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STATE-OF-THE-ART IN TECHNIQUES FOR REHABILITATION OF BUILDINGS

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ABSTRACT

An overview of the state-of-the-art in techniques for seismic rehabilitation of existing buildings was presented in this paper with emphasis on research and practice. First typical techniques used for reinforced concrete, steel and masonry buildings were summarized in accordance with the aims of rehabilitation. New approaches to utilize seismic isolation and supplemental damping as well as conventional strengthening techniques to infill, to brace and to jacket existing structure were described. Over twenty years research data were reviewed to discuss the improved behavior of rehabilitated structures and components with various techniques. Examples of both postearthquake and preearthquake rehabilitations of existing buildings were described in some detail. Finally the observed behavior of several rehabilitated buildings during particular earthquakes were introduced to discuss the effect of rehabilitation.

KEY WORDS

seismic performance, repair, upgrading, retrofitting, strengthening, infill wall, braces, jacketing, seismic isolation, seismic damper

INTRODUCTION

In earthquake engineering, the term "rehabilitation" is used as a comprehensive term to include all the concepts of "repair", "upgrading", "retrofitting" and "strengthening" that lead to reduce building earthquake vulnerability. In early years of the world conference on earthquake engineering (WCEE), the major topic in the technical session of rehabilitation was the development of techniques to repair and to strengthen existing structures. After experiences of significant damage to buildings due to several destructive earthquakes, particularly, those which hit highly densed urban areas (for examples, 1978 Miyagiken-oki, 1985 Mexico and 1989 Loma Prieta earthquakes), many cases of practice of rehabilitation as well as development of rehabilitation techniques were reported in the proceedings of WCEE. Thus, the number of papers on seismic rehabilitation has been increasing in the WCEE with the increase of total number of technical papers (Fig. 1), and the ratio of the number of rehabilitation papers to the total has been also increasing, reaching at over 4% in the latest conference of 10WCEE in 1992. This indicates that the importance of seismic rehabilitation of existing buildings has been recognized year after year in our society. The recent two earthquakes, i.e., the 1994 Northridge earthquake and the 1995 Kobe earthquake could have strongly pushed our society to recognize the importance of earthquake

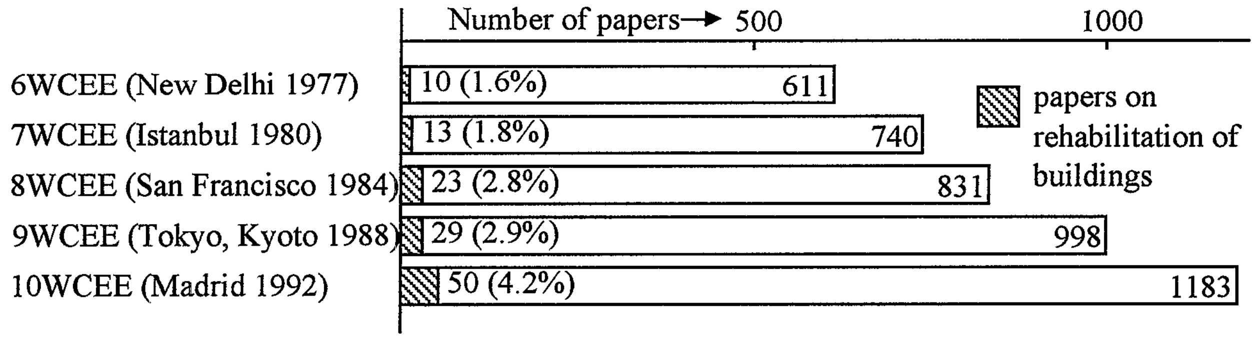


Fig. 1 Number of papers on seismic rehabilitation of existing buildings in the proceedings of WCEE

countermeasures for existing vulnerable buildings.

A large number of existing buildings in earthquake prone areas over the world need seismic rehabilitation due to various reasons and motivations, such as code change or earthquake damage. Earthquake damaged buildings may need strengthening along with repair of damaged portion for reuse (postearthquake rehabilitation). Generally, they are rehabilitated so that their improved seismic performance may satisfy the required performance by current code. Seismically inadequate buildings, the design of which do not comply with current code, may also need rehabilitation (preearthquake rehabilitation) so that they meet the requirements of the code in force. Many rehabilitation techniques were investigated recent twenty or more years to apply to both preearthquake and postearthquake rehabilitations. They are techniques to infill, to brace and to back up existing frames and to jacket existing framing members so that lateral resistance and ductility of a building may be increased. In addition to these conventional seismic resistant type techniques, another approaches to reduce seismic response of a building have been recently adopted. Seismic isolation and supplemental damping are such new techniques for rehabilitation, though they have been investigated for long time to use for new buildings.

This paper describes the present state of research and practice of techniques for seismic rehabilitation of existing buildings. First typical techniques which have been used for reinforced concrete, steel and masonry buildings are summarized in accordance with the aims of rehabilitation. Because of the large volume of existing data available, most of the techniques described herein are those for reinforced concrete buildings. Examples of techniques used for both postearthquake and preearthquake rehabilitations are described in some details. Recent approaches to utilize seismic isolation and supplemental damping as well as conventional infilling, bracing and jacketing techniques are described. Over twenty years research data have been reviewed to discuss the improved seismic behavior of rehabilitated buildings and components with various techniques. Finally the observed behavior of some rehabilitated buildings during particular earthquakes are introduced to discuss the effect of rehabilitation.

REHABILITATION STRATEGY AND TECHNIQUES

Rehabilitation Strategy

As shown in Fig. 2, the aims of seismic rehabilitation are;

1) to recover original structural performance,
2) to upgrade original structural performance, and
3) to reduce seismic response

so as to reduce building earthquake vulnerability. To recover original structural performance, damaged or deteriorated portions of a building may be repaired with adequate material or replaced with new element or material. To upgrade original structural performance there are several approaches (Fig. 2). General approach to

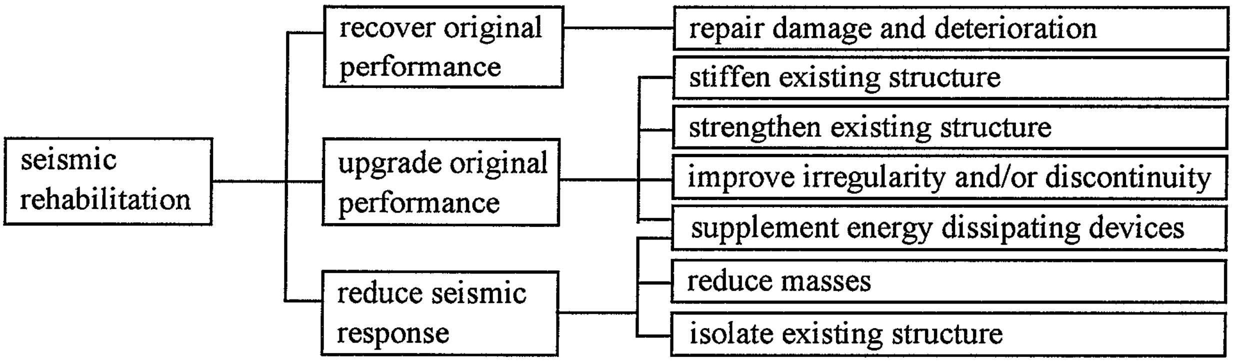


Fig. 2 Seismic rehabilitation strategy and measures

upgrade original performance is to strengthen existing structure by the methods described in the following section. To reduce excessive response displacement, a building must be stiffened. Irregularity or discontinuity of stiffness or strength distribution which may result in failure or large distortion at particular portion of a building must be eliminated by changing structural configuration. It is effective to supplement energy dissipating devices in the structure to enhance the capability to dissipate seismic energy and as a result to reduce seismic response. Another concept to reduce seismic response is to isolate existing structure from the ground (seismic isolation) as well as to reduce building masses. For important buildings which must be functioned after an earthquake or which must preserve expensive and valuable contents, for example, it is particularly effective approach.

