INTEGRATED RELIABILITY-BASED DESIGN OPTIMIZATION OF ISOLATED CONCRETE BUILDINGS UNDER SPECTRUM LOADING

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ABSTRACT :

In conventional seismic design of base-isolated concrete buildings, not only are the superstructure and the isolation system analyzed and designed separately, but also the determination of satisfactory dynamic responses in both the superstructure and isolation system requires a highly iterative trial-and-error reanalysis and redesign process even with the aid of today's computer software. It is intended in this research that both the structure and base isolation, as a whole, are simultaneously optimized to achieve optimal performance-based design. Besides, since uncertainties are not considered in the conventional deterministic optimization, such optimized structures may generally result in higher failure probabilities than optimal reliability-based structures. Therefore, structural reliability theory should be incorporated into the structural optimization process. Reliability-based structural optimization can provide a good balance between the structural reliability and optimal design objectives, while specified performance requirements are satisfied.
This paper presents an effective numerical deterministic and reliability-based optimization technique for the design of base-isolated concrete building structures under spectrum loading. Attempts have been made to automate the integrated spectrum analysis, reliability analysis and design optimization procedure and to minimize the total cost of the base-isolated building subject to multiple design performance criteria in terms of the inter-story drift of the superstructure and the lateral displacement of the isolation system or corresponding reliability constraints. An illustrative example shows that the deterministic design optimization cannot ensure designs with satisfactory reliability level whilst reliability-based design optimization can achieve the objective through consideration of uncertainties.

KEYWORDS: Spectrum, reliability, optimization, virtual work, isolation, concrete

1. INTRODUCTION

Seismic isolation has been increasingly used in earthquake-prone regions for protecting structures from damages by limiting earthquake attacks (Zhou 1997; Kelly 1997). Traditionally, not only are the superstructure and the isolation system designed separately in a building, but also the determination of satisfactory dynamic responses in both the superstructure and isolation system requires a highly iterative trial-and-error reanalysis and redesign process even with the aid of today's computer software. It is intended in this research that both the structure and base isolation, as a whole, are simultaneously optimized to achieve optimal performance-based design. Besides, since uncertainties are not considered in the conventional deterministic optimization, such optimized structures may generally result in higher failure probabilities than optimal reliability-based structures. Reliability-based structural optimization can provide a good balance between the structural reliability (e.g., the safety needs of the structure) and optimal design objectives (e.g., reducing its cost), while specified performance requirements are satisfied. In recent years, extensive research has been carried out on reliability-based design optimization of structural systems (Moses 1982; Frangopol 1985; Wen 1995; Cheng et al. 1998; Li 1998). Zou (2002, 2008), Zou and Chan (2001, 2004, 2005a, b), and Zou et al (2007a, b) developed a novel systematic optimization technique for the seismic design of fixed-base elastic and inelastic building structures, which were designed subjected to deterministic seismic design performance criteria. Important efforts are still needed to develop an effective way for reliability-based design optimization of isolated buildings subjected to seismic drift performance reliability criteria.

This paper presents an effective numerical deterministic and reliability-based optimization technique for the design of base-isolated concrete building structures under spectrum loading. Attempts have been made to automate the integrated spectrum analysis, reliability analysis and design optimization procedure and to minimize the total cost of the base-isolated building subject to multiple design performance criteria in terms of the inter-story drift of the superstructure and the lateral displacement of the isolation system or corresponding reliability constraints. In the optimal design formulation, the cost of the superstructure can be expressed in terms of concrete member sizes while assuming all these members to be linear elastic under a specified design earthquake action. However, the base-isolation is assumed to behave nonlinearly and its cost can be related to the effective horizontal stiffness of each isolator. Using the principle of virtual work, the drift responses and corresponding reliability indexes can be explicitly formulated and the integrated optimization problem can be solved by an Optimality Criteria (OC) method. The technique is capable of achieving the optimal balance between the costs of the superstructure and isolation systems whilst the seismic drift performance or corresponding reliability of the building can be simultaneously considered. An illustrative example shows that the deterministic design optimization cannot ensure designs with satisfactory reliability level whilst reliability-based design optimization can achieve the objective through consideration of uncertainties. It is believed that such an optimization technique will develop an effective tool for earthquake-resistance structural design.

