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SEISMIC RELIABILITY OF BASE-ISOLATED BUILDING FRAMES

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ABSTRACT

The reliability against first passage failure of base-isolated and fixed base steel buildings frames due to earthquake ground motion is investigated. The members of the frames are designed as per UBC code. The stationary response of the system is obtained by using spectral analysis. The power spectral density function of ground motion is defined in terms of the earthquake magnitude and soil-characteristics. The first passage failure probability of the column is computed by the convolution of the conditional probability of failure with the probability density function of earthquake magnitude. The response quantity of interest is the flexural stress in the column due to earthquake ground motion. By assuming the occurrence of earthquake as a Poison's process, the reliability of the column as well as the whole frame is computed for the specified design life. The reliability of base-isolated frame is compared with that for fixed base frame. In addition, the reliability of both system is investigated under important parameters. It is found that the base-isolated frame is more reliable than the fixed base frame.

KEYWORDS

Base isolation, steel frame, reliability, soil-characteristics, earthquake, UBC-1991 and system parameter

INTRODUCTION

To protect structures from earthquake damages, the use of base isolation systems have been suggested in contrast to the conventional technique of strengthening the structural members. The main concept in base isolation is to reduce the fundamental frequency of structural vibration to a value lower than the predominant energy containing frequencies of earthquake ground motions. The other purpose of an isolation system is to provide means of energy dissipation and thereby, reducing the transmitted acceleration into the superstructure. Accordingly, by using base isolation devices in the foundations, the structure is essentially uncoupled from the ground motion during earthquakes. Although the concept of base isolation has been used for aseismic design of many buildings, it has not yet gained wide popularity. Main reasons for this include: (1) code provisions for design of base isolated buildings are still in a developing stage; (2) the design and analysis of such building require additional effort and attention; and (3) the total construction costs is likely to increase. The first design guide on base isolated structure was published by Structural Engineers

Association of California (SEAOC) (Recommended, 1990). Later, guidelines also appeared in the International Conference of Building Officers' (ICBO's) Uniform Building Code (1991). Excellent reviews of earlier work and recent work on base isolation system are provided by Buckle and Mayes (1990) and Jangid and Datta (1995).

Several base isolation systems including laminated rubber, frictional, and roller bearing have been developed. One of the most attractive devices is the laminated rubber bearing (LRB), which offer various advantages over other devices, such as lower cost, simplification of layout and high damping at a small level of amplitude. Other devices include the friction-type base isolators such as: pure-friction, the resilient-friction base isolator (R-FBI) system (Mostaghel and Khodaverdian, 1987), the "Electricite de France" (EDF) system (Gueraud et al., 1985) and the friction pendulum system (Zayas et al., 1990). These systems utilise Teflon-steel interface to create sliding bearings with some amount of restoring force or recentering capability. The effectiveness of various base isolation system for reducing the earthquake forces in a structure is widely studied. However, there have been a little attention for the seismic reliability of base-isolated frame.

Here-in, the seismic reliability of multi-storey steel building frame with fixed and isolated base is presented. The specific objectives of the study are: (i) to study the reliability against first passage failure of fixed base and base-isolated frame during earthquake ground motion and (ii) to study the effects of important parameters on the reliability of base-isolated frame.

STRUCTURAL AND BASE ISOLATION MODEL

Fig. 1 shows a moment resisting planar frame (part of a typical office building) having (i) fixed base and (ii) the isolated base. For isolated base, the laminated rubber bearings (LRB) is installed between the base mass and the foundation of the structure. The LRB system is characterised by the two parameters: lateral stiffness (k_{max}) and the damping constant (c_b). The viscous damping constant of the LRB system is expressed as

$$c_b = 2\xi_b (W/g)\omega_b \tag{1}$$

where ξ_b is the damping ratio of the LRB system; W is the total weight of the isolated structure; g is the acceleration due to gravity; $\omega_b = 2\pi/T_b$ is the base isolation frequency; and T_b is the period of base isolation defined as:

