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ORIGINAL CONTRIBUTION

Base Isolation Versus Dual Design Philosophy for Seismic Design of Buildings: Preliminary Case Study

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Abstract The structures are generally designed through dual design philosophy or more broadly known as performance-based design. In this philosophy, the strength is limited to minimize the cost relying on damage-absorbing capacity or ductility capacity of structural members. Still lack of understanding of many issues of nonlinear behavior of structural member makes this method an interesting topic for further research. Base isolation technique is not possible to adopt many a times due to financial limitation. However, this technique may be made more economic and practically implementable through further research. Further, design methodology can also be simplified. Thus, possibly such methodology can be used for an identified class of buildings through further research in this direction. Example case studies presented in the paper for both structures on base isolator and those designed by dual design philosophy clearly indicate intuitively understandable findings. Finally, the paper provides *a qualitative insight* for economically viable use of base isolation system. It also shows the possibilities of how inelastic excursion-based dual design philosophy can be simultaneously used along with base isolation for reducing the cost further.

Keywords Base isolation · Performance-based design · Response reduction factor · Deformation in base isolator

Introduction

A structure may encounter moderate-to-severe earthquake during its lifetime. On the other hand, it might be possible that the structure is not experiencing any kind of severe earthquake at all. This ambiguity raises a question about how to design the structures so that it becomes a reasonable balance between economy and safety. Such safety may be achieved by two possible philosophies on which scientists and engineers are researching extensively. One of them, known as control of seismic response, tries to reduce the response. Seismic response control for a structure can be classified majorly into two groups, namely active control and passive control. Active control is a methodology by which the controlling force on the structure increases as it undergoes more deformation due to external time varying force.

On the other hand, passive control generates a control in response according to its own characteristics, which is not dependent on the earthquake that the structure is experiencing, unlike the active control systems. In base isolation methods (which are one of the passive control methodologies), the building gets isolated to some extent from the direct influence of the ground motion. Since base isolation technique is relatively new and its reliability is yet to be established as compared to cost involved, traditionally the structural cost is limited by providing lesser yield strength as per dual design philosophy. This implies that in case of severe earthquake structure relies on ductility of member for facing severe earthquake pushing the structure beyond yield point. This traditional method known as dual design philosophy or performance-based design is less costly and thus frequently exercised.

The present computational study focuses on the effect of base isolator in reducing the seismic force as well as

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displacement of the structure relative to the base isolator. Validation of the program used has been done with the available experimental results [1]. In the limited scope, this paper is an effort to present a comparative picture of deformation and other response of structures. Further, detailed studies in this direction are needed to identify the category of structures for which base isolation is appropriate. On the other hand, it is also needed to categorize the class of structure for which traditional response reduction factor-dependent performance-based philosophy is more suitable from viewpoint of striking a balance between economy and safety.

Base Isolation

The base isolator can be considered as a group of structural elements that has its own dynamic properties that isolate the superstructure above it from the substructure below. In this case, the modeling has been done for a stable unbound fiber-reinforced elastomeric isolator (SU-FREI). The hysteresis properties for the isolator are available in the literature [1]. The nonlinear hysteresis behavior of the base isolator has been discussed by several researchers [3–5]. The area enclosed by the loop being small indicates that the loss of energy by the hysteresis loop is not the major reason for transmitting lesser effect to the structure. It is further intuitively guessed that the low stiffness value for the base isolator leads to the maximum extent of the isolating effect between the superstructure and the substructure.

The base isolator is idealized to behave as a flexible spring connected in series with the superstructure above. For finding out the equivalent linear stiffness of the base isolator, a methodology has been followed. A typical hysteresis curve of unbound elastomeric isolator (SU-FREI) is shown in Fig. 1a. The red lines show the actual hysteretic behavior exhibited by the base isolator. On the other hand, a line joining the points showing the mean values of the force obtained due to various particular values of displacements is presented in blue color. This curve has been utilized to obtain equivalent linear stiffness of the isolator used in the present study through nearly linear narrow hysteresis loops. Large hysteretic energy dissipation occurs at the level of the isolation devices, and the superstructure behaves very much like a rigid body with respect to the very flexible behavior of base isolator. Base isolator reduces the seismic force as well as deformation of the overall structure. It also does not allow the material of the superstructure to yield and go in the inelastic region. So, the structures such as masonry (response reduction factor = 1.5), ordinary RC moment-resisting frame (response reduction factor = 3.0) where allowable response reduction factor is less as per any standard seismic code, e.g., IS 1893 [6], and base isolator can be more useful for response reduction in comparison with the performance-based design philosophy. But, major problem in using base isolator lies in its initial as well as maintenance cost. Also, site should be such that it allows base isolator to displace 0.3–0.4 m for building of 4–5 storeys or sometimes even more than that.