2. DETERMINISTIC OPTIMAL DESIGN PROBLEM

For a base-isolated concrete building having b=1, 2, …, N_b base isolators and i=1, 2, …, N_i members, the structural design optimization problem can be explicitly expressed in terms of the design variables, i.e. the horizontal effective stiffness K_b of each isolator, the width B_i and depth D_i of a rectangular concrete member, as

$$F(K_b, B_i, D_i) = \sum_{b=1}^{N_b} (m_1 K_b + m_2) + \sum_{i=1}^{N_i} w_i B_i D_i \tag{2.1}$$

The first part of the total cost F in Eqn. (2.1) is the isolation system cost which is assumed to be linearly related to K_b; m_1 and m_2 are the cost coefficients of the b^{th} base isolator, which can be obtained through a statistical investigation based on the discrete cost data provided by the manufacturer; the second part is the concrete cost and w_i is the cost coefficient for the i^{th} member of the superstructure.

2.1. Target Period and Displacement Constraints at Base Floor Level

For the purpose of reducing external forces transferred to the structure, there is usually a good separation between the fixed-base period of vibration and the base-isolated period for a building structure. Under the condition that the isolation system damping is temporarily fixed, the target period of the isolation system, T_B, can be achieved by controlling lateral seismic displacement at base floor level. Specifically, in order to attain sufficient flexibility so as to lengthen the period of the base isolation system, the isolation system is required to deform to maintain a minimum lateral displacement as follows

$$u_0 \geq \Gamma^{(1)}\phi_0^{(1)}\left(\frac{T_B}{2\pi}\right)^2 S_a^{(1)}(T_B,\zeta_B) \tag{2.2}$$

where u_0 is the lateral displacement at the top of the isolation system under the seismic loading; $\Gamma^{(1)}$ is the 1st modal participation factor; $\phi_0^{(1)}$ is the 1st modal amplitude at base story; $S_a^{(1)}$ is the 1st modal spectral acceleration; ζ_B is the total effective damping of the isolation system. Besides, it is necessary that each individual isolator does not deform excessively beyond the shear deformation capacity of the isolator. Therefore, u_0 should be limited within the smallest allowable deformation capacity of isolators in the isolation system, as

$$u_0 \leq \min_b(\chi_b) \tag{2.3}$$

where χ_b is the allowable deformation limit for each base isolator.

2.2 Lateral Drift Constraints in the Superstructure

The lateral inter-story drift of a multistory building is an important parameter which measures the damage level of the building under earthquake loading. Therefore, a set of inter-story drift constraints can be stated as follows:

$$\Delta u_j = u_j - u_{j-1} \leq \delta_j^U \qquad (j=1,2,\ ...,N_j) \tag{2.4}$$

where Δu_j is the inter-story drift at the two adjacent j^{th} and $(j\text{-}1)^{th}$ floor levels; δ_j^U is the corresponding inter-story drift limit, respectively. Based on the modal member internal forces obtained from the spectrum analysis, the principle of virtual work is employed to formulate all individual modal drift responses. Specifically, the total virtual work $u_j^{(n)}$ (i.e., the n^{th} modal displacement at the j^{th} level of a concrete building) can be written as

$$u_j^{(n)} = \sum_{i=1}^{N_i}\left(\frac{C_{1ij}^{(n)}}{B_iD_i} + \frac{C_{2ij}^{(n)}}{B_iD_i^3} + \frac{C_{3ij}^{(n)}}{B_i^3D_i}\right) + \sum_{b=1}^{N_b}\left(\frac{C_{0bj}^{(n)}}{K_b}\right) \tag{2.5}$$