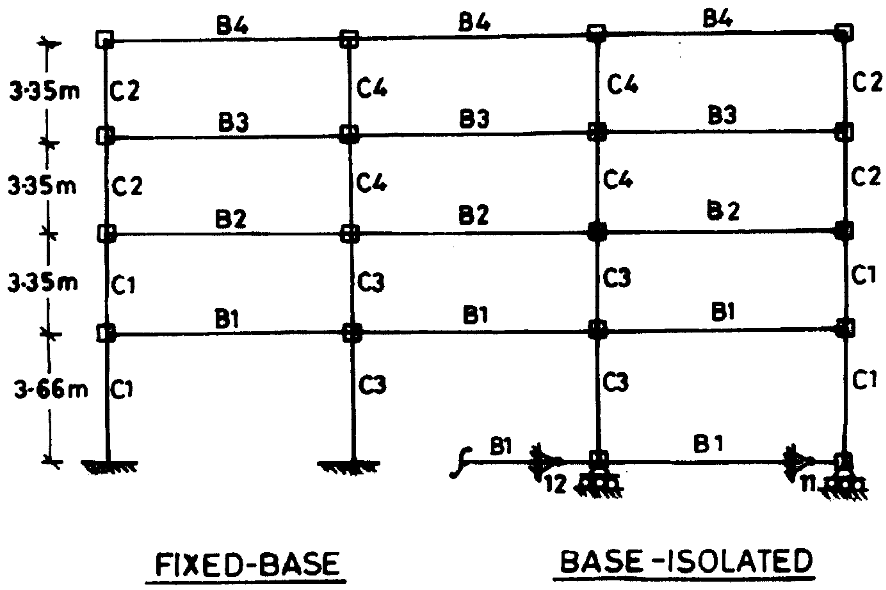

Fig. 1 Moment resisting fixed base and base-isolated building frame.

$$T_b = 2\pi\sqrt{\frac{(W/g)}{k_{max}}} \tag{2}$$

The total design base shear V, for a fixed base frame is given by (UBC-1991)

$$V = \frac{1.25ZIS}{R_w (c_t)^{2/3} \sqrt{h_n}} W \tag{3}$$

here Z and I are the seismic zone and importance factor; S is the site-soil coefficient; R_W is the coefficient which measures the ability of a structure to sustain inelastic deformation without collapse; c_t is a coefficient which takes the value of 0.035 for moment resisting frame; and h_n is the height of the building (ft).

For a base-isolated structure, the design base shear is

$$V = \frac{K_{max} D}{R_{wl}} \tag{4}$$

where D is the design displacement of the isolation system; and R_{wl} is similar to R_W (not equal in magnitude). The design displacement, D (in.) is given by

$$D = \frac{10ZNS_i T_b}{B} \tag{5}$$

where N is a coefficient related to the proximity of the building to the nearest active fault; S_i is the site soil coefficient for the isolated structure; and B is a coefficient related to the effective damping of the isolation system.

The recommended seismic design forces for fixed base and base-isolated building in UBC code follow the base shear approach. The lateral force at any level of the fixed base structure are proportional to the weight at that level and the height from the base. On the other hand, for the base-isolated buildings, the lateral forces are distributed to each floor proportional to the weights of the floors only. The shear at any level is obtained by the summation of all the lateral forces above that level.

Earthquake Ground Motion

Earthquake ground motions are inherently random and multi-dimensional. To describe such ground motions, multi-variate random process model has been proposed. In the present study, the Clough-Penzien spectral model (Clough and Penzien, 1993) of ground acceleration is used. The power spectral density function (PSDF) of earthquake ground acceleration is given by

$$S_{\ddot{x}_g}(\omega) = S_0 \left(\frac{1 + 4\xi_g^2 (\omega/\omega_g)^2}{\left[1 - (\omega/\omega_g)^2\right]^2 + 4\xi_g^2 (\omega/\omega_g)^2} \right) \left(\frac{(\omega/\omega_c)^4}{\left[1 - (\omega/\omega_c)^2\right]^2 + 4\xi_c^2 (\omega/\omega_c)^2} \right) \tag{6}$$

in which S_0 is the constant spectral density of the white-noise input; ω_g, ξ_g, ω_c and ξ_c are the ground filter parameters. For the firm soil, ω_g,= 15 rad/s, ω_c= 0.1ω_g and $\xi_g = \xi_c$= 0.6.

The peak ground acceleration is related to the magnitude of earthquake and focal distance of the site (Esteva and Rosenbluth 1964) by

$$a_{max} = b_1 e^{b_2 M} R^{-b_3} \tag{7}$$

where a_{max} is in units of cm/s^2, M is the magnitude of earthquake, R is the focal distance (in km) which is taken as 100 km, and b_1, b_2 and b_3 are the constants having the values 2000, 0.8 and 2, respectively.

