

Methods for Seismic Retrofitting of Structures

Retrofitting of existing structures with insufficient seismic resistance accounts for a major portion of the total cost of hazard mitigation. Thus, it is of critical importance that the structures that need seismic retrofitting are identified correctly, and an optimal retrofitting is conducted in a cost effective fashion. Once the decision is made, seismic retrofitting can be performed through several methods with various objectives such as increasing the load, deformation, and/or energy dissipation capacity of the structure (FEMA, 2000). Conventional as well as emerging retrofit methods are briefly presented in the following subsections.

Conventional Strengthening Methods

Conventional retrofitting methods include addition of new structural elements to the system and enlarging the existing members (Newman, 2001). Addition of shear walls

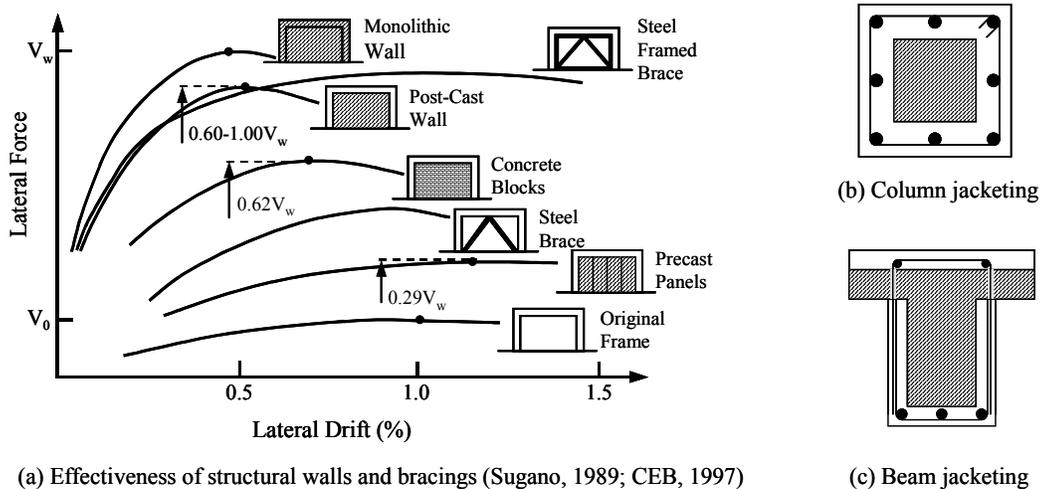


Fig. 1 Conventional strengthening methods used for seismic retrofitting

and bracings shown in Fig. 1(a) is the most popular strengthening method due to its effectiveness, relative ease, and lower overall project cost compared to column and beam jacketing shown in Fig. 1(b) and (c), respectively. Relative effectiveness of various wall and bracing configurations are compared in Fig. 1(a). From this figure, it is seen that post-cast shear walls and steel braced frames are the most effective strengthening techniques. Although the latter is more effective due to its much higher ductility, post-cast concrete shear walls are the most commonly applied method due to their lower cost and familiarity of the construction industry with the method. Design of additional shear walls is performed to resist a major fraction of the lateral loads likely to act on the structure. This reduces the demand on the beams and columns, hence increasing their safety. Those still likely to be overstressed are strengthened through concrete or steel jacketing, which are relatively more laborious applications. Fig. 2 shows applications of various conventional strengthening methods such as post-cast shear wall (a), additional foundation to support the shear walls to be constructed around the stairs (b), concrete jacketing of a column (c), and addition of column members to

remedy vertical irregularities (d). The main research need associated with conventional strengthening methods is optimization of the retrofit design to achieve a satisfactory structural performance level at a minimum cost based on reliably characterized seismic demand and structural capacity.