where $C_{1ij}^{(n)}, C_{2ij}^{(n)}, C_{3ij}^{(n)}, C_{0bj}^{(n)}$ are the so-called n^{th} modal virtual strain energy coefficients corresponding to the n^{th} modal displacement $u_j^{(n)}$ and details of derivation are shown in Zou (2002, 2008). Once the explicit modal story displacement is formulated, the maximum value of the inter-story drifts can be expressed by combination rules such as the complete quadratic combination (CQC) rule. The inter-story drift, Δu_j, can be determined by the modal drifts given in Eqn. (2.5) as

$$\left[\Delta u_j\right]_{CQC} = \sqrt{\sum_{n=1}^{N_n}\sum_{m=1}^{N_n}\rho_{nm}\cdot\Delta u_j^{(n)}\cdot\Delta u_j^{(m)}} \tag{2.6}$$

where N_n denotes the total number of modes considered in the response spectrum analysis; ρ_{nm} is the modal correlation coefficient.

3. RELIABILITY-BASED OPTIMAL DESIGN PROBLEM

In a reliability-based optimal design problem, the design variables consist of deterministic and uncertain variables. Like the deterministic design optimization aforementioned, K, B and D are taken as deterministic design variables, as structural geometry uncertainties are not considered in the study. Earthquake action, structural responses and allowable elastic story drift are all treated as random variables. Specifically, the inter-story drift response is taken as an uncertain design variable, denoted by $\Delta\overline{u}$ and assumed to have the same probability distribution of the earthquake actions as the extreme value Type II distribution during a design period of 50 years (Gao and Bao 1985). The allowable story drift limit is also taken as an uncertain design variable and denoted as $\overline{d}$, following normal distribution (GBJ68-84 1984).

Uncertainties of objective functions should be properly considered in reliability-based design optimization. Due to the lack of reliable and proper cost data for assessing the reliability of an objective function, it is commonly acceptable to consider the cost function as a deterministic function. Therefore, the uncertainties of the design objective are not considered in this research. The objective function is the same as that of the deterministic design optimization problem presented in Eqn. (2.1).

Uncertainties are generally accounted for through probabilistic constraints in a reliability-based structural optimization under earthquake loadings. A probabilistic design constraint is defined that the reliability index must be greater than its allowable value, i.e., a minimum level of reliability. The drift reliability constraint specifies that the reliability index β_j of the j^{th} inter-story drift should be larger than its corresponding target value $\lfloor \beta_j \rfloor$, as follows:

$$\beta_j \geq \lfloor \beta_j \rfloor \qquad (j = 0, 1, 2, \ ..., N_j) \tag{3.1}$$

where N_j is the number of inter-story drift reliability constraints. It should however be noted that in the present design codes there are generally no specific values of the target reliability indices corresponding to inter-story drift responses. The objective function (i.e., concrete cost) increases and the structural lateral drift deformation reduces with the increase of the target value $[\beta]$. Selecting a suitable value of $[\beta]$ can make a good balance between the cost and publicly acceptable risk-level (Cheng et al. 1998). Besides, for each story level, the target value $[\beta]$ given in Eqn. (3.1) may be the same or different, i.e. uniform target reliability or weighted target reliability. Similarly, in order to facilitate numerical solution of the design optimization problem, the inexplicit reliability design constraints in Eqn. (3.1) should be explicitly expressed in terms of the deterministic design variables.