For a given magnitude of earthquake, the corresponding value of the parameters S_0 is obtained by equating the a_{max} to the three times the root mean square (r.m.s) value of the ground acceleration. The r.m.s. value of the ground acceleration is the square root of the area under the PSDF curve. The probability of maximum value of the ground acceleration of exceeding to three times the r.m.s. value is 1.1% only (Nigam, 1993), therefore, it is taken as the maximum value.

RELIABILITY EVALUATION

The safety of the frame under consideration during an earthquake is related to the safety of its components (columns and beams). However, the columns are more vulnerable as compared to beams. Therefore, from safety point of view the stresses in the column should not exceed the specified barrier level. For a given earthquake of magnitude M, the probability of first passage failure i.e. the probability that the flexural stress, f in the column is larger than a threshold value $\bar{f}$ within the time interval (0,T] is determined by the relation

$$p(f > \bar{f}|M) = 1 - \exp[-N(\bar{f})T] \tag{8}$$

where T is the duration of earthquake ground motion; and $N(\bar{f})$ is given by

$$N(\bar{f}) = \frac{1}{2\pi}\left(\frac{\sigma_{\dot{f}}}{\sigma_f}\right) \exp(-\bar{f}^2 / 2\sigma_f^2) \tag{9}$$

in which, σ_f and $\sigma_{\dot{f}}$ denotes the r.m.s. value of the maximum stress and its derivative, respectively which are obtained by carrying out the spectral analysis for the specified PSDF function of the ground acceleration. The lateral displacement at each floor of the frame is considered as the dynamic degree-of-freedom. For base-isolated frame one additional degrees of freedom is considered at the base mass. The damping matrix of the frame is not known explicitly, however, it is constructed by assuming the modal damping ratio in each mode of vibration.

The probability of first passage failure of a column during an earthquake is evaluated by the convolution of the conditional probability of failure with the probability density function of earthquake magnitude (Ang and Tang 1975) i.e.

$$P_E = p(f > \bar{f}) = \int_{M_0}^{M_1} p(f > \bar{f}|M)\, f_M(M)\, dM \tag{10}$$

where M_0 and M_1 are the lower and upper limit of the magnitude of the interest, respectively, $f_M(M)$ is the annual probability density function of the earthquake ground motion which would take the form

$$f_M(M) = k_m \beta \exp[-\beta(M - M_0) \qquad M_0 \le M \le M_1 \tag{11}$$

Here β is the constant ranges mostly between 1.5 to 2.3, k_m is the normalisation constant given by

$$k_m = \{1 - \exp[-\beta(M_1 - M_0)]\}^{-1} \tag{12}$$

If the occurrence of earthquake is modelled as a Poison's process with ν as the average number of earthquake per year in the magnitude range of interest, the probability of at least one failure in **m** years is given by

$$p_f = 1 - \exp(-\nu m p_E) \tag{13}$$

The reliability against the first passage failure of the column (referred as component reliability) is given by

$$R_c = 1 - p_f \tag{14}$$

Similarly by assuming that failure of one column will cause the failure of whole frame, the system reliability, R_s can be obtained from

$$R_s = \prod_j (1 - p_f^j) \tag{15}$$

where p_f^j is the first passage failure probability of jth column.

NUMERICAL EXAMPLE

Frame used by Lin and Shenton (1992) is considered in the present study. which was designed as per UBC-1991 provisions. The frame is a part of a rectangular four-storey office building located in seismic zone 4 in the United States and founded on firm soil. The roof and floor decks consist of a bar joist/metal deck/light weight concrete fill system. Loading on the frame is taken as specified by UBC-1991 code. Three types of frame are considered for seismic reliability, (i) the fixed base design as per UBC-1991 recommended lateral forces, (ii) the fixed base design as per UBC-1991 recommended lateral forces but mounted on base isolation system and (iii) the base-isolated design as per UBC-1991 recommended lateral forces. These three types are subsequently reffered in this paper as (i) fixed base, (ii) base isolated - 0 and (iii) base isolated - 1. The member sizes of these frames are given by Lin and Shenton (1992). Vlues of the various parameters are : $Z = 1$, $I = 1$, $S = 1.2$, $N = 1$, $S_i = 1.5$, $B = 1.35$, $R_w = 12$, $R_{wl} = 3$, $T_b = 2.5$ s and $\xi_b = 15\%$.