The mean ordinate is obtained at an interval of 25 mm calculating the arithmetic mean of ordinates of available points at that particular abscissa. Thus, points of various abscissas are obtained with mean ordinates that do not form an exact straight line as shown in Fig. 1b. Thus, the mean line by least mean square method has been obtained and stiffness of the same is obtained from the gradient of this line. On the other hand, for performance-based design very much accurate nonlinear, inelastic analysis is needed to be carried out for calculating accurate ultimate deformation. Thus, optimization between these two design philosophies is a great challenge for the researchers. In the present study, BI property has been taken from [1] and analysis has been done for this.

Force Reduction in Dual Design Philosophy

Dual design philosophy is the widely used seismic design methodology to reduce cost. The name itself suggests its dual natured philosophy which prescribes (a) structures should be designed to behave elastically only under moderate earthquakes. (b) Further, structures should be allowed to experience post-elastic range of vibration due to strong ground shaking, without reaching ultimate deformation. This may be more clearly visualized from the example of the frame given below. The response of the column marked in the figure is given by a straight line denoting elastic response and hysteresis loop denoting inelastic excursion dissipating imparted seismic energy.

Figure 2 clearly shows that maximum strength is needed to be provided for inelastic excursion; F_y is considerably less than the strength $F_{\max}$ needed to be provided if it could have been designed to behave elastically even for the severe earthquake. Thus, adopting various combination of dual-level approach depending on the occupancy requirement helps to achieve a reasonable compromise between economy and safety.

Idealization of Structure and Structural Parameters

For the computational study, rigid diaphragm model with 4 columns at the 4 corner is used as shown in Fig. 3a. The same rigid diaphragm model has been extended storey-

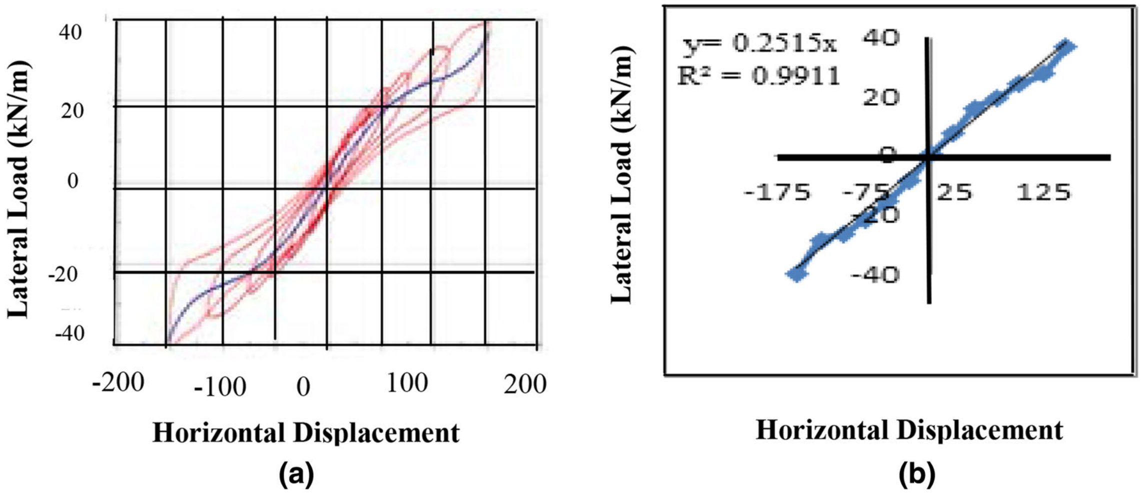
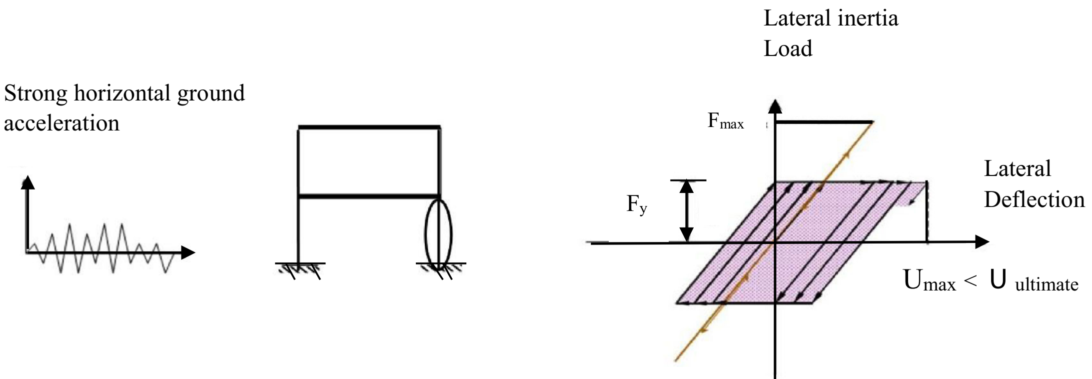


Fig. 1 **a** Typical hysteresis loops of the base isolator [1]. **b** A straight line drawn through the mean value of the ordinate in order to have an approximate linearization of stiffness



(a) Idealized structural system subjected to earthquake ground acceleration

(b) Behavior of the column in response to the earthquakeground acceleration Strength provided $F_y = F_{max}/R$, where R = response reduction factor.