Strengthening Techniques

Many approches and techniques have been studied and practiced for recent twenty or more years to strengthen existing structures. Some of them include to stiffen existing structure and/or to improve irregularity or discontinuity in distributin of stiffnes or srength of a building. The aims of seismic strengthening are to provide 1) increased strength, 2) increased ductility, and 3) a proper combination of these two features, so as to satisfy the required seismic performance (Fig. 3). The required performance is evaluated in terms of strength and/or ductility. The combination of strength and ductility involves the proper balance between strength and stiffness. Providing increased strength is the most promising approach for low- to medium-rise buildings. Even if sufficient ductility is provided, adequate strength is required to reduce inelastic displacement. Spandrel walls may be separated from a column to eliminate "captive column" to increase ductility.

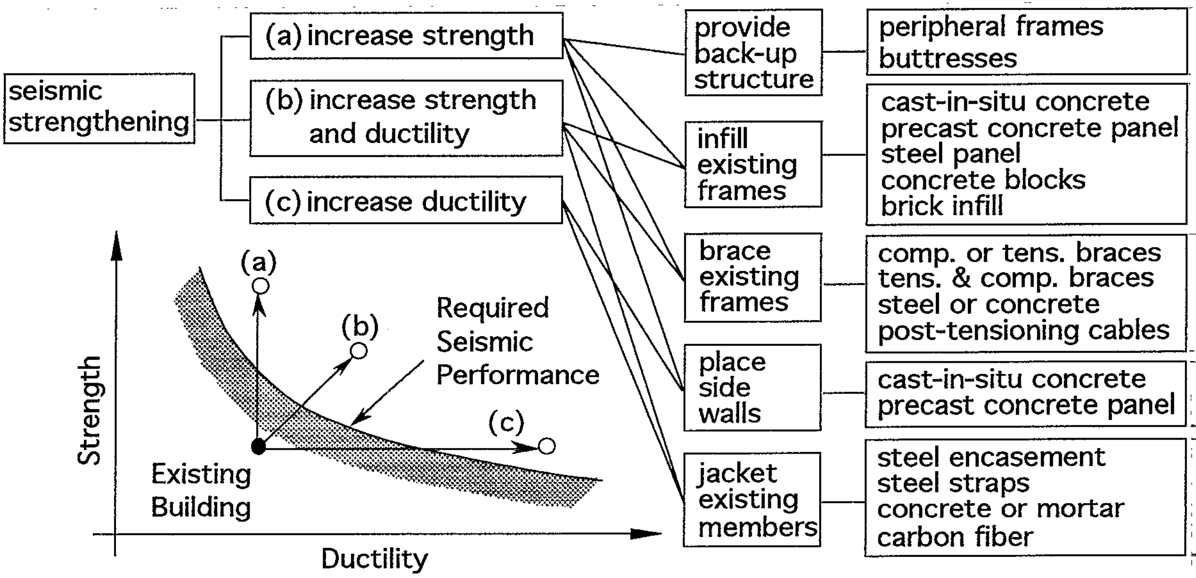
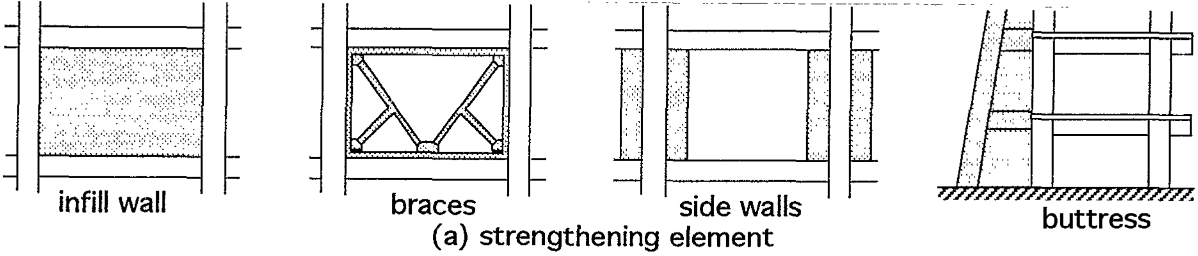
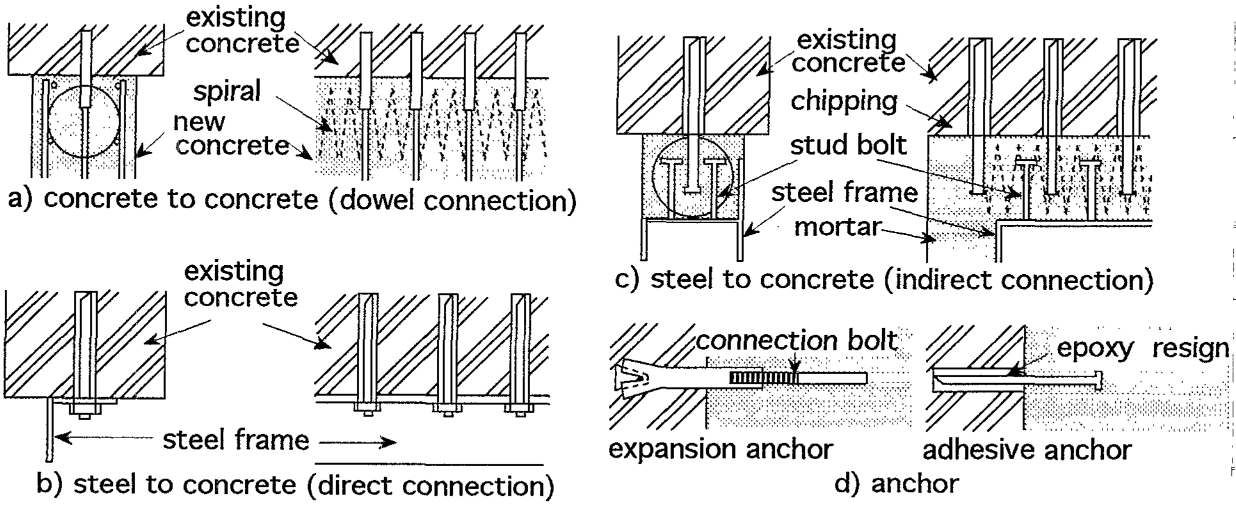


Fig. 3 Typical strengthening methods

Typical strengthening techniques are summarized in Figs. 3 through Fig. 9. Generally, new elements are added to existing frames to provide increased strength (Fig. 4(a)), or existing framing elements are reinforced with new materials to increase flexural capacity (Fig. 5(a)) and/or to improve ductility (Fig. 5(b)). Infill walls and side walls are cast-in-situ or precast wall elements to be attached to frames or to beams. Generally, walls are of cast-in-situ concrete infilling existing bare frame. Steel panel may also be a element to infill existing frame. It is necessary to provide connections along with all the periphery when as much strength as that of monolithic wall is required. Spandrel walls inside the existing frame may be a part of the infill wall when the opening is



(a) strengthening element



a) concrete to concrete (dowel connection)