The reliability (both component and system) against first passage failure during the design life of the above frames are investigated. The component reliability is taken as the minimum reliability of any bottom storey column. These reliability are studied against variation of the barrier level ($\bar{f}$), duration of the earthquake (T), the period of base isolation (T_b) and the damping ratio of the isolator (ξ_b). The parameters considered for the earthquake ground motion are : $M_0 = 4$, $M_1 = 9$, $\beta = 2$, and $\nu = 0.5$. It is assumed that yield stress of the steel used in column, $f_y = 250$ MPa, $m = 50$ years and the modal damping ratio is 2% of critical in each mode of vibration.

Fig. 2 shows the variation of R_c and R_s against the barrier level of the stress for the fixed base as well as the base-isolated frames. A 30 s duration earthquake is considered for analysis. The figure indicates that the base-isolated frame is more reliable than the fixed base frame. Further, the frame designed as a fixed base (as per UBC-1991) and mounted on the isolator is more reliable than the base-isolated design (compare between base-isolated - 0 and 1). As expected, both R_c and R_s increase with increased barrier level for both types of design. Thus, the base isolated frame is more reliabile against the first passage failure than the fixed base system.

In Fig. 3 the variation of R_c and R_s is plotted against the duration of the earthquake. The barrier level for the stress in the column is considered as 25 % of f_y. As expected, both R_c and R_s decrease with increased duration of the earthquake for both types of design. Further, the figure clearly shows that the reliability of base-isolated frame is more as compared to the fixed base frame.

To study the effects of isolator parameters on the reliability, the period and damping ratio of the isolator for the base-isolated - 0 frame are varied. Variation of R_c and R_s against the period and damping ratio of the base isolation system are presented in Figs. 4 and 5 , respectively. It is seen from the figure that the reliability of base-isolated frame increases with the increase in time period and damping ratio of the isolator. This happens due to fact that increase in the period of base isolation reduces the earthquake forces attracted by the structure. On the other hand, increase in the damping of the isolator dissipates more seismic energy. As a result, less earthquake forces are transmitted to the structure. Thus, reliability of base-isolated frame increases with the increase in period as well as damping of the base isolation system.

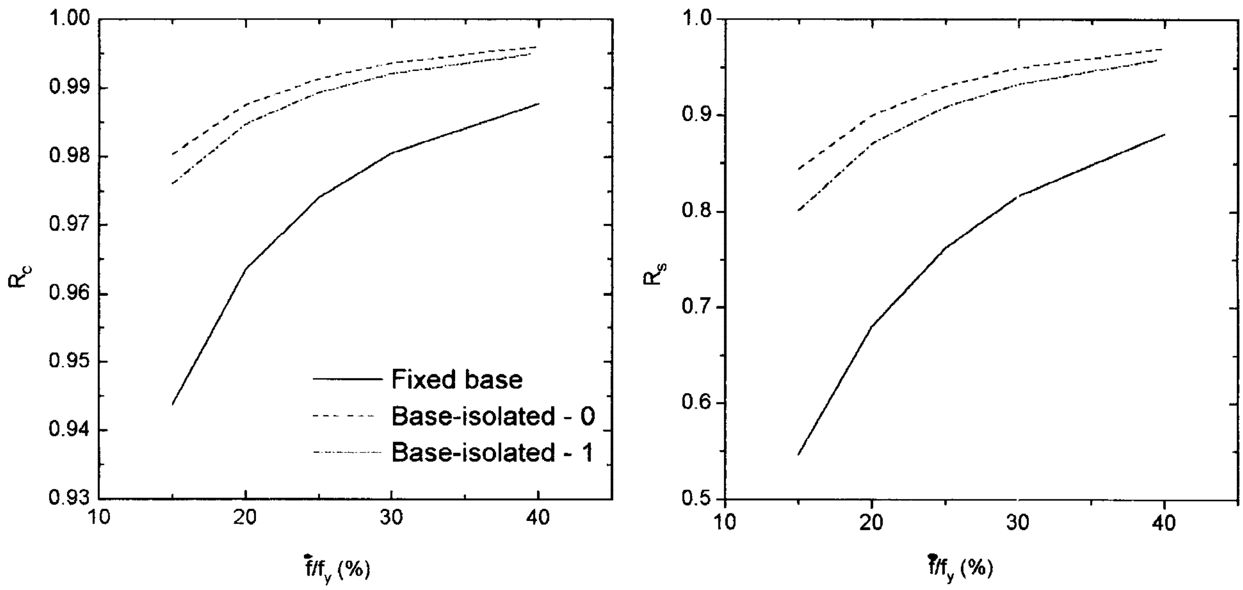

Fig. 2 Variation of R_c and R_s against the barrier level. (T = 30 sec., T_b = 2.5 s and ξ_b = 0.15)