Fig. 2 Philosophical explanation of dual-level approach. **a** Idealized structural system subjected to earthquake ground acceleration, **b** behavior of the column in response to the earthquake ground acceleration. Strength provided $F_y = F_{max}/R$, where R = response reduction factor

wise to achieve two-, three-, four-, and five-storied system, respectively. The fundamental period is calculated as per the formula prescribed in the IS 1893 [6], which is given by $0.075\ h^{0.75}$, where the total height h of the building is obtained by considering each storey height to be 3 m. Then, the individual storey stiffness is calculated by Dunkerley's method [7] knowing fundamental lateral period. Storey stiffness is equally distributed in four columns as mentioned.

For a better visualization, a single-storied system with and without base isolation is considered; a schematic representation through mass–spring–dashpot system is shown in Fig. 3b. For higher storeys, m_s, k_s and C_s have been added similarly. The verification of the computational methodology has been cross-checked from the experimental results given in the literature [1]. The mass of each storey comes to be around 20835.88 kg and that of base isolator 5208.97 kg as obtained from the literature earlier. The mean stiffness of base isolator has been taken from the lateral load–displacement curve of SU-FREI bearings [1] as shown in Fig. 1b, and the mean value was taken as 251.15 kN/m, from the best fit straight line as explained earlier. Damping ratio 0.05 for each of the mode has been used.

Response Parameters and Methodology

As understood from the title of the paper, this paper provides response analysis of same structures, once with base isolator and then next time designed with dual design philosophy. For the present study, the analysis of the fixed

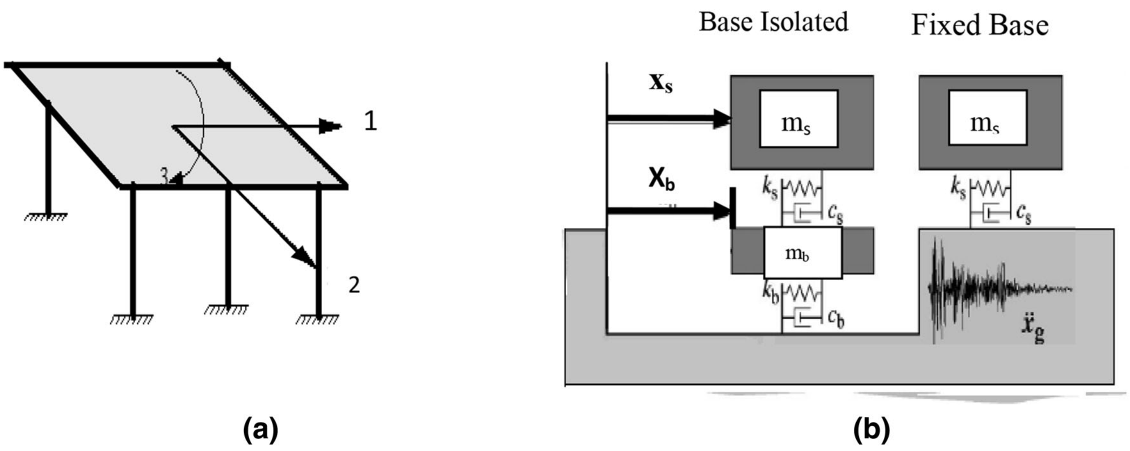


Fig. 3 Idealized single-storied structure; **a** elevation view, **b** idealized model used for analysis. *Note* k_s stiffness of the structure, k_b stiffness of the base isolator, C_s damping coefficient of the structure, C_b damping coefficient of the structure

base model has been done for different cases and the results are presented for the sake of understanding and interpretation. Comparison of the responses of buildings having base isolation, with the responses of the building designed as per dual design philosophy with response reduction factor, $R = 1$ and 4, helps to develop the physical insight. The study has been carried out for five different structures starting from 1 to 5 storeys for $R = 2$, 4, and 6. The acceleration time history used is El Centro Earthquake history with a scale-up factor of 1.32 which results in a peak ground acceleration of 0.46 g. The equation of non-linear dynamic equilibrium is numerically solved in time domain by Newmark's $\beta - \gamma$ integration [8]. For better accuracy, modified Newton–Raphson technique [9] is used and $P - \Delta$ effect is incorporated.