Retrofit of Structures Using Innovative Materials

Current research on advanced materials in civil engineering is mainly concentrated on high performance concrete and steel, and fiber reinforced plastic (FRP) composites. FRP composite materials have experienced a continuous increase of use in structural

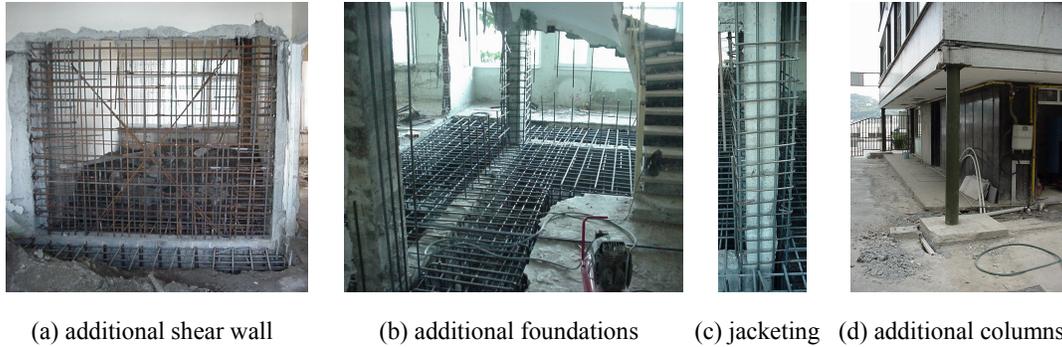


Fig. 2 Applications of conventional strengthening methods

strengthening and repair applications around the world in the last fifteen years. High specific stiffness and specific weight combined with superior environmental durability of these materials have made them a competing alternative to the conventional strengthening methods. It was shown through experimental and analytical studies that externally bonded FRP composites can be applied to various structural members including columns, beams, slabs, and walls to improve their structural performance such as stiffness, load carrying capacity, and ductility (Büyüköztürk and Hearing, 1998).

FRP composites have enjoyed varying degrees of success in different types of

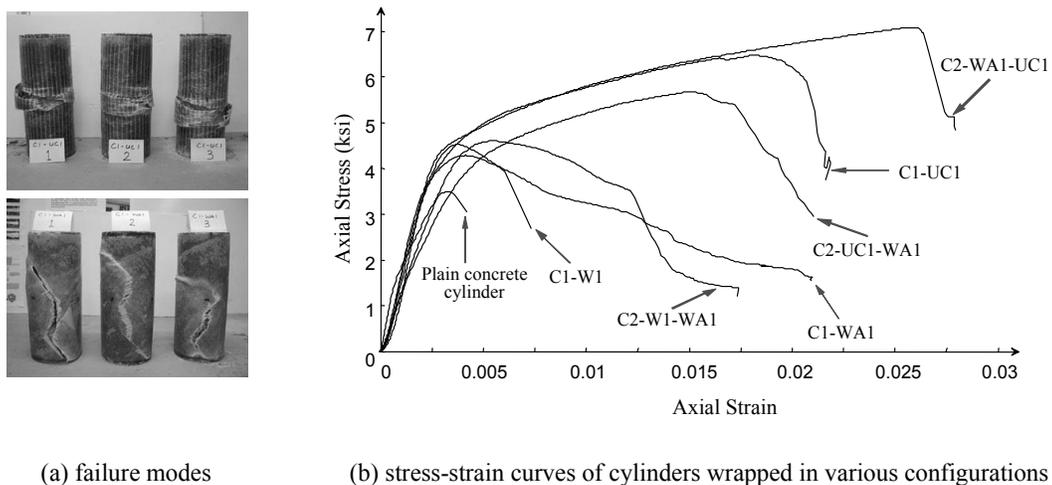


Fig. 3 Performance and failure modes concrete cylinders wrapped with FRP composites in various fiber orientations