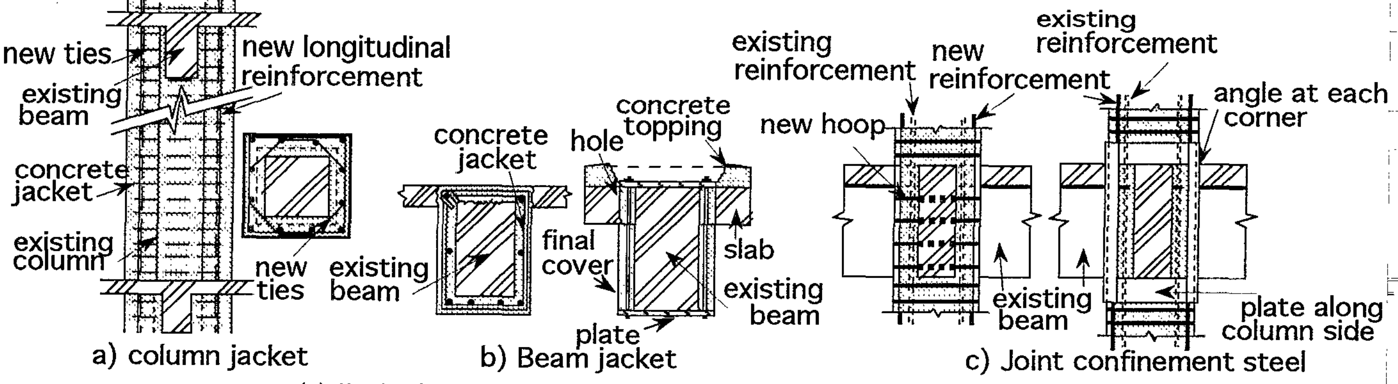
b) steel to concrete (direct connection)

c) steel to concrete (indirect connection)

d) anchor

(b) Connection

Fig. 4 Typical frame strengthening techniques

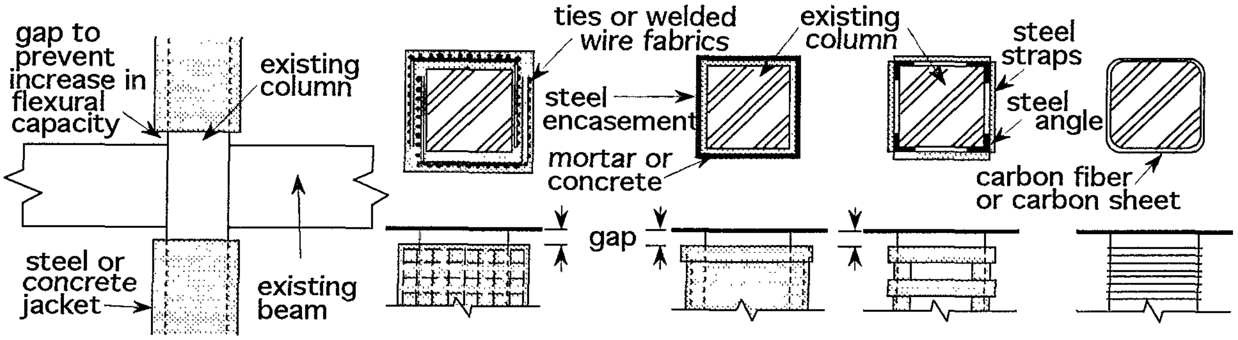


a) column jacket

b) Beam jacket

c) Joint confinement steel

(a) Jacketing techniques to increase frame flexural capacity



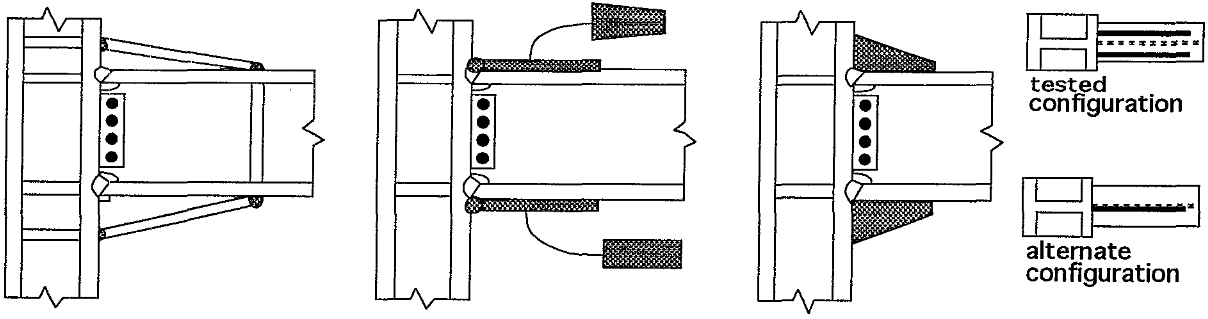
(b) Jacketing techniques to increase column shear capacity

Fig. 5 Typical member reinforcing techniques infilled with concrete. An existing structural wall may be strengthened by placing new concrete wall panel along with the existing wall.

Typical details of connections to existing concrete are given in Fig. 4(b). Dowel connections in Fig. 4a) are used for infill walls and side walls. The expansion and adhesive type anchors for dowel connection are illustrated in Fig.4d). Steel elements may be simply attached to the existing concrete through mortar fill, as shown in Fig. 4c), while they may be directly attached to the frames by bolting (Fig. 4b). Steel systems of braces and panels with peripheral frame were studied by Yamamoto (1983, Fig.11) and Aoki (1992) using the connection in Fig. 4c). The steel elements were welded or bolted to the peripheral frame, and the steel frame was attached to existing frame through mortar fill. Stud bolts were welded to steel frame and adhesive anchors were installed along the existing frame. These bolts and anchors acted as dowels through mortar fill, though they were not connected each other. This connection tolerates more error in dimension of the steel system to be attached to existing frame than the direct connection.

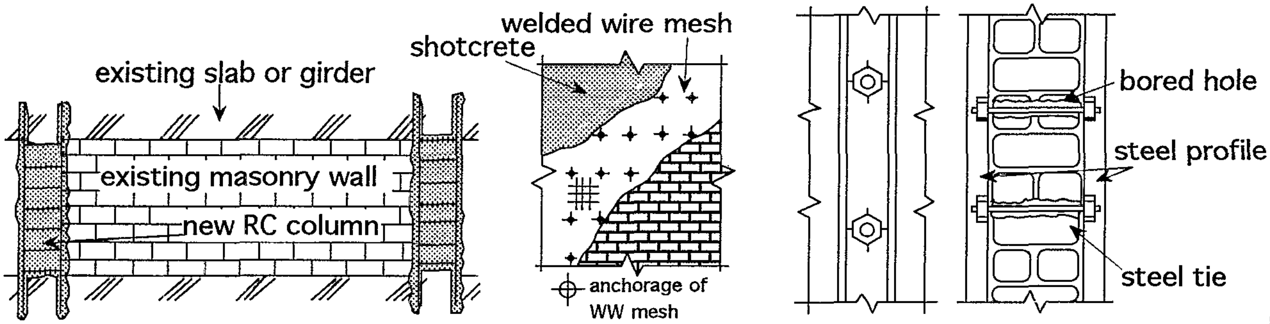
Flexural capacity of frames may be increased with concrete or steel jacket shown in Fig. 4(a) providing with new longitudinal and lateral reinforcements. It is important to adequately arrange lateral reinforcements to achieve ductile behavior. Beam-to-column connection may need confinement with steel element, though the construction is not easy (Alcocer 1995, Hakuto, Park 1995). Column ductility may be improved with jacketing techniques shown in Fig. 5(b). An existing column is jacketed with concrete or steel encasement. In increasing ductility of columns with these techniques, the aim is to increase their shear capacity providing new concrete and/or reinforcement. It is very important to provide a narrow gap at the end of steel or concrete encasement to avoid undesired increase of shear forces resulting from the increase of flexural capacity.