Results and Discussion

A parametric study has been conducted for fixed base systems with periods varying as 0.098 s, 0.17 s, 0.24 s, 0.31 s, and 0.38 s, respectively. These structures are considered as single storey, two storeys, three storeys, four storeys, and five storeys, respectively, to be compatible with their fundamental lateral periods. The results are presented in Figs. 4, 5, 6, 7, 8, and 9, respectively.

Thus, the study enables to have comparison of response of systems designed with dual design philosophy for different extent of inelasticity characterized by different values of response reduction factor R.

Validation of the Computational Methodology

Validation of the computational methodology implemented through program used has been made for both the fixed base and base isolated system [1] with the help of an existing well-accepted program [10]. The fixed base system in the experimental study did not yield. Thus, the system can be considered as fixed base with $R = 1$. Initially, dynamic analysis has been carried out to match with the experimental results available for two-storied building presented in the literature [2] for the sake of validation.

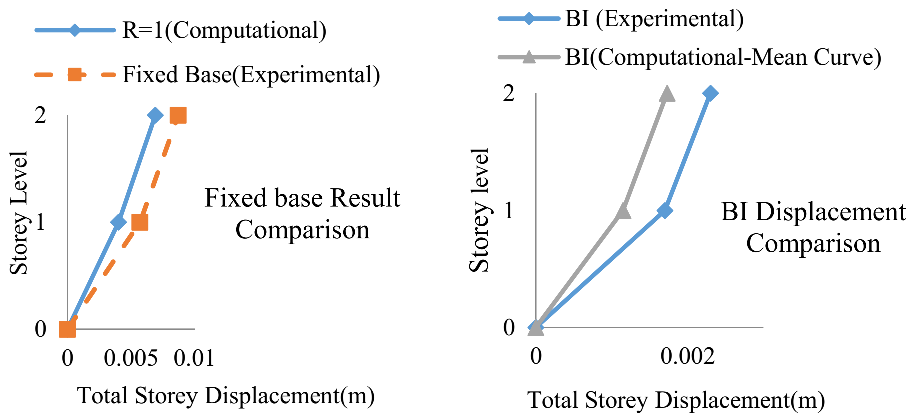
Reasonable matching of the results has been found. While considering the effect of base isolation, average stiffness of the isolator is obtained in the same way as mentioned earlier. Interestingly, the matching of the results is quite acceptable. In fact, base isolator effectively acts as another storey of very low stiffness in comparison with the other ones. The comparison with the experimental and computational results both obtained using base isolator is shown in Fig. 4. The reduction in base shear using base isolator for the experimental study was 71.85%, and by the computational study 74.28%, showing a very marginal difference. This shows the effectiveness of simplified behavioral assumption of base isolator to be fairly acceptable.

Responses of Structures with Different Storeys and Corresponding Periods

Responses of Single-Storied System

The response for single-storied structure incorporating base isolation and various response reduction factors are presented in Fig. 5. Legends in figure indicate the corresponding curves. For sake of understanding, similar legends are attempted to be used in figures exhibiting results of case studies corresponding to different storey buildings. The displacement due to $R < 4$ appears to be considerably lesser. As presented in Table 1, using the base isolator, the base shear is reduced by 63.29%. The base isolator has a displacement of 125 mm (Table 1).

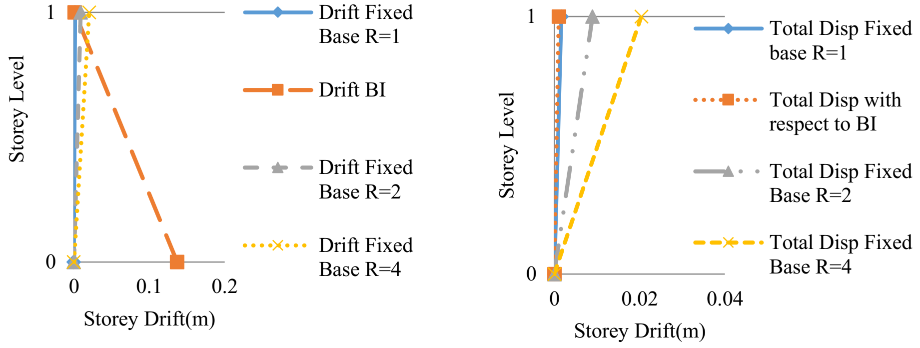
Fig. 4 Comparison of displacement obtained by experiment and that by computation for: **a** fixed base condition; **b** base isolated (BI) system



(a)

(b)

Fig. 5 Response of single-storied system: **a** storey level versus inter-storey drift; **b** storey level versus total storey displacement



(a)

(b)

Responses of Two-Storied System

The response for two-storied structure incorporating base isolation and various response reduction factors are presented in Fig. 6. However, base isolator has a displacement of 125 mm (Table 1) and the base shear is reduced by 25.77%. Hence, provision should be there to accommodate the same adequately.

