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Japanese seismic rehabilitation of concrete buildings after the Hyogoken-Nanbu Earthquake

Hiroshi Fukuyama [a,*], Shunsuke Sugano [b]

[a] International Institute of Seismology and Earthquake Engineering, Building Research Institute, Ministry of Construction, 1 Tatehara, Tsukuba, Ibaraki 305-0802, Japan

[b] Research and Development Institute, Takenaka Corporation, 1-5-1, Ohtsuka, Inzai, Chiba 270-1395, Japan

Abstract

After the Great Hansin-Awaji Earthquake Disaster caused by the 1995 Hyogoken-Nanbu Earthquake (Kobe Earthquake), new approaches to utilize seismic isolation, supplemental damping and continuous fiber wrapping have been applied for seismic rehabilitation of reinforced concrete buildings as well as conventional strengthening techniques to infill, to brace and to jacket existing framing members. An overview of the state-of-the-art in techniques for seismic rehabilitation of existing reinforced concrete buildings is presented in this paper with emphasis on research and practice. Response to the lessons from the Great Hansin-Awaji Earthquake Disaster is summarized, firstly. The rehabilitation strategy and techniques, improved behavior of rehabilitated structures and components with various techniques, examples of both post-earthquake and pre-earthquake rehabilitation of existing buildings are introduced. Since application of the continuous fiber wrapping has been increased drastically after the Kobe Earthquake, the characteristics and detail of this technique are described. Finally, subjects to be considered in the future are summarized.

Keywords: Seismic rehabilitation; Concrete building; Seismic isolation; Seismic damper; Continuous fiber wrapping

1. Introduction

1.1. Importance of seismic rehabilitation

After experiences of significant damage to buildings due to several destructive earthquakes, particularly, those which hit highly dense urban areas (for example, 1978 Miyagiken-oki, 1985 Mexico and 1989 Loma Prieta Earthquakes), the importance of seismic rehabilitation of existing buildings has been recognized year after year. The recent two earthquakes, i.e., the 1994 Northridge Earthquake and the 1995 Hyogoken-Nanbu Earthquake (Kobe Earthquake) have strongly pushed our society to recognize the importance of earthquake 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 (post-earthquake rehabilitation). Generally, they are rehabilitated so that their improved seismic performance may satisfy the required performance by current codes in force. Seismically inadequate buildings, the design of which does not comply with current code, may also need rehabilitation (pre-earthquake rehabilitation) so that they meet the requirements of the codes in force. Many rehabilitation techniques were investigated recent 20 or more years to apply to both pre-earthquake and post-earthquake rehabilitation. 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 techniques", other approaches to reduce seismic response of a building have been recently adopted for rehabilitation of existing buildings. They are seismic isolation and supplemental damping which are "response reduction techniques", though they have been developed for new buildings. Thus, the seismic rehabilitation technique is recently in wide variety.

* Corresponding author.

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1.2. Objectives and scope

In this paper, the emphasis is laid upon the seismic rehabilitation of existing reinforced concrete buildings, which has been considered as one of the most urgent earthquake preparedness since the Hyogoken-Nambu Earthquake.

The lessons from the Hanshin-Awaji Earthquake Disaster are summarized firstly to present the importance of seismic rehabilitation in Japan. The typical rehabilitation techniques used for reinforced concrete buildings are summarized classifying as conventional techniques that is infilling, bracing and jacketing techniques using steel and concrete materials, and recent approaching techniques utilizing seismic isolation, supplemental damping and continuous fiber wrapping, which have been applied mainly after the Hyogoken-Nanbu Earthquake. Over 20 years research data have been reviewed to discuss the improved seismic behavior of rehabilitated buildings and components with various techniques. Examples of techniques used for both post-earthquake and pre-earthquake rehabilitation are introduced. Some observed behaviors of rehabilitated buildings during recent earthquakes are introduced to discuss the effectiveness of seismic rehabilitation. Since application of the continuous fiber wrapping has been increased drastically after the Hyogoken-Nanbu Earthquake, the characteristics and detail of this technique are described. Finally, subjects to be considered in the future are summarized.

The term "rehabilitation" is recently used in the earthquake engineering field as a comprehensive term to include all the concepts of "repair", "upgrading", "retrofitting" and "strengthening" that lead to reduce building earthquake vulnerability.

2. Response to the lessons from the Great Hanshin-Awaji Earthquake Disaster [1]

2.1. Lessons from the Great Hanshin-Awaji Earthquake Disaster

The lessons that from the Great Hanshin-Awaji Earthquake Disaster caused by the 1995 Hyogoken-Nambu Earthquake on concrete buildings could be summarized as follows. The detailed results of the damage investigation of reinforced concrete building structures are described in other papers [2–4].

(1) Most new buildings designed and constructed according to the present seismic codes showed fairly good performance from the view of preventing severe structural damage and/or collapse for life safety as a minimum requirement, even to such severe earthquake ground motions.

(2) The collapsed or seriously damaged ratio of reinforced concrete building was 7.8% in the most affected areas, which reported seismic intensities "7" in JMA scale. The ratio of severely damaged buildings with soft first story, i.e., 17.0%, was much higher than that without soft first story, i.e., 7.0% (Fig. 1; note that the ratio of unknown buildings which were demolished at the investigation is counted because most of those can be regarded as seriously damaged buildings.).

(3) The damage to reinforced concrete buildings was serious for those constructed before 1981, especially before 1971, because Japanese seismic design codes in 1950, which was basically same as the first Japanese seismic design codes for buildings in 1924, was revised in 1971 and 1981. The collapsed or seriously damaged ratios of buildings designed and constructed in accordance with the codes before 1971 revision, before 1981 revision and of current are, 8.1%, 3.7% and 1.1% for buildings without soft first story, and 12.2%, 11.7% and 2.4% for buildings with soft first story, respectively [2].

Therefore, urgent needs of seismic performance evaluation to identify seismically vulnerable buildings, which have not experienced severe earthquake ground motion yet, and of seismic strengthening to upgrade their seismic performance have been strongly recognized. A lot of projects to carry out seismic upgrading of existing vulnerable buildings have launched since the Hyogoken-Nanbu Earthquake.