Since $\Delta\bar{u}$ is a random variable representing an inter-story drift response, the cumulative distribution function $F_{\mathrm{II}}(\Delta\bar{u})$ following the Type II distribution for the response $\Delta\bar{u}$ can be defined by

$$F_{\mathrm{II}}(\Delta\bar{u}) = \exp\left[-\left(\frac{\alpha}{\Delta\bar{u}} \right)^k \right] \tag{3.2}$$

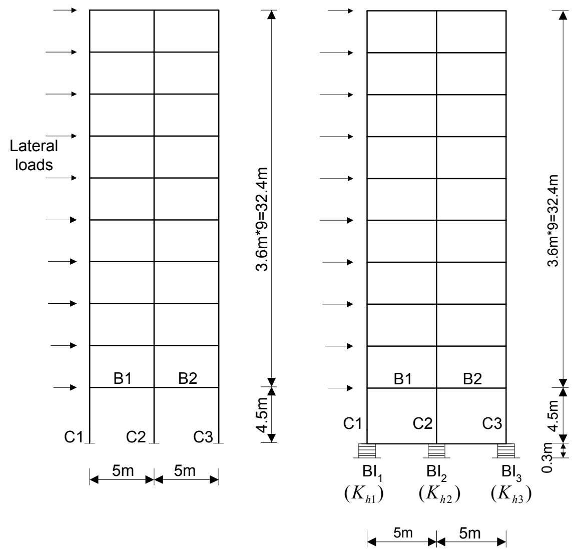
Where α is the largest characteristic value of the initial variable $\Delta\bar{u}$; k is the shape parameter. $\mu_{\Delta\bar{u}}$ and $\sigma_{\Delta\bar{u}}$ are assumed to be the mean value and standard deviation of the random variable $\Delta\bar{u}$. It is found from a statistical study that during a design period of 50 years, $\mu_{\Delta\bar{u}}$ is related to the characteristic value Δu such as $\mu_{\Delta\bar{u}} = 0.597\Delta u$; the coefficient of variation $\delta_{\Delta\bar{u}}$ is 1.267, i.e. $\sigma_{\Delta\bar{u}}$ is related to $\mu_{\Delta\bar{u}}$ such as $\sigma_{\Delta\bar{u}} = 1.267\mu_{\Delta\bar{u}}$ (Gao and Bao 1985).Thereby, $\sigma_{\Delta\bar{u}}$ is derived as $\sigma_{\Delta\bar{u}} = 0.756\Delta u$, $k = 2.35$ and $\alpha = 0.385\Delta u$.

Since the probability of the random variable $\Delta\bar{u}$ follows the extreme value Type II distribution rather than a normal distribution, it is necessary to first transform the extreme value Type II distribution into an equivalent normal distribution, i.e., the equivalent normal mean value, $\sigma^N_{\Delta\bar{u}}$, and normal standard deviation, $\mu^N_{\Delta\bar{u}}$, which are a function of Δu. As a result, they can be explicitly formulated in terms of the deterministic design variables, K_b, B_i and D_i. Similarly, the normal mean value and standard deviation of the random variable $\bar{d}$ (following the normal distribution), $\sigma^N_{\bar{d}}$ and $\mu^N_{\bar{d}}$, can be determined as $\mu^N_{\bar{d}} = 1.410d$ and $\sigma^N_{\bar{d}} = 0.268d$.

As a result, the reliability index β given in Eqn. (3.1) becomes a function of d and Δu. The reliability constraint given in Eqn. (3.1) can be explicitly expressed in terms of the inter-story drift Δu and furthermore in terms of the deterministic design variables: K_b, B_i and D_i.

4. AN ILLUSTRATIVE EXAMPLE

A ten-story, two-bay planar frame with and without base isolation is used to illustrate the deterministic and reliability-based optimal isolation methods for minimum cost design subjected to spectral displacement and drift constraints. The structural geometries of the fixed-base and base-isolated buildings are shown in Figures 1(a) and (b), respectively. The structure is subjected to the lateral loads derived from the seismic design response spectrum with the peak acceleration of 0.32g and the damping ratio of 5% in accordance with the Chinese seismic design code (GB 50011-2001).