Responses of Three-Storied System

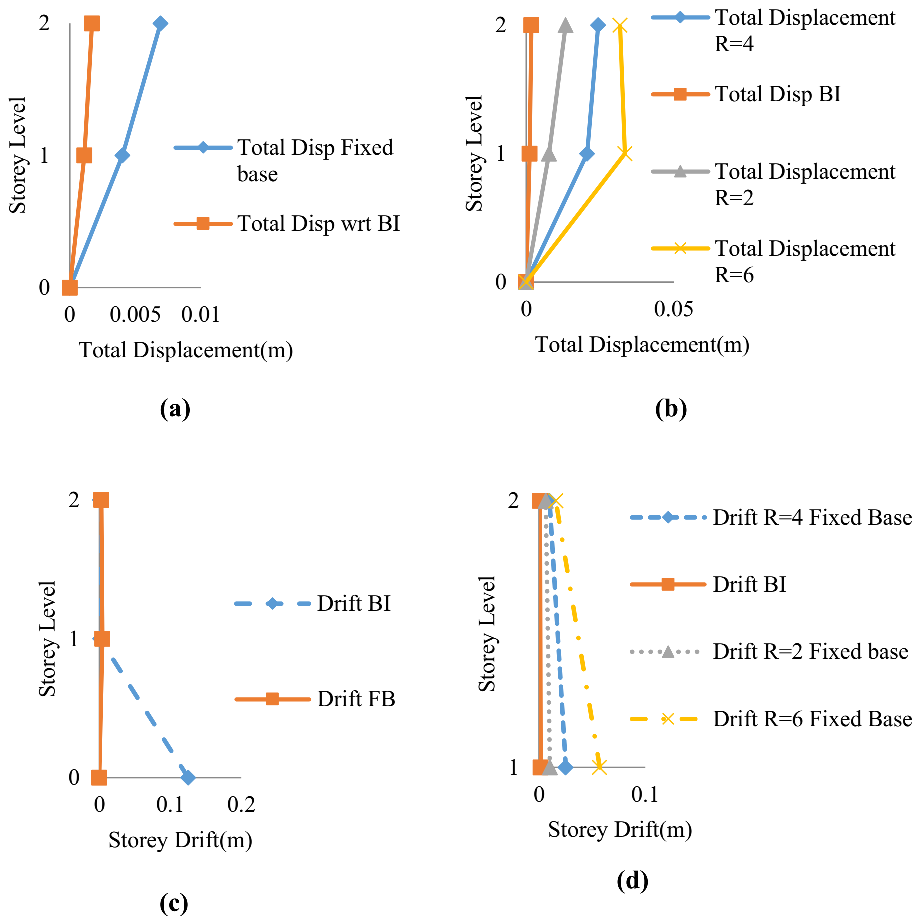
Figure 7 represents the similar results for three-storied system. Using the base isolator, the base shear is reduced by 22.77% (Table 1) which is again almost similar to the reduction in dual design philosophy using $R = 4$. But, the inter-storey drift using base isolator with respect to what obtained by fixed base equivalent of $R = 4$ is significantly low. On the other hand, base isolator has a displacement of 174 mm as presented in Table 1. This reduces storey displacement and drift indicating low stress and better safety of the entire superstructure. However, displacements and drifts obtained due to $R > 6$ seems to be considerably low and high, respectively, even compared to $R = 4$ or of course those due to base isolator. Physically saying, in this limited study, base isolator reduces the force which could have been attained due to $R = 4$, keeping deformation much lower and thus maintaining safety of the building. This in turn makes the building less prone to $P - \Delta$ effect.

Responses of Four- and Five-Storied System

Figure 8 represents the similar results for four-storied system. Using the base isolator, the base shear is reduced by 24.27% (Table 1) and also displacement obtained by base isolator with respect to fixed base of equivalent $R = 4$ is significantly low which is in line with previous observations. But, base isolator exhibits a displacement of 258 mm as presented in Table 1.

Similarly, Fig. 9 represents the similar results for five-storied system. In this case also, while using the base isolator, the base shear is reduced by 22.42% (Table 1) which is almost similar to the reduction in dual design

Fig. 6 Response of two-storied system: **a** comparison between displacements of fixed base (FB) and base isolated (BI) system; **b** comparison among displacements of fixed base systems with different extent of inelasticity and BI system; **c** comparison between storey drifts of FB and BI system; **d** comparison among storey drifts of fixed base systems with different extent of inelasticity and BI system



(a)

(b)

(c)

(d)

philosophy using $R = 4$. As expected, the maximum displacement as well as inter-storey drift using base isolator with respect to the displacement obtained by fixed base equivalent of $R = 4$ is significantly low with increase in the displacement of base isolator 317 mm (Table 1). Further, displacement and storey drift for $R < 2$ and $R > 4$ are in general lower and higher, respectively, as observed earlier, so all the results follow similar trend. In fact, the deformation of base isolator increases with the number of storeys because of increase in weight which is intuitively understood.