applications. In general, applications that allow complete wrapping of the member with FRP have proven to be effective. Wrapping of columns to increase their load and deformation capacity is the most effective and most commonly used method of retrofitting with composites. However, certain performance and failure mode issues regarding different wrapping configuration and fiber orientations, shown in Fig. 3, still need to be well understood (Au, 2001). When wrapping is difficult or not allowed, such as when strengthening beams, slabs, or walls, success of the method is sometimes hindered by premature debonding failures (Güneş, 2002). Fig. 4 shows the performance of beams strengthened using pultruded FRP plates in various configurations. It can be seen from this figure that flexural strengthening of beams without proper attention to brittle shear and debonding failure modes not only renders the strengthening application ineffective, but also harms the member by decreasing its ductility. This constitutes one of the main factors, along with their high material costs, hindering wide-range use of FRP materials (Büyüköztürk et al., 1999, Güneş, 2002). Such problems can be reduced through proper design and anchorage of the external FRP reinforcement (Büyüköztürk et al., 2002a, 2002b, 2002c). Thus, decision makers must approach using these materials with caution and must ensure that the design is performed with adequate knowledge and skill, and verified through laboratory testing.

Limited research and applications regarding seismic retrofitting of building systems with FRP composites have shown that composites retrofitting does not significantly alter the stiffness and dynamic properties of the building. The main benefit of retrofitting with composites is the increase in deformation capacity of the building, and in its load capacity to an extent. This may achieve the retrofit objectives for buildings with lightly insufficient seismic resistance. For buildings with large seismic deficiencies, a combination of conventional and FRP strengthening techniques may prove to be an effective retrofitting solution. Fig. 5 shows such an application where a historical school building in Istanbul was retrofitted using steel and FRP composites. The 3-D computer model of the building is shown in Fig. 5(a), the analysis of which revealed that under seismic design loads excessive cracking is expected around the openings in the exterior unreinforced concrete walls in the short direction due to stress concentrations as shown in Fig. 5(b). As a practical and economical solution, the retrofit

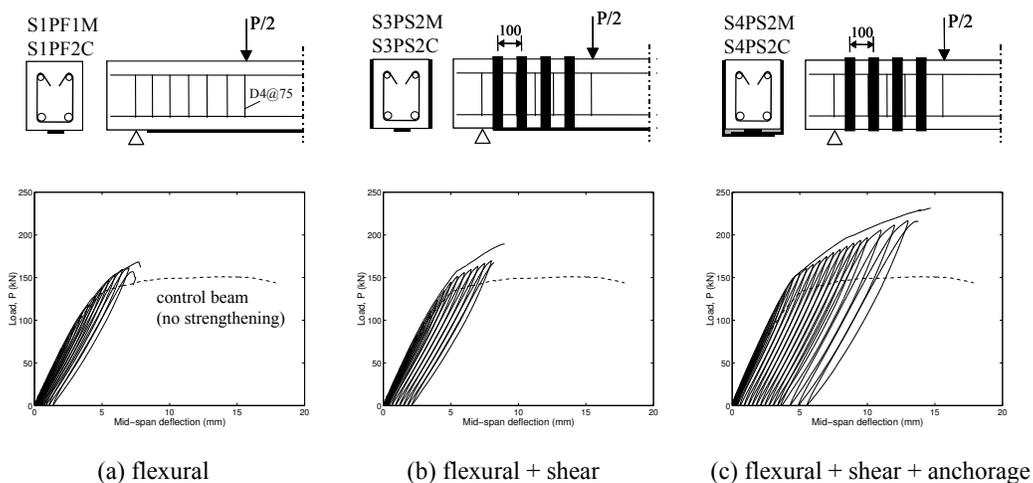


Fig. 4 Influence of shear strengthening and anchorage on FRP strengthened beam behavior under cyclic loading

design involved replacement of the existing window frames with structural steel frames constructed from steel C-sections. A verification analysis of the retrofitted building showed that installation of steel window frames largely decreased the stress concentrations, but did not suffice to reduce all stresses to acceptable levels. For this reason, additional retrofitting was designed using externally bonded FRP composites around the openings in the walls to prevent or delay concrete crack propagation by bridging the stresses at crack locations. Thus, by combining conventional and innovative materials, an effective and economical retrofit design was achieved that did not significantly interfere with the function or historical and architectural character of the building.