Based on the lessons learned from the damage to steel connections by the 1994 Northridge earthquake, some modification methods for steel connection are proposed (FEMA 1995). The aim of the methods shown in Fig. 6 as examples is to shift the plastic hinge away from the connection using haunch, cover plate or rib. These



(a) Top and bottom haunch modification (b) Cover plate connection modification (c) Upstanding rib connection modification

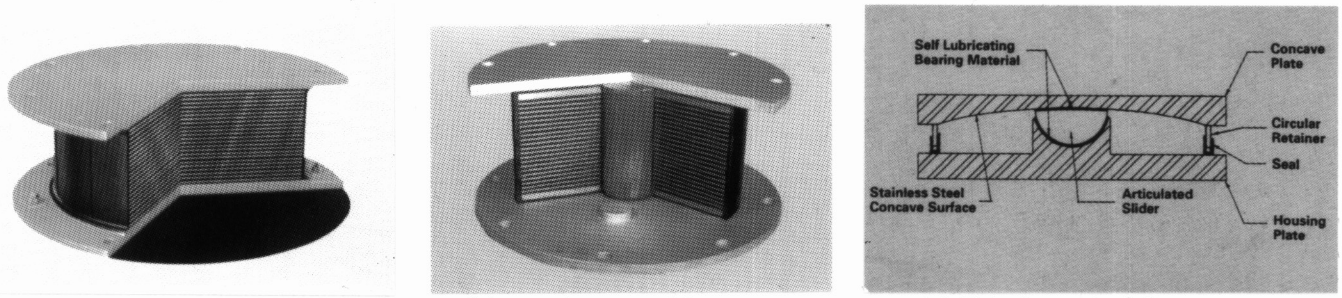
Fig. 6 Examples of post-earthquake modification of steel connection (FEMA 1995)



(a) Addition of RC column (Hidalgo 1995) (b) Strengthening by welded wire mesh (Alcocer 1994) (c) Confinement with steel section

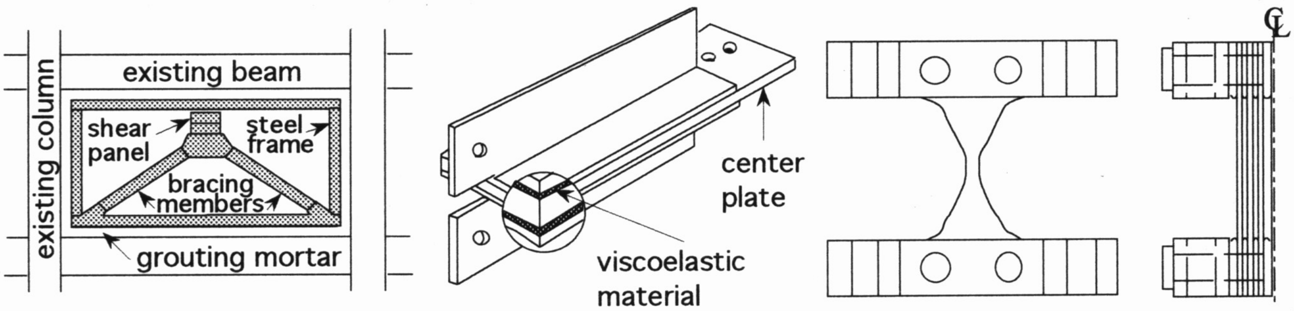
Fig. 7 Strengthening of masonry infill wall methods can be applied to new construction. Existing masonry infill walls may be strengthened by the addition of new reinforced concrete column (Hidalgo 1995, Fig. 7(a)), by jacketing with concrete and welded wire fabrics (Alcocer 1994, Fig. 7(b)) or by confining with steel section (Fig. 7(c)).

Recently seismic isolation has been adopted for rehabilitation of critical or essential facilities, buildings with expensive and valuable contents, and structures where superior seismic performance is required. The seismic isolation system significantly reduces the seismic impact on building structure and assemblies. For isolation bearings elastomeric systems(high-damping rubber and lead core rubber) or friction pendulum system are presently available (Fig. 8). In other cases, rubber bearings accompany damping element such as viscous damper. Energy dissipation devices have been also adopted recently to reduce inelastic deformation demand. Many ideas are proposed for new buildings, however, shear yielding damper (Okada, Seki 1992), viscoelastic damper (Scholl 1986, Soong 1993) and added damping and stiffness (ADAS) elements (Scholl 1990, Kelly 1993) are presently available for seismic rehabilitation.



(a) High-damping rubber (b) Lead core rubber (c) Friction pendulum system

Fig. 8 Isolation bearings used for seismic rehabilitation



(a) shear yielding damper (Okade, Seki 1992) (b) viscoelastic damper (Scholl 1986, Soong 1993) (c) added damping and stiffness (ADAS) element (Scholl 1990, Kelly 1993)

Fig. 9 Dampers used for seismic rehabilitation

BEHAVIOR OF REHABILITATED STRUCTURES

Research on Rehabilitated Structures

The earliest tests in rehabilitation research were aiming at repair of damaged structure (Plecnic 1977, Gulkan 1977) and the improvement of column ductility by jacketing with steel encasement, steel straps or welded wire fabrics (Sasaki 1975, Higashi and Kokusho 1975, Kahn 1980). They were also aiming at the boosting of the strength of frames by the addition of precast or cast-in-situ walls (Higashi and Kokusho 1975, Kahn 1977, Higashi and Ohkubo 1977). In addition, one-story infilled frames with various connection details and bracing systems were examined (Higashi 1980, Sugano and Fujimura 1980). Three-story frames, strengthened by infilling and bracing techniques, were also tested (Higashi 1984). Further tests were those for infill walls (Aoyama 1984, Ramirez 1992), steel bracing systems (Yamamoto 1983, Katsumata 1989, Goel 1992, Aoki

1992) and jacketed columns with steel straps (Arakawa 1980), with carbon fiber (Takeda and Katsumata 1988, 1992), with steel encasement (Yoshimura 1992, Aboutaha 1994) and with concrete (Park, Rodoriguez 1992). Beam-column joints of jacketed frames were also tested by Alcocer 1992, and Park and Hakuto 1995.

Shear transfer at the connection between new ans existing elements was another issue in strengthening. The behaviors of fasteners and connections were investigated by Eligehausem 1988, Jirsa 1988, Shimizu 1988, Akiyama 1992, Hosokawa 1992 and Valluvam 1994.

Behavior of Strengthened Frames

Examples of the behavior of strengthened frames with various construction techniques are shown in Fig. 10 (Sugano and Fujimura 1980). Infill wall behaved similarly to monolithic wall, though the strength was slightly less. Concrete blocks also extensively increased the strength of original frame. Tension braces provided good ductility properties while compression braces and steel panel did not develop their yield strength due to the failure of existing columns or connections. The behavior of strengthened frames with steel systems are summarized in Fig. 11 (Yamamoto 1983). Both the X and V braces and a panel with opening were capable of significantly improving not only strength but also ductility of original frame. The double K braces (Aoki 1992) also indicated significantly improved both strength and ductility of original frame. Note that even a steel peripheral frame alone could significantly improve both the strength and ductility. Another recent test of V-braces system with hinge device at the joint to the steel frame (Okada, Seki 1992) indicated significantly increased energy dissipating capability resulting from yielding of shear panel.

Typical load-displacement relationships of strengthened frames with various construction techniques are illustrated in Fig. 12. This is only qualitative indication of the order of strength and ductility that might be attained using different techniques. The findings from the figure were summarized as follows. 1) When adequate connections were provided, infill walls exhibited almost the same strength as monolithic wall. 2) Multiple precast panels provided good ductility properties, however as expected, much less strength was attained. 3) The predominance of bending behavior in three story frame was observed in contrast to shear dominance in one-story frames. 4) Steel framed braces indicated significantly increased both strength and ductility. 5) Concrete blocks and brick masonry also significantly increased strength.