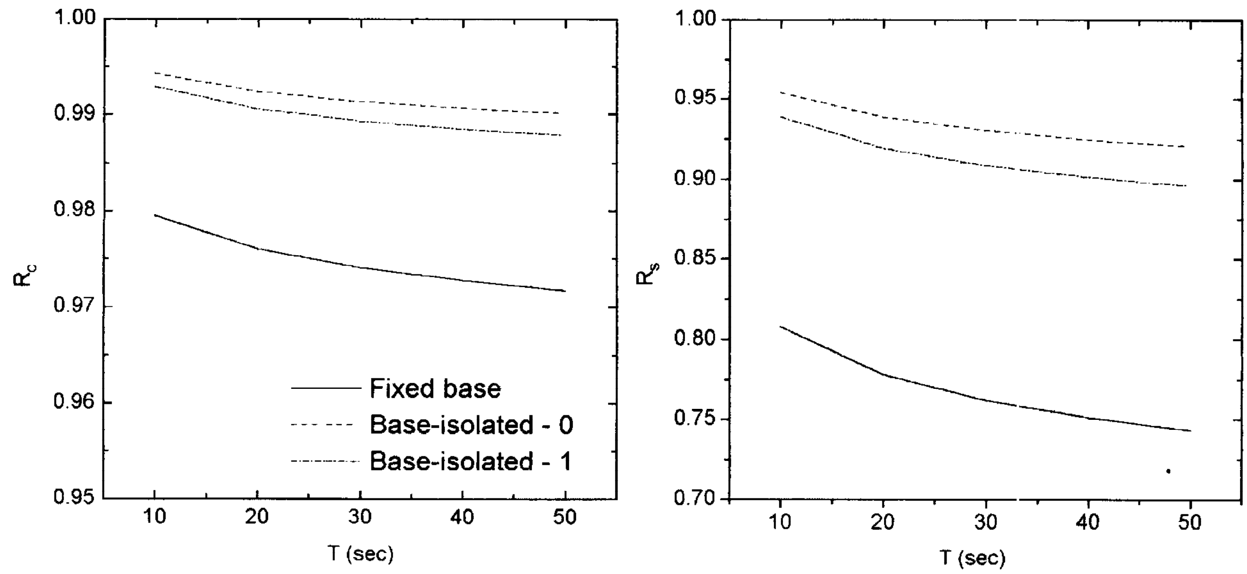

Fig. 3 Variation of R_c and R_s against the duration of earthquake ($\bar{f}/f_y$ = 25 %, T_b = 2.5 s and ξ_b = 0.15)

CONCLUSIONS

The seismic reliability of fixed base and base-isolated building frame is studied. The reliability is computed by the convolution of the conditional probability of failure with the probability density function of earthquake magnitude. The earthquake ground motion is modelled as a stationary random process specified by its power spectral density function. From the results presented herein, it can be observed that (i) the base-isolated frame is more reliable than the fixed base-design, (ii) the reliability of both fixed base and base-isolated frame decreases with the increasd duration of earthquake and it increases with the increased barrier level and (iii) the reliability of base-isolated frame increases with the increase in the period as well as in damping of the base isolation system.