FRP composites are widely recognized for their potential use in seismic retrofitting applications. To achieve wide-range use of these materials, however, there is need for further research into a number of issues related to mechanics, design, and durability of FRP retrofitted concrete and steel systems. Despite considerable progress in these areas since early last decade (ACI-440F, 2000), further improvements are necessary to meet the needs of the retrofit industry. Failure mechanisms, with emphasis on brittle shear and debonding failures, must be thoroughly understood and associated design procedures must be incorporated in design codes. Influence of cyclic and fatigue loading on the FRP strengthened member performance must be characterized and accounted for in the design process. Although FRP composites are known for their favorable durability characteristics, only limited information is available on long-term durability and performance of FRP bonded concrete and steel systems. These issues need to be investigated through accelerated test studies and related design, application and protection requirements must be included in the design codes.

Base Isolation

The seismic base isolation technology involves placing flexible isolation systems between the foundation and the superstructure. By means of their flexibility and energy absorption capability, the isolation systems reflect and absorb part of the earthquake input energy before this energy is fully transmitted to the superstructure, reducing the energy dissipation demand on the superstructure. Base isolation causes the natural period of the structure to increase and results in increased displacements across the isolation level and reduced accelerations and displacements in the superstructure during an earthquake. This not only provides safety against collapse, but also largely reduces

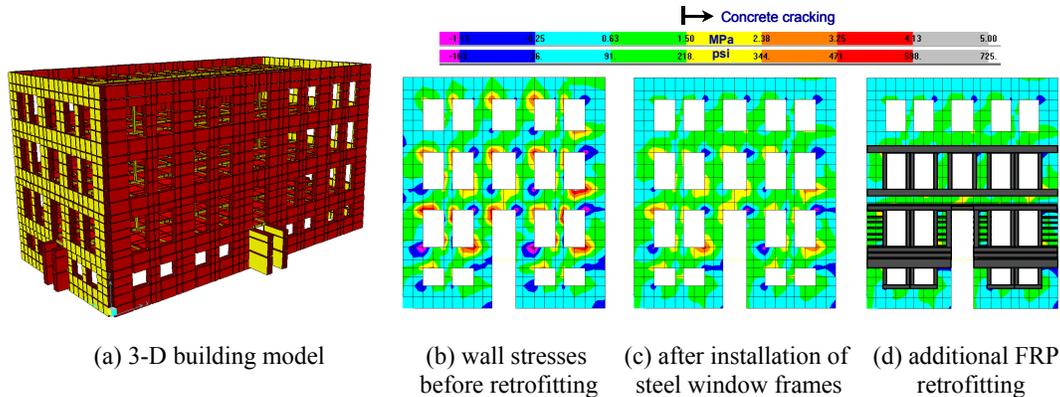


Fig. 5 A retrofit application combining conventional and composites retrofitting

damage, which is crucial for facilities that should remain operational after severe earthquakes such as emergency response centers, hospitals, and fire stations (EERI, 1990; ATC, 1993; Kelly, 1993; Skinner et al., 1993; Connor and Klink, 1996; Komodromos, 2001). Base isolation can also be used in seismic retrofitting of historic structures without impairing their architectural characteristics by reducing the induced seismic forces. Fig. 6 shows the results of a feasibility study for base isolation of a historical school building in Istanbul (Bachas et al., 2001). The structural system of the building is formed by thick exterior unreinforced concrete walls resisting lateral loads and interior steel frames carrying the vertical loads. A combination of lead-plug rubber bearings and natural rubber bearings were considered for the exterior walls and the interior frames, respectively. The basic design philosophy shown in (a) is to increase the fundamental period of the structure so that the effective seismic demand on the structure is less than that can safely be resisted by the structure. Analysis results showing the deformed shape of the building before and after the base isolation in (b) and (c), respectively, make it clear that base isolation reduces the deformations and hence the stresses in the building.