Major Observations

This limited example-based study shows that different types of base isolators can be identified which will limit the force domain as that demanded by different performance states as allowed in dual design or its more extended form known as performance-based design [11–13]. A chart to this effect can be made to popularize base isolator wherever affordability permits. Figure 10 makes an attempt to show the reduction in base shear due to SU-FREI, which is equal to the base shear reduction caused by how much value of response reduction factor in a performance-based design and called as equivalent R. This equivalent R is different for building with different storeys and is presented in Fig. 10a.

Normally, equivalent R shows an increasing trend with number of storeys. The similar study is also needed to be carried for other base isolators along with their costs and viability of maintenance. Such detailed studies can provide complete guidelines for categories of buildings, about the economic viability and other issues facilitating development of guidelines for routine use of base isolators. Another observation has been found that with higher storied structure and higher R value the higher modes have considerable domination. Figure 10b shows that deformation in base isolator increases with number of storeys implying reduction in deformation and stress in superstructure. It also indicates that the use of base isolator may be economic for building with more number of storeys.

Further, the present study indicates a conceptual viewpoint that linearization of stiffness of base isolator yields reasonably accurate results. This issue should be verified with a number of case studies involving a number of base isolators. In fact, once this concept is established, seismic

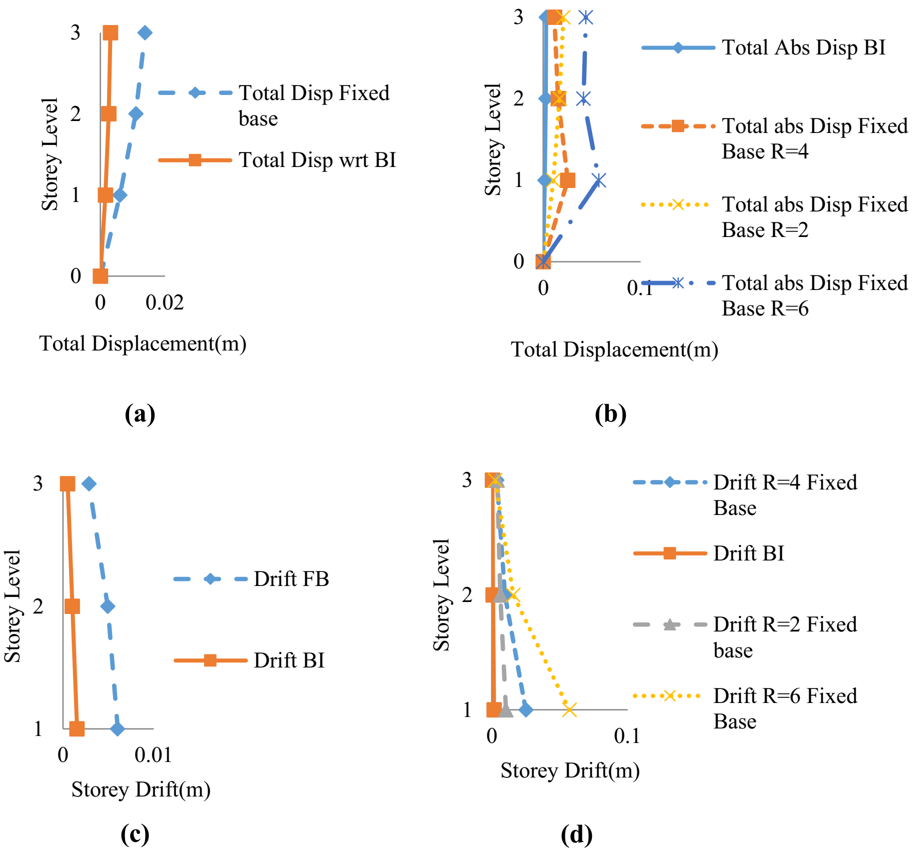


Fig. 7 Response of three-storied system: **a** comparison between displacements of fixed base (FB) and base isolated (BI) system; **b** comparison among displacements of fixed base systems with different extent of inelasticity and BI system; **c** comparison between storey drifts of FB and BI system; **d** comparison among storey drifts of fixed base systems with different extent of inelasticity and BI system