Behavior of Reinforced Members

Fig. 13(a) shows the dramatic improvement of ductility attained by a column using welded wire fabric wrapping and mortar (Kokusho 1975). Thick lines in the figure show the brittle failure of this type of short column that has been observed in many damaged buildings due to destructive earthquakes. Displacement ductility larger that 6 could be attained in this case. Also the significant improvement of ductility by steel encasement is shown in Fig. 13(b) for the test by Yoshimura 1992. While original columns with average and heavy reinforcement failed in shear, jacketed columns could sustain the displacement larger than 2%.

Typical load-displacement relations of reinforced columns with various techniques are shown in Fig. 14. This is also qualitative indication of the order of strength and ductility that might be attained using different techniques. The findings are summarized as follows. 1) Anyone of wrapping techniques to use steel encasement, concrete encasement, carbon fiber and steel straps resulted in considerable increase in ductility, 2) Columns with concrete jacket indicated significantly increased both strength and ductility. 3) Steel encasement without end gaps resulted in decrease of strength, though higher strength was obtained. 4) Separation of spandrel walls considerably increased ductility while the strength was significantly reduced.

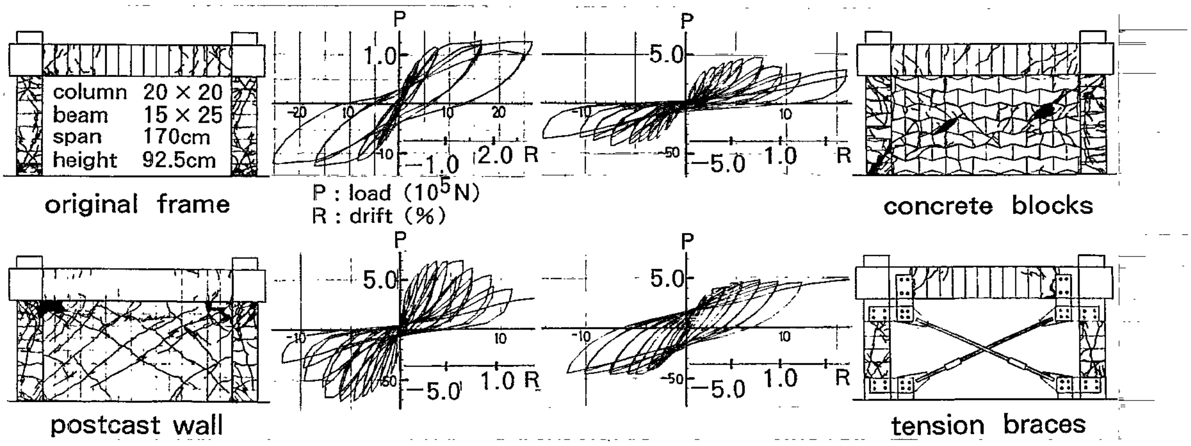


Fig. 10 Hysteretic behavior of strengthened frames with various techniques (Sugano, Fujimura 1980)

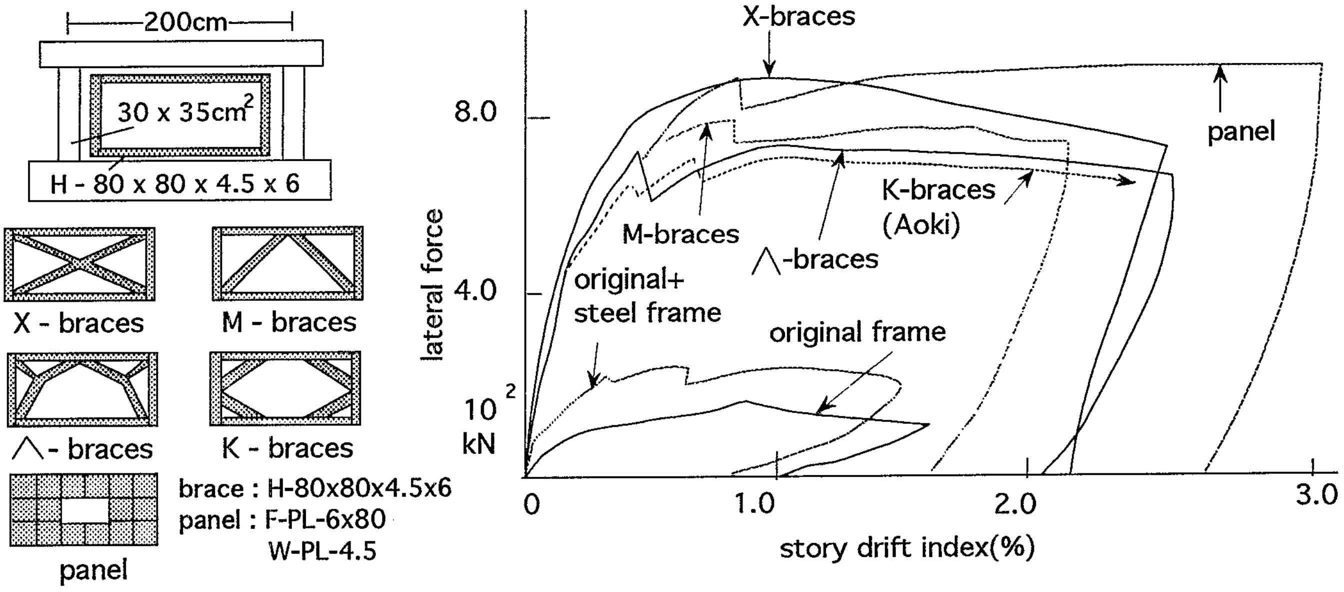


Fig. 11 Behavior of strengthened frame with steel systems (Yamamoto 1983, Aoki 1992)