Base isolation is generally suitable for low to medium rise buildings, usually up to 10-12 stories high, which have their fundamental frequencies in the range of expected dominant frequencies of earthquakes. Superstructure characteristics such as height, width, aspect ratio, and stiffness are important in determining the applicability and effectiveness of seismic isolation. The seismicity of the region and the underlying soil conditions should also be considered in the feasibility studies and design process. Base isolation should be avoided in areas where expected fundamental frequencies of the earthquakes are in the lower frequency domain or on soft soil sites where amplification of low earthquake frequencies may occur. One other constraint in the application of base isolation is the large relative displacements between the superstructure and the supporting ground at the isolation level. A clearance around the building must be provided and maintained through the life of the structure to accommodate the expected large displacements. Such displacements may be reduced with the incorporation of additional stiffness and energy dissipation mechanisms in the isolation system.

The International Building Code (IBC, 2000) and FEMA 356 (FEMA, 2000) specify the methodologies according to which seismically isolated structures can be designed. Both the isolation system and the isolated structure are required to be designed to resist the deformation and stresses produced by seismic events. Two levels of earthquake input are considered in design. The design earthquake (475-year return period) is used to calculate the total design displacement of the isolation system and the lateral forces and displacements of the isolated structure, and the maximum considered earthquake (1000-year return period) is used to calculate the total maximum displacement of the isolation system to ensure its integrity even at extreme ground shaking. Deformation characteristics of the isolation system is required to be based on properly substantiated prototype tests with predefined sequence and number of loading cycles.

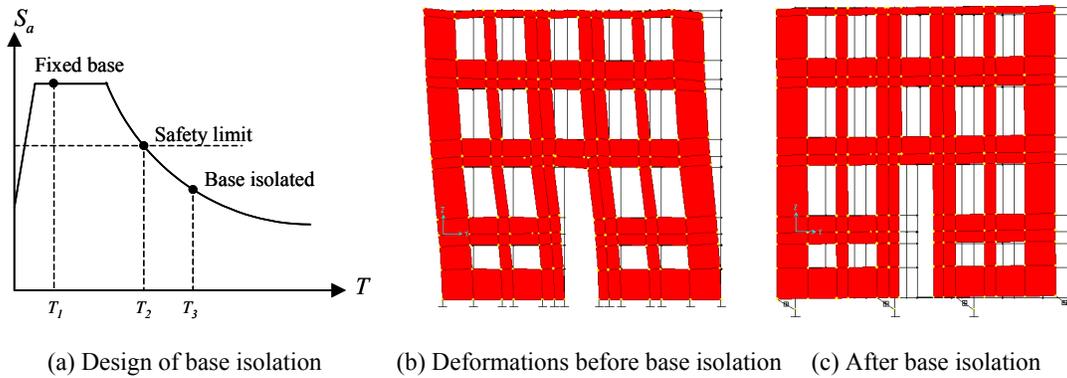


Fig. 6 Analysis and design of building base isolation

Seismic isolation is proven to be a very effective method for protecting buildings and other structures against seismic hazards (Skinner et al., 1993; Kitagawa and Midorikawa, 1998; Komodromos, 2001). An important disadvantage of the method, however, is that it cannot be applied partially to structures, unlike most other seismic retrofitting methods. For this reason, the cost of base isolation is often significantly higher than alternative retrofitting methods. This often limits the application of base isolation to (1) special buildings, such as certain industrial, research, public and hospital buildings that contain sensitive equipment or strict operational and performance requirements, (2) historical buildings, the architectural and historic character of which may be harmed by alternative retrofitting methods, (3) bridges, for which relatively less number of isolators are required and installation is easier. In order to increase the cost competitiveness of base isolation for buildings, there is need for research in the areas of reducing the application costs through efficient design and specialized equipment, and optimization of isolator types, combination, and arrangement.

