen, 2000) (left: ductile connections and right: brittle connections).

according to the uniform-risk redundancy factor method, no increases in design force are required for the systems with smaller number of bays. The ρ factor, on the other hand, requires an increase of 25% for the systems with smaller number of bays. Details can be found in Song and Wen (2000).

4. Conclusions

Nonlinear response analyses of the dual and moment frame systems under SAC ground motions and probabilistic performance evaluation are carried out. Results indicate that due to the dominance of excitation uncertainty, the effect of structural configuration such as number, size and layout of lateral resisting components and members is only moderate. Effect of ductility capacity and brittle member failure and ensuing 3-D response including torsional motions, however, may cause larger differences in structural response, reliability/redundancy, and required design forces.

A uniform-risk redundancy factor is developed that can be used in conjunction with the current code format to ensure structures of different redundancy to achieve a target reliability. The approach is verified by the performance evaluation of a dual system redesigned according to the proposed method. The NEHRP ρ factor, which basically depends only on the structural configuration, is shown to give inconsistent results. It generally overestimates the effect of structural configuration and underestimates those of ductility capacity and 3-D motions.

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