(a) Fixed-base structure (b) Base-isolated structure
Figure 1 A ten-story two-bay concrete frame

In this example, linear and nonlinear isolators are mixed used. The nonlinear isolators BI_1 and BI_3 with 20% damping ratio, and linear isolator BI_2 with 5% damping ratio, result in 17% damping ratio of the entire isolation system. Their bounds and initial values of horizontal stiffness are shown in Table 1. A typical allowable inter-story drift ratio limit is assumed to be 1/800 for the superstructure and the target period of the base isolated structure is assumed to be 2.7s. According to Eqn. (2.2), the allowable minimum displacement limit of the base story can be approximately computed and it is equal to 0.027m. Based on the discrete cost data provided by Shantou Vibro Tech Industrial and Development Co. Ltd. (Guangdong Province, China), the relationship between the cost and horizontal effective stiffness of each isolator is established and transformed into a linear continuous function by a regression analysis. Four cases are considered in this example: Cases A-1 and A-2 are for deterministic optimization and Cases B-1 and B-2 are for reliability-based optimization.

4.1 Deterministic Optimization

The purpose of Cases A-1 and A-2 is to compare the optimal base-isolated structure with the optimal fixed-base structure subjected to the same earthquake loads. Case A-1 commences the optimal design of the fixed-base structure. The fixed-base structural optimization method is used to find an optimal building design with the natural period as 1.1s. The target period of 2.7s, which is approximately 2.6 times of the optimal fixed-base structure, is desired for the base-isolated building in Case A-2.

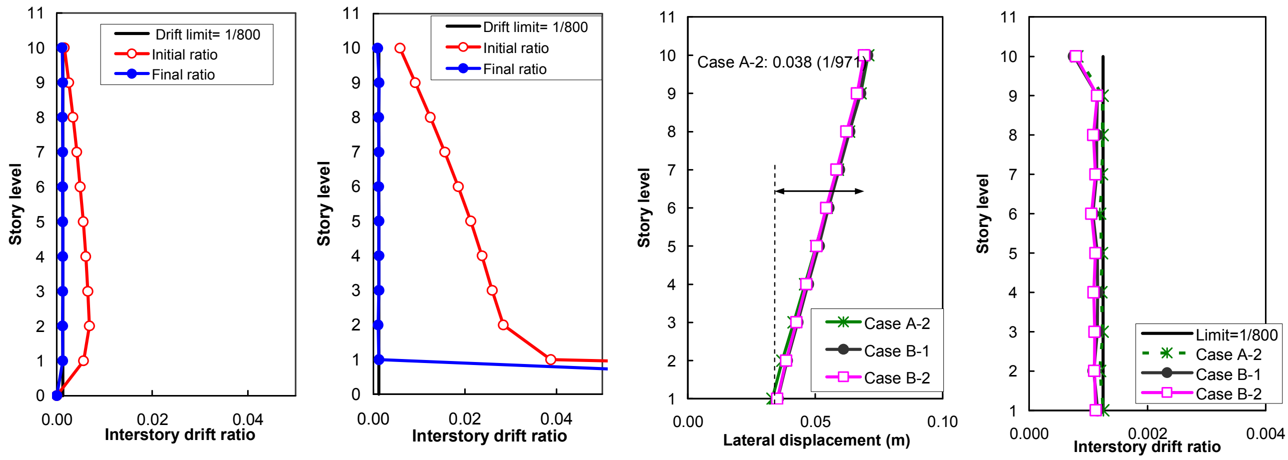
Table 1 shows the initial and optimal member sizes for Cases A-1 and A-2, respectively. Moreover, the member depths of the isolated structure are much smaller than those of the fixed-base structure. The ratio of the member depth for the fixed-base structure over the depth for the isolated structure is more than 1.3 It indicates that the isolation system results in a significant decrease in earthquake loads so that the superstructural internal forces, member sizes as well as concrete cost are reduced. Table 1 also shows the initial and optimal horizontal effective stiffness of each isolator in Case A-2. The optimal effective stiffness is found higher than corresponding initial one for each isolator. The stiffness in the initial design is indeed so small that excessive base story displacement occurs.