Supplemental Energy Dissipation and Structural Control

An alternative and often more cost efficient retrofitting strategy compared to base isolation is installation of supplemental energy dissipation devices in structures as a means for passive or active structural control (Housner et al., 1997; EERI, 1993; Constantinou and Symans, 1993; Symans and Constantinou, 1999; Soong, 1990; Soong and Dargush, 1997, FEMA, 2000). The objective of structural control is to reduce structural vibrations for improved safety and/or serviceability under wind and earthquake loadings. Passive control systems reduce structural vibration and associated forces through energy dissipation devices that do not require external power. These devices utilize the motion of the structure to develop counteracting control forces and absorb a portion of the input seismic energy. Active control systems, however, enhance structural response through control forces developed by force delivery devices that rely on external power to operate. The actuator forces are controlled by real time controllers that process the information obtained from sensors within the structure. Semi-active control systems combine passive and active control devices and are sometimes used to optimize the structural performance with minimal external power requirements. Fig. 7 shows the basic principles of various control systems commonly used to control wind and seismic forces acting on building structures.

The severity of seismic demand on a structure is proportional to its stiffness and inversely proportional to its damping or energy dissipation capacity. Thus, installing

supplemental energy dissipating devices in the structure reduces the seismic demand and results in increased safety of the structure and its contents from the damaging effects of earthquakes. In recent years, considerable attention has been paid to research and development of structural control devices, with particular emphasis on improving wind and seismic response of buildings and bridges. In both areas, efforts have been made to develop the structural control concept into a workable technology, and as a result, such devices have been installed in a variety of structures around the world. The most challenging aspect of vibration control research in civil engineering is the fact that this is a field that requires integration of a number of diverse disciplines, some of which are not within the domain of traditional civil engineering. These include computer science, data processing, control theory, material science, sensing technology, as well as stochastic processes, structural dynamics, and wind and earthquake engineering. These coordinated efforts have facilitated collaborative research among researchers from a diverse background and have accelerated the research to the implementation process. Continued research is essential in this area to develop effective and affordable retrofitting solutions for structures with insufficient seismic resistance.

A special concern regarding the use of energy dissipation devices in structures with high characteristic variability is the fact that the effectiveness of such devices is dependent on the deformation capacity of the structure. For structures that suffer from inadequate seismic detailing, which translates into insufficient deformation capacity, great caution must be exercised in use of these devices for seismic retrofitting. A feasible solution may be to combine this technique with deformation enhancement measures to ensure their effectiveness. This constitutes an important research area with valuable potential contribution and high potential benefits.

Effects of Seismic Retrofitting on Structural Performance

The seismic retrofit techniques briefly presented in the preceding sections vary in the mechanisms that they decrease the seismic risk of structures (ATC, 1996). Fig. 8 graphically illustrates these mechanisms by means of their effects on the seismic demand and structural capacity curves shown in Part 2. These effects are presented in the following paragraphs at a simplified conceptual level.

The typical effect of conventional strengthening methods is shown in Fig. 8(a). Conventional strengthening applications generally lead to an increase in both the stiffness and the lateral load capacity of the structure. This is shown by the capacity curve of the strengthened structure, C_s , which has a higher slope and peak compared to the capacity curve before strengthening, C_u . Due to the increased stiffness, which translates into a decreased fundamental period, the seismic demand on the structure is also increased, as shown by the demand curve for the strengthened structure, D_s , compared to that for the unstrengthened structure, D_u . Although the capacity increase is partly alleviated by the increase in seismic demand, the overall performance of the structure is improved as shown by the locations of the performance points on the spectral displacement axis for before and after strengthening.

Increasing the overall deformation capacity of a structure is also an effective seismic retrofitting method. Insufficient deformation capacity of structural members is usually caused by their inadequate seismic detailing. Ductility of these members can be increased through various measures such as providing additional confinement by additional stirrups or wrapping with FRP composites. Fig. 8(b) shows the effect of deformation or ductility enhancement on the structural performance. While the capacity curve of the structure prior to retrofitting does not intersect the demand curve, an intersection i.e. a performance point is obtained after retrofitting. It is important to note that since the stiffness and damping characteristics of the structure are not significantly altered, the demand curve remains essentially the same after retrofitting.