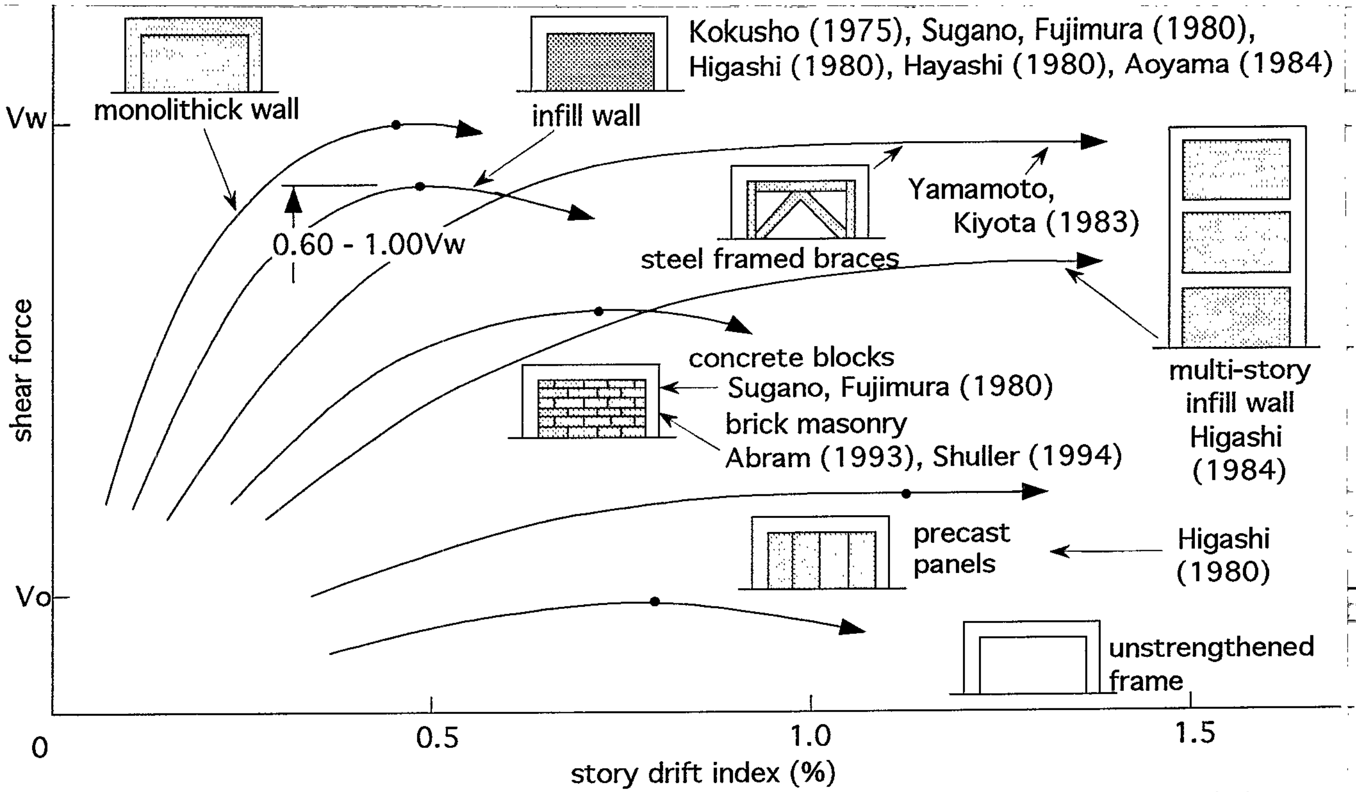
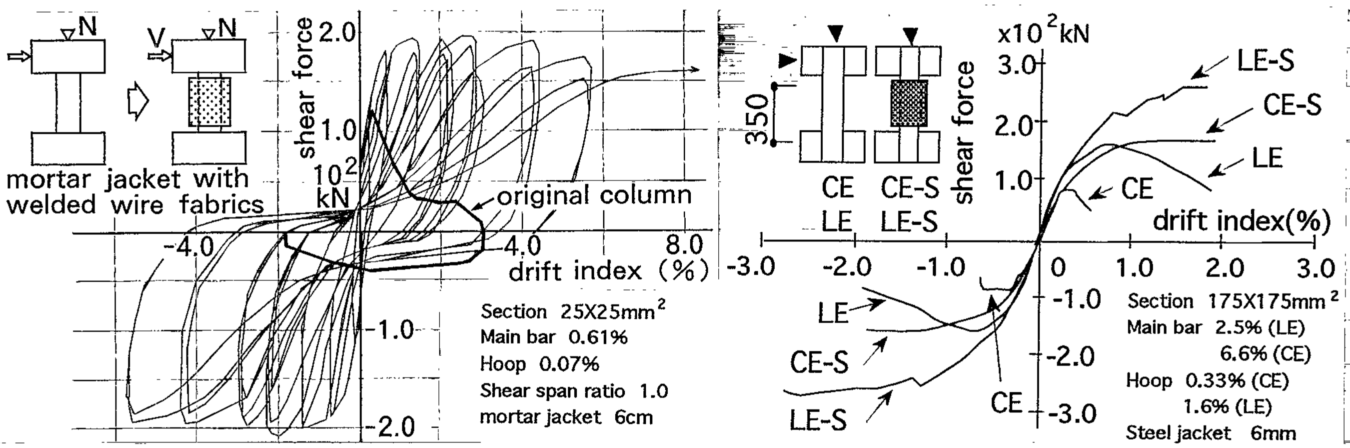


Fig. 12 Typical load-displacement relationships of strengthened frames with various techniques



(a) Concrete jacket (Kokusho 1975) (b) Steel jacket (Yoshimura 1992)

Fig. 13 Behavior of jacketed columns

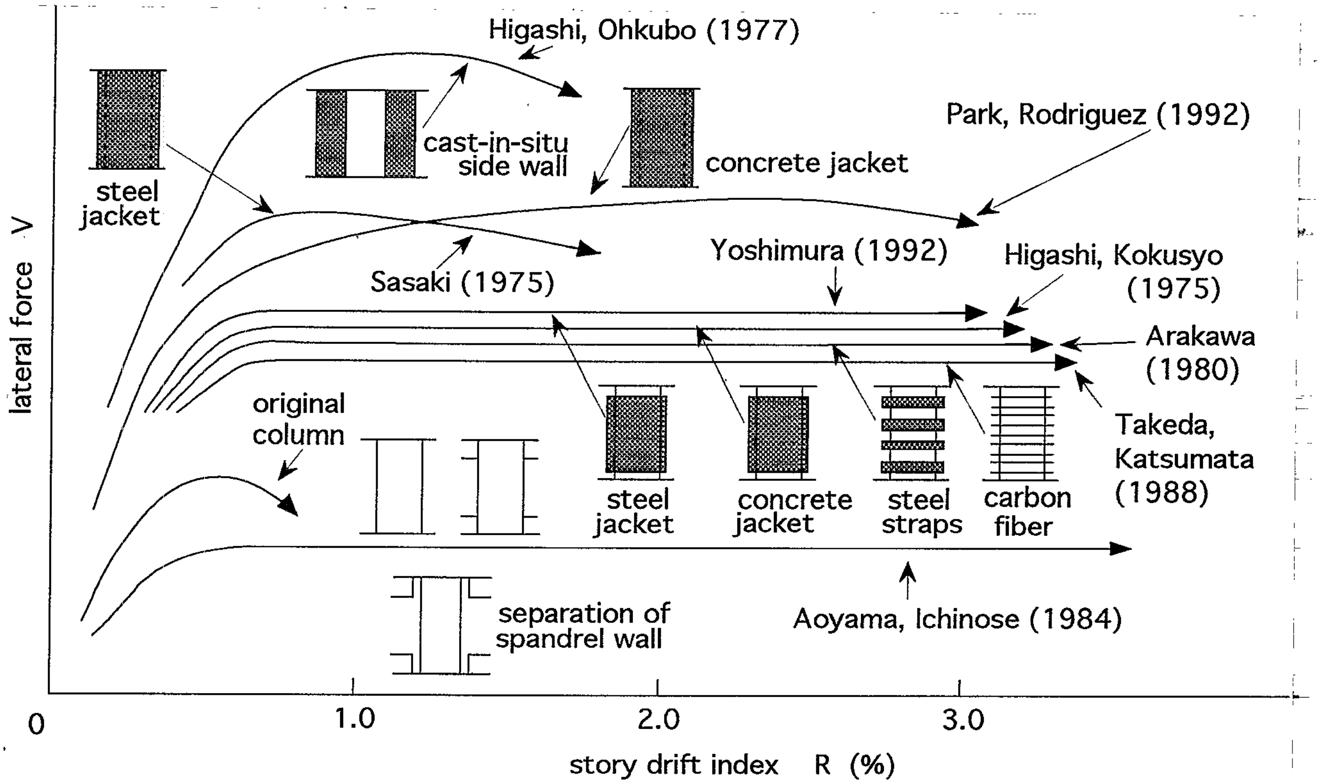


Fig. 14 Typical load-displacement relationships of columns reinforced with various techniques