The isolator stiffness is therefore increased by the optimization process.

Table 1 Initial and optimal member sizes and isolator stiffnesses

Isolated structure	Element type	Story level	Mem. group	Case A-1 Optimal sizes Width (mm)	Depth-1 (mm)	Case A-2 Optimal sizes Width (mm)	Depth-2 (mm)	Ratio Depth-1/Depth-2	Case B-1 Optimal sizes Width (mm)	Depth (mm)	Case B-2 Optimal sizes Width (mm)	Depth (mm)
Superstructure	Column	9th~10th	C1,C3	300	458	300	350	1.3	300	350	300	350
			C2	300	683	300	350	2.0	300	350	300	350
		7th~8th	C1,C3	300	519	300	367	1.4	300	368	300	361
			C2	300	790	300	577	1.4	300	495	300	493
		5th~6th	C1,C3	300	604	300	386	1.6	300	402	300	410
			C2	300	812	300	578	1.4	300	595	300	594
		3rd~4th	C1,C3	300	682	300	423	1.6	300	441	300	444
			C2	300	840	300	595	1.4	300	618	300	624
		1st~2nd	C1,C3	300	785	300	505	1.6	300	526	300	533
			C2	300	887	300	675	1.3	300	693	300	688
	Beam	9th~10th	B1,B2	250	583	250	450	1.3	250	450	250	450
		7th~8th	B1,B2	250	815	250	457	1.8	250	485	250	492
		5th~6th	B1,B2	250	866	250	614	1.4	250	626	250	630
		3rd~4th	B1,B2	250	903	250	623	1.4	250	645	250	649
		1st~2nd	B1,B2	250	883	250	669	1.3	250	674	250	678
Isolation	Element type	Story level	Mem. group	Stiffness bounds (kN/m)		Case A-2 Initial stiffness (kN/m)	Optimal stiffness (kN/m)		Case B-1 Initial stiffness (kN/m)	Optimal stiffness (kN/m)	Case B-2 Initial stiffness (kN/m)	Optimal stiffness (kN/m)
	Isolator	Base	BI_1,BI_3	1420~4000		1420	2294.9		1420	2290.3	2294.9	2298.7
			BI_2	610~2000		610	1007.5		610	1010.2	1007.5	1005.3

Figures 2(a)-(b) show the initial and final inter-story drift responses. The inter-story drift constraints are substantially violated for the initial structural design with and without isolators. No violation in inter-story drift can be found in the optimal design. The optimal structure is found to be stiffened and most of the lateral drifts are very close to the allowable inter-story drift limit of 1/800, resulting in uniform story ductility over all stories of the building. The proposed OC technique is able to automatically distribute the structural stiffness to satisfy the specified stiffness design criteria.



(a) Case A-1 (b) Case A-2 (c) Cases B-1 and B-2

Figure 2 Lateral displacement profiles and inter-story drift ratios

4.2 Reliability-Based Optimization

Cases B-1 and B-2 are selected for the optimal reliability-based design process so as to investigate the effect of reliability on member sizes of the superstructure and the impact of different initial member sizes on the convergence of the optimization process. In Case B-1, the initial stiffness of each isolator is the same as that in Case A-2, as shown in Table 1. In Case B-2, the final optimal sizes and stiffness produced from Case A-2 are taken as initial values. A target reliability index is assumed to be 1.2 for the inter-story drift responses of the superstructure. The reliability-based design optimization is subjected to inter-story drift reliability index constraints for the superstructure, whilst the reliability index of the base story displacement for the isolation system is not taken as a design constraint in the example. The base isolation system is only subjected to the displacement constraints shown in Eqns (2.2) and (2.3). The allowable minimum displacement limit of 0.027m is adopted at the base story, which is the same as Case A-2.