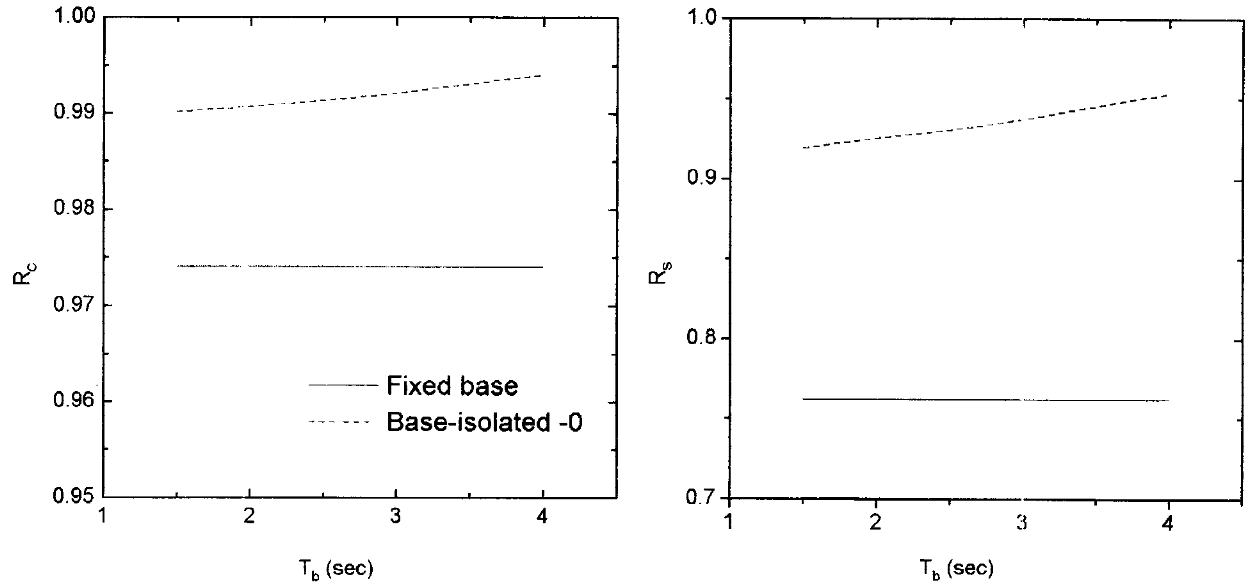

Fig. 4 Variation of R_c and R_s against the period of base-isolation (T = 30 sec., $\bar{f}/f_y$ = 25 % and ξ_b = 0.15)

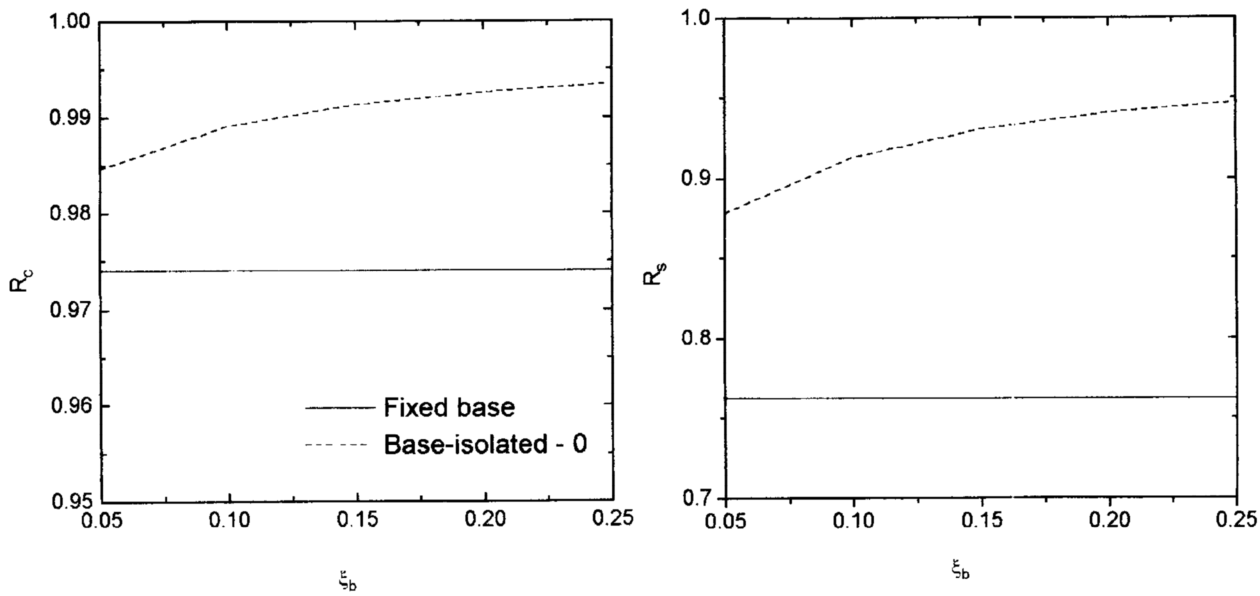

Fig. 5 Variation of R_c and R_s against the isolator damping (T = 30 sec., T_b = 2.5 s and $\bar{f}/f_y$ = 25 %)

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