SEISMIC REHABILITATION OF EXISTING BUILDINGS

Postearthquake Rehabilitation

Recent over 25 years, many buildings were rehabilitated after the damage by destructive earthquakes using various types of techniques. The criteria how to restore a damaged building depends on the level of its damage and the intensity of the earthquake which caused the damage (Table 1). Generally they were rehabilitated to upgrade their seismic performance so that they may meet the requirement of code in force. The major aims of the rehabilitation are to recover original function of the building and to prepare measures against possible stronger earthquake. Used techniques were in wide variety. In early cases, mostly concrete shear walls were selected because they were capable of providing large lateral resistance. The building in Photo 1 was severely damaged by the earthquake of 1968 (Tokachi-oki earthquake) and it was rehabilitated one year after the earthquake by placing concrete walls along with repair of damaged columns in shear. It was first experience

Photo 1 Strengthening with shear walls
(after 1968 Tokachi-oki earthquake)

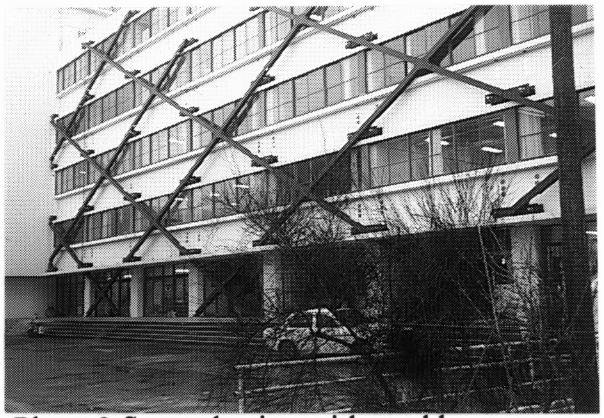


Photo 2 Strengthening with steel braces
(after 1978 Miyagiken-oki earthquake)

Photo 3 Strengthening with buttresses
(after 1980 Livermore earthquake)

Photo 4 Concrete jacketing
(after 1985 Mexico earthquake)

Photo 5 Steel jacketing
(after 1985 Mexico earthquake)

Photo 6 Rehabilitation with seismic isolation
(after 1989 Loma Prieta earthquake)

for Japanese engineers to extensively strengthen existing structure for future earthquake. The shear wall strengthening, however, takes disadvantages due to 1) increased weight of the building, and 2) separation of space. Diagonal steel bracing is another solution to provide large lateral resistance of a building, in addition, possible large displacement capacity. In the building in Photo 2 which suffered severe damage due to shear failure of short columns by the 1978 Miyagiken-oki earthquake, steel diagonal braces were placed along both longitudinal exterior frames through the stories. The increased lateral resistance and the ductility were verified by laboratory tests (Kawamata 1980). The steel bracing can provide large lateral resistance and large opening for lighting without increased weight followed by the rehabilitation.

Buttresses were used for the building in Photo 3 damaged by the Livermore earthquake of 1980 (Freeland 1984). Sharpe 1990 reported another case of buttress strengthening for another building in the same site. The buttress does not disturb interior building space and function, therefore, it is effective method when outer space is sufficiently provided. Photos 4 and 5 show jacketing of existing frame elements with concrete and steel straps which were seen in Mexico City after the earthquake of 1985. Because of significantly increased design seismic forces after the code revision, massive jacketing was necessary to meet the code requirements. The building in Photo 6, consisting of wooden bearing walls, was affected by the Loma Priete earthquake of 1989 and seismic isolation was adopted for rehabilitation. Friction pendulum system was used for isolation bearing.

Restoration of Damaged Buildings in Kobe

A large number of reinforced concrete, steel reinforced concrete and steel buildings in Kobe City suffered severe damage by the earthquake of 1995. Many damaged buildings needed repair for reuse while collapsed or some of severely damaged buildings were demolished. The criteria for restoration depends on damage level and the intensity of the earthquake which damaged the buildings. Table 1 shows a proposed criteria for restoration (Japan Building Disaster Prevention Association 1991). In the areas which reported seismic intensities VI (in JMA scale) or greater, restoration by only "repair" was underway in most of damaged buildings. The restoration design and construction for damaged buildings were achieved following existing guidelines. Figure 15 shows examples of recommended repair techniques for reinforced concrete and steel buildings (Building Center of Japan 1995).

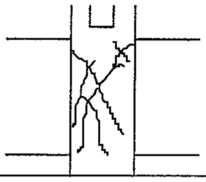
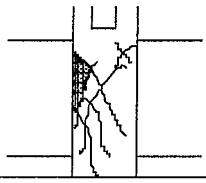
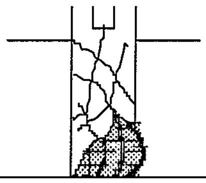
Table 1 Criteria for restoration of damaged buildings

	Damage Level	Light	Minor	Medium	Major	Collapse
Seismic Intensity Scale(JMA)	lower than 5	○	△	×	×	×
	5	○	○	△	×	×
	higher than 5	○	○	○	△	×

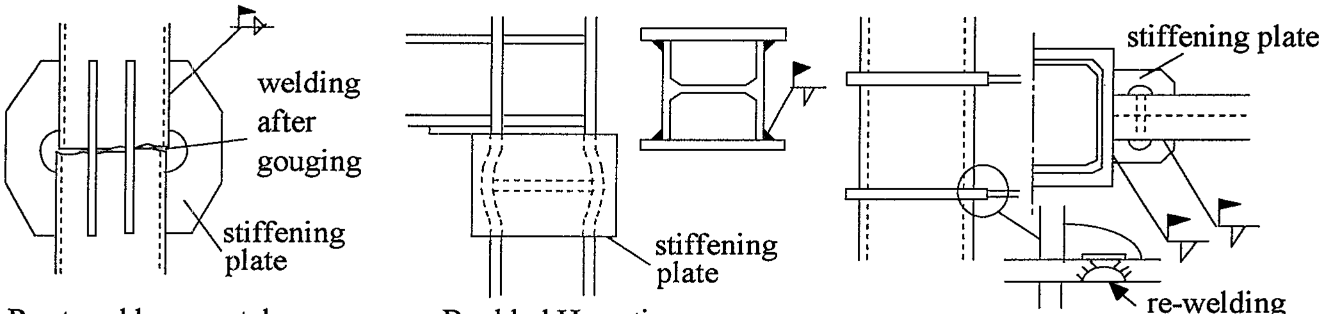
restoration by : ○repair, △repair or strengthening, ×strengthening or demolition

JMA Scale	0	1	2		3	4		5	6		7	
MM Scale	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII

JMA:Japan Meteorological Agency

Damage rank	Rank III or less	Rank IV	Rank V
Sketch of damage			
Repair method	Repair cracks Repair cracks and partial loss of concrete Repair partial loss of concrete	Grout mortar or cast concrete Jacket with welded wire fabrics and morter Jacket with steel plate and grout morter	Jacket with concrete Jacket with steel plate and grout mortar Jacket with steel plate, add vertical reinforcement and grout mortar

(a) Repair of damaged concrete columns



Ruptured base metal

Buckled H-section

Cracked welding portion

(b) Repair of damaged steel members

Fig. 15 Examples of repair techniques after 1995 Kobe Earthquake (Building Center of Japan 1995)

Preearthquake Rehabilitation

Since the publication of the "Standards for Seismic Capacity Evaluation of Existing Reinforced Concrete Buildings" (Japan Building Disaster Prevention Association 1977) a large number of existing buildings have been evaluated in Japan. Particularly, several agencies in charge of administration of a number of public buildings have performed the evaluation as a part of seismic countermeasure program. The cases of such evaluation of the Shizuoka Prefecture, Yokohama City and the Tokyo metropolis are summarized in Table 2 (Hirosawa 1992). The Shizuoka Prefecture, where a magnitude 8 or more earthquake is presumed, has evaluated 1896 public buildings including schools, city offices hospitals, etc by the year of 1986. Sixty five or more percent buildings were judged to be rebuilt or to need rehabilitation. 465 building were actually rehabilitated during the