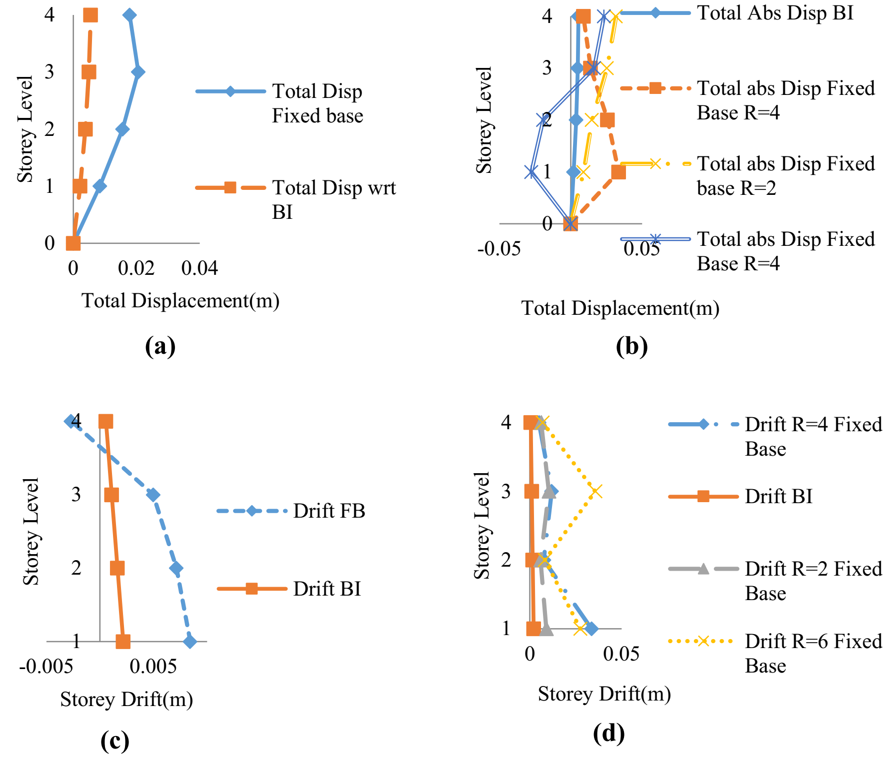
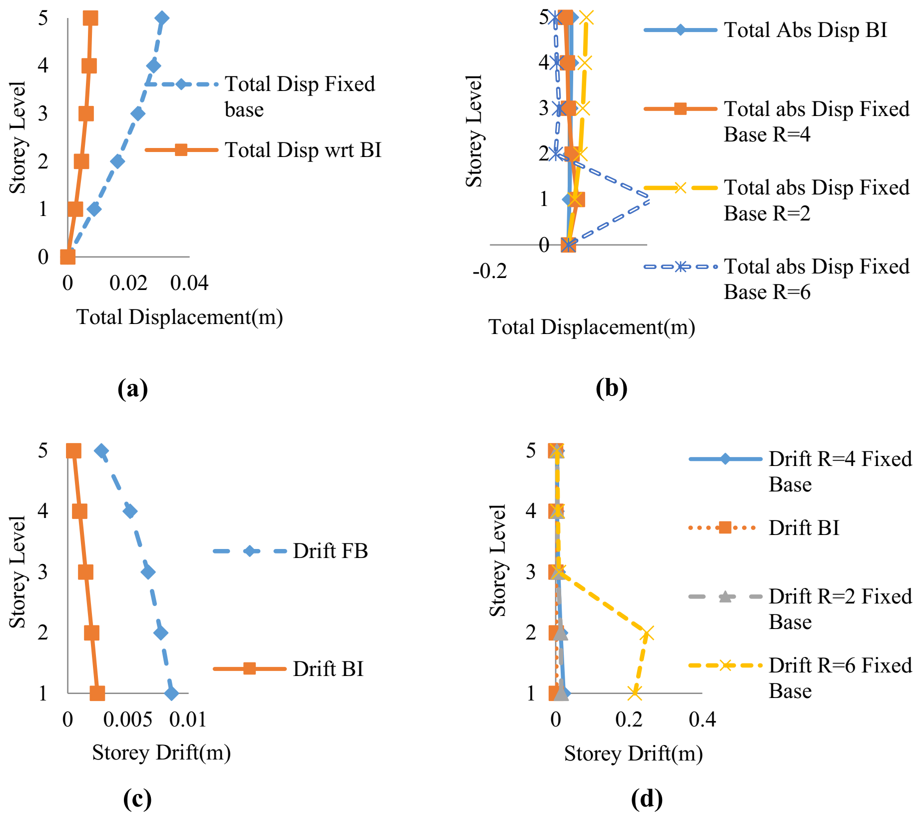