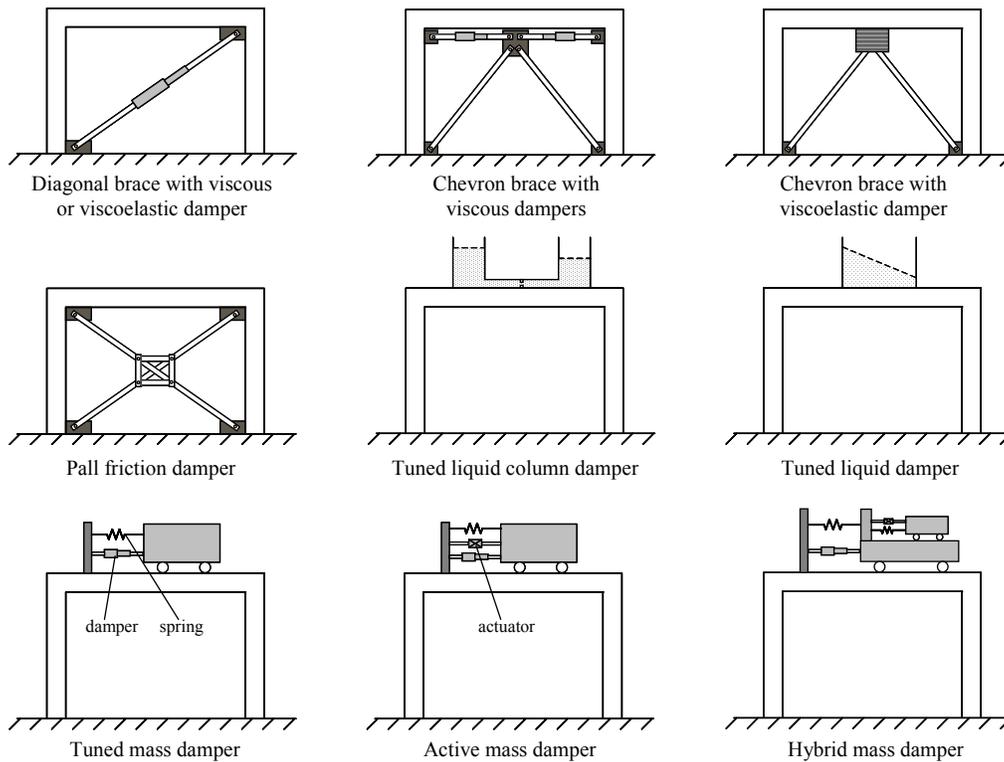


Fig. 7 Supplemental energy dissipation devices

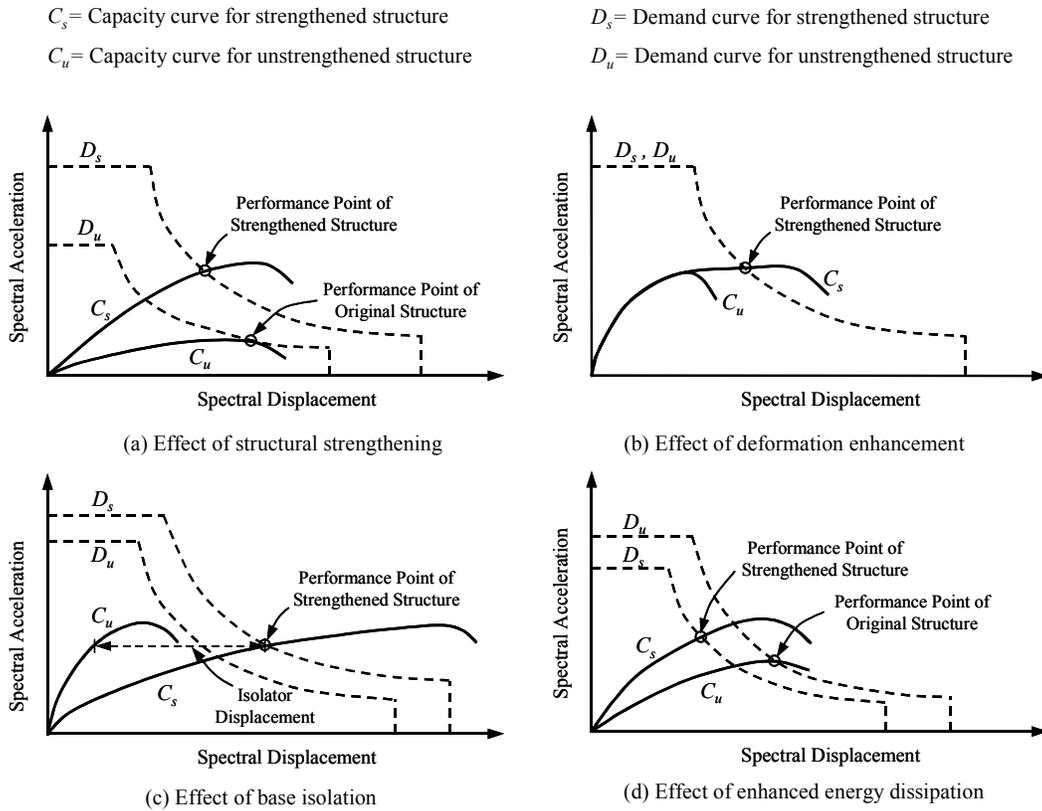


Fig. 8 Effects of various retrofit measures on structural performance

The effectiveness of seismic base isolation in increasing the structural performance during seismic events is shown in Fig. 8(c). Base isolation significantly increases the effective fundamental period and deformation capacity of the structure. This is apparent from the capacity curve of the base isolated structure, C_s , shown in Fig. 8(c). It seems somewhat contradictory, however, that the demand curve for the base isolated structure, D_s , is shown as higher than the fixed-base condition, D_u , since base isolation is known to decrease the seismic demand on the structure. This is due to the fact that the energy dissipation in a base isolated structure is significantly different than the same structure in fixed-base condition. Due to relatively lower stiffness of the isolation system, the effective damping for a certain spectral displacement is lower in the base isolated structure, resulting in a higher apparent seismic demand. However, since the deformation capacity of the structure is significantly increased, a major portion of which takes place at the isolation level, the building can safely tolerate this apparent increase in the seismic demand, resulting in a satisfactory performance level.

Seismic retrofitting of structures using energy dissipation devices such as those shown in Fig. 7 result in an increase in the stiffness, load capacity, and effective damping of the structures. Effects of these on the structural performance is shown in Fig. 8(d). As can be seen from the figure, the effect of energy dissipation devices on the capacity curve is similar to structural strengthening with conventional methods shown in Fig. 8(a). Additional advantage of using energy dissipation devices is that the seismic demand on the structure is also reduced due to increase in the effective damping of the structure. Comparing the seismic demand curves before (D_u) and after (D_s) retrofitting in Fig. 8(a)

and (d), it is apparent that use of energy dissipation devices results in a more desired performance level compared to conventional strengthening methods.

Selection of a particular retrofitting technique depends on the seismic demand, structural capacity, the required performance level, functional characteristics and the importance of the structure. The main challenge is to achieve a desired performance level at a minimum cost, which can best be achieved through a detailed nonlinear analysis as demonstrated by Part 2 and the above discussions. Ideally, each structure must be evaluated in detail to determine the optimum retrofit strategy compatible with its characteristic. In the case of large building stocks, however, a classification of structures according to their current and required performance levels may lead to development of common standardized retrofit strategies for structures in the same group, which in turn may prove to be a more rapid and cost effective overall methodology.