Table 2 Examples of rehabilitation project of public buildings in Japan

Municipality	Seismic Evaluation			Seismic Retrofit		
	No of Bldgs	Use	Period	No of Bldgs	Period	Construction Techniques
Shizuoka Prefecture	2078	school, city office, etc.	'77~'86	465	'82~'87	infill walls, steel braces and panels, column jacket
Yokohama City	870	school, city office, etc.	'82~'84	30~40% of the total	'87~ underway	steel braces, column jacket
Tokyo Metropolis	48	apartment houses	'79~'81	46	'81~'83	infill walls, side walls, column jacket

reference : Hirosawa 1992, Usami et al 1988

Table 3 Seismically Isolated Buildings for Rehabilitation

Building (city, country, yr. completed)	Original Structural System	Floors/size (m^2)	Isolation System
Salt Lake City and County Building (Salt Lake City, Utah, USA 1989)	Steel braced frame	5/16000	LRB
Rockwell Seal Beach Facility (Seal Beach, California, USA 1991)	RC moment frame	8/28000	LRB
Mackay School of Mines (Reno, Nevada, USA 1991)	URM bearing wall	3/4700	HDR & PTFE sliders
Marina Apartments (San Francisco, California, USA 1994)	Wood bearing wall / Steel moment frame	4/1900	FPS
Channing House Retirement Home (Palo Alto, California, USA 1994)	RC frame / RC shear wall	11/19600	LRB
Long Beach Hospital (Long Beach, California, USA 1995)	RC shear wall	12/33000	LRB
Oakland City Hall (Oakland, California, USA 1995)	Steel frame / URM infill	18/14000	LRB
U.S. Court of Appeals (San Francisco, California, USA 1995)	Steel frame / URM infill	5/33000	FPS
Kerckhoff Hall, UCLA (San Francisco, California, USA 1995)	RC frame / URM infill	6/9300	LRB
San Francisco City Hall (San Francisco, California, USA 1996)	Steel frame / URM	5/56000	LRB
Los Angeles City Hall (Los Angeles, California, USA 1996)	Steel frame / RC shear wall / URM infill	32/82000	HDR & PTFE sliders
Parliament House (Wellington, New-Zealand, 1995)	URM bearing wall	5/26500	LRB
Parliament Library (Wellington, New-Zealand, 1995)	URM bearing wall	5/6500	LRB
Houtoku-Ninomiya Temple (Odawara, Japan, 1997)	Wood frame	1/112	Rubber Bearing + V.Damper

RC : Reinforced Concrete
URM : Unreinforced Masonry
HDR : High Damping Rubber Bearings
LRB : Lead Rubber Bearings
FPS : Friction Pendulum System
PTEE : Poly-Tetra-Fluoro-Ethylane

Reference : Mayes 1995, Soong 1992, Kelly 1992, Japan Society of Seismic Isolation 1996 period of 1982 to 1987. The major construction technique was to use concrete infill walls so that they may provide very high lateral desistance against the presumed huge earthquake. However, in later part of the project, steel systems in Fig. 11 were also used to avoid the increased weight of building associated with the strengthening and to provide large opening for lighting.

In the USA, also many buildings have been evaluated, particularly, since the Loma Prieta earthquake of 1989. The rehabilitation project for UCLA campus buildings, for example, is reported (Ingham 1994). Both damaged or undamaged buildings may be rehabilitated using conventional techniques (for example, Amin 1994). New techniques such as seismic isolation and supplemental damping, however, are used recently (Hart 1994, Mayes 1995, Soong 1992). Particularly, seismic isolation has been selected in more than ten buildings for rehabilitation (Table 3). The motivating factors for selecting seismic isolation are (Soong 1992);

1) Historical building preservation,
2) Functionality,
3) Design economy
4) Investment protection, and
5) Content protection.

The adopted isolating bearings are 1) high damping rubber bearings, 2) lead rubber bearings and 3) friction pendulum system. The techniques has been used mainly for historical buildings or important building since it was first applied to the historical Salt Lake City and County Building (Table 3).

BEHAVIOR OF REHABILITATED BUILDING DURING EARTHQUAKE

Most of extensively rehabilitated buildings have not yet experienced strong ground motion. Only a couple of cases of buildings which experienced strong ground motion after rehabilitation were reported. The followings are the buildings in such cases.

A twelve-story reinforced concrete frame building in Mexico City was repaired and strengthened after suffering extensive damage during a moderate earthquake that shook the city in 1979 (Photo 7). The building suffered no damage during the event of 1985 even though the shaking was much greater than that in 1979. The results of forced vibration tests and analytical studies indicated that the steel braced frames that were attached to the building for strengthening stiffened the structure, shifting its natural period away from the predominant ground period of 2.0sec (Del Valle 1988). This is the case of successful rehabilitation and similar successful case with steel bracing was reported by Hjelmstad 1988.

A three-story reinforced concrete building in Photo 8, which is structurally identical to the building in Photo 1, suffered severe damage to first story columns due to the earthquake of 1968. The building was rehabilitated with shear walls at the damaged first story only. Unstrengthened 2nd story columns suffered severe shear cracks due to the recent earthquake of 1994. While adjacent building in Photo 1 which were rehabilitated up to 2nd story did not suffer any severe damage. Importance of balanced configuration of strengthening elements is indicated in this case (Nakano 1995).

An old building in Photo 9 was constructed in 1918 in Kobe and ten month before the event of 1995, construction for seismic rehabilitation was completed. Existing brick walls were confined by new concrete frames and existing concrete frames were reinforced with new steel frames arranged along with the existing frames. As a result of the countermeasure, the building did not suffer any damage while some other historical buildings suffer severe damage in the same area. This is very encouraging case to indicate the effectiveness of preearthquake rehabilitation (Nikkei Architecture 1995).

Photo 7 A rehabilitated building in Mexico City before the earthquake of 1985 (no damage)

Photo 9 An old building in Kobe rehabilitated ten month before the earthquake of 1995 (no damage)

Photo 8 A rehabilitated building with concrete walls after 1968 Tokachi-oki earthquake. Unstrengthened 2nd story suffered severe damage by the earthquake of 1994

CONCLUDING REMARKS

The present state of techniques for seismic rehabilitation of existing buildings has been overviewed based on the survey of literatures and data of research and practice. The reaults of the review are summarized as follows.

1) Because of the experience of earthquake damage and the data availabe, most techniques described herein are those for reinforced concrete buildings. Many typical techniques to strengthen existing structures have been well investigated in terms of improved performance and they have been utilized. Although a few data have been available regarding the rehabilitaion of steel structures, the recent two earthqauakes, the 1994 Northiridge earthquake and the 1995 Kobe earthquake would have strongly pushed the studies on rehabilitation of steel structures, therefore, more data will be available in future. The concepts of strengthening methods described here for brick infil walls to confine with concrete frame or with steel elements, or to jacket with concrete and lateral reinforcement can be commonly used, though materials, design and constrution may be different in each region.

2) In addition to conventional seismic resistant type rehabilitation techniques, another approach to isolate the existing strucuture from the ground or to supplement energy dissipating devices to reduce seismic response have been adopted. Seismic isolation can be applied to critical or essential facilities, buildings with expensive and valuable contents, and structures where superior seismic performance is desired. Their applications are only in smll numbers now, however, they will be widely used for seismic rehabilitation.

3) Rehsbiitation techniques may be selected in accorodance with required performance level. Generally the seismic rehabilitation is achieved to upgrade the original performance to current code level. However, the codes do not clearly figure out the postearthquake condition of designed building. Design approaches corresponding to more detailed performance level will be neccessary.

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