The distribution of the final section sizes for Cases B-1 and B-2 is shown in Table 1. The member depths from the two reliability-based optimal designs are found to be larger than those from the deterministic optimization such as Case A-2. It is also observed that Cases B-1 and B-2 result in almost the same optimal member sizes, although their initial member sizes are quite different. The optimal isolator stiffness in Cases B-1 and B-2 is found to be almost the same as that in Case A-2, since the three cases have the same displacement constraint and allowable minimum displacement limit of 0.027m at the base story.

Figure 2(c) shows the final lateral displacement and inter-story drift responses of the superstructure. It is found that in Case B-2, the final top lateral displacements of the superstructure relative to the base level is 0.038m (corresponding to 1/971 of the height of the superstructure); the top relative displacement is reduced to 0.035m for Case B-1 and 0.034m for Case B-2. The final inter-story drift ratios in Cases B-1 and B-2 are very close to each other but far below the inter-story drift ratio limit of 1/800, which again indicates that the optimal designs are insensitive to initial member sizes. As compared to the final design of Case A-2, the optimal designs in Cases B-1 and B-2 are associated with smaller lateral top displacement and inter-story drift values since the reliability-based designs impose higher levels of reliability, thereby resulting in stiffer structures.

Figure 3 presents a comparison of the initial and final reliability indices. It is noted that most of the reliability indices corresponding to the final inter-story drifts of the deterministic design optimization (i.e., Case A-2) are within 1.0~1.2, which are less than the target reliability index of 1.2. The deterministic design optimization cannot guarantee to generate a design with a satisfactory reliability level. Although the reliability index constraint for each story is initially violated in Cases B-1 and B-2, it is observed that after the reliability-based optimization, all the reliability index constraints in the two cases are very close to the target value of 1.2. Such results indicate that the reliability index can be improved by the optimization procedure. The entire structural stiffness is distributed in a way that an almost fully constrained state, i.e. uniform target reliability design, is obtained.

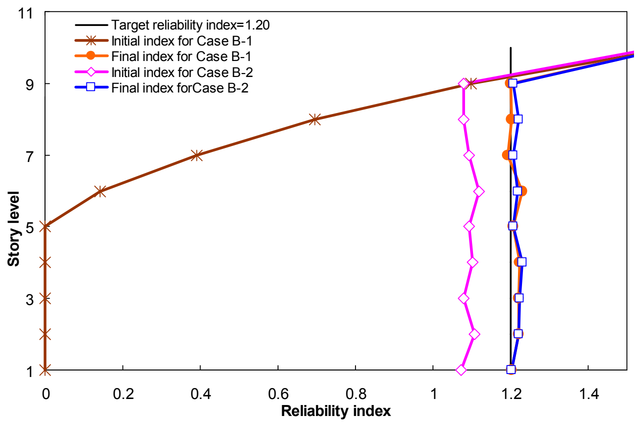


Figure 3 Initial and final reliability indices for Cases B-1 and B-2

5. CONCLUDING REMARKS

The proposed reliability-based optimization technique for isolated building structures is an effective tool for earthquake-resistance optimal structural design. Such a technique integrates response spectrum seismic analysis, structural reliability theory, isolation strategies and an OC optimization technique.

It has been exhibited from the illustrative example that the proposed algorithm for base-isolated building structures is able to drive an initial structural natural period to a target period in the optimization process. The OC technique developed is able to optimize the base-isolated structure so as to automatically distribute member sizes and isolator effective stiffnesses to satisfy all code-specified design performance criteria and to satisfy uniform drift reliability through the consideration of the uncertainties of earthquake loadings. Furthermore, conventional deterministic design optimization cannot ensure designs with satisfactory reliability level. However, the reliability-based design optimization can achieve uniform or weighted system target reliability for building structures.

It is believed that the proposed optimal design methodology can provide a rational basis for using full nonlinear analysis such as nonlinear time history analysis, and incorporating other uncertainties such as structural modeling uncertainties, aside from the uncertainties in seismic loadings.

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