Fig. 8 Response of four-storied system: **a** comparison between displacements of fixed base (FB) and base isolated (BI) system; **b** comparison among displacements of fixed base systems with different extent of inelasticity and BI system; **c** comparison between storey drifts of FB and BI system; **d** comparison among storey drifts of fixed base systems with different extent of inelasticity and BI system

Fig. 9 Response of five-storied system: **a** comparison between displacements of fixed base (FB) and base isolated (BI) system; **b** comparison among displacements of fixed base systems with different extent of inelasticity and BI system; **c** comparison between storey drifts of FB and BI system; **d** comparison among storey drifts of fixed base systems with different extent of inelasticity and BI system



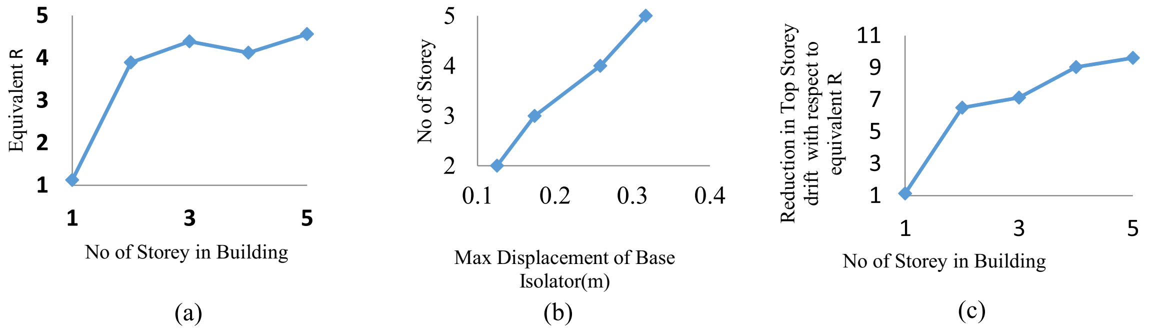
(a) (b)

(c) (d)

Table 1 Total number of storeys in the building versus lateral deformation in the base isolator and reduction in base shear

No. of storeys	Lateral deformation of base isolator (in mm)	Reduction in base shear due to base isolator (in percentage)
1	132	63.29
2	125	25.77
3	174	22.77
4	258	24.27
5	317	22.42

design using base isolators will be extremely convenient. Figure 10c presents that the base isolator deformation increases with number of storeys expressed in terms of equivalent R. As expected, storey level drift as well as displacement increases with response reduction factor, R, as large inelastic deformation invites self-increasing $P - \Delta$ effect which may lead to collapse. This danger can be drastically reduced by an equivalent base isolator which is shown in the form of an example.



(a) (b) (c)

Fig. 10 **a** Equivalent R versus no. of storeys of the system; **b** number of storeys in the system versus maximum displacement of the base isolator; **c** Reduction in drift of top storey versus the number of storeys in the building

Conclusions

This paper leads to the following broad conclusions.

1. Study indicates that the use of base isolation may be a more feasible option with the increase in storeys, i.e., weight or in other way degree of importance of structure. However, dual design philosophy induces damage in the structure and requires post-earthquake repairing.
2. Major reduction in transmitted force occurs due to less stiffness of the isolator rather than its hysteresis behavior. This property, i.e., contribution of lesser overall stiffness with or without some contribution of narrowed down hysteresis loops, opens up another area for research.
3. Further, the flexible spring behavior of isolator increases lateral natural period of structure, hence taking fundamental period away from the dominant periods of the catastrophic input motion.
4. However, if a base isolator is provided then soil is separated to a large extent from direct interaction with structure. Thus, it may well intuitively understood that effect of soil flexibility may marginalized once an isolator is provided. So, such a study was not included in the limited scope of the present paper.

Future Scope

Along with the above major conclusions of the study, the research in the following directions may be carried out for efficient and cost-effective use of base isolation system.

1. It is still required to be investigated about how by widening the area of hysteresis loop the seismic force reducing effect of base isolation can be increased.
2. Research needs to be carried out for partial development, i.e., use of both base isolator and dual design philosophy. That would lead to a simultaneous achievement of safety as well as economy.
3. Low-cost rubber sheets of various types and thicknesses can be used for isolation of masonry buildings. Masonry buildings all over the world cause tremendous casualties and property loss, particularly belonging to low- to middle-class economic background (because of their natural tending to undergo seismic damage).
4. On the other hand, cost analysis can be an important issue as well, but it depends not only on type and nature of isolator but many other factors. In fact, our knowledge about base isolation in the implementation level is in a primitive stage as only counted numbers of buildings all over the world are base-isolated. However, increase in number of storeys seems to have dominating effect in cost reduction, while other aspects are open for further detailed studies.
5. Further, a detailed study providing a comparative picture on the effectiveness of various base isolators should also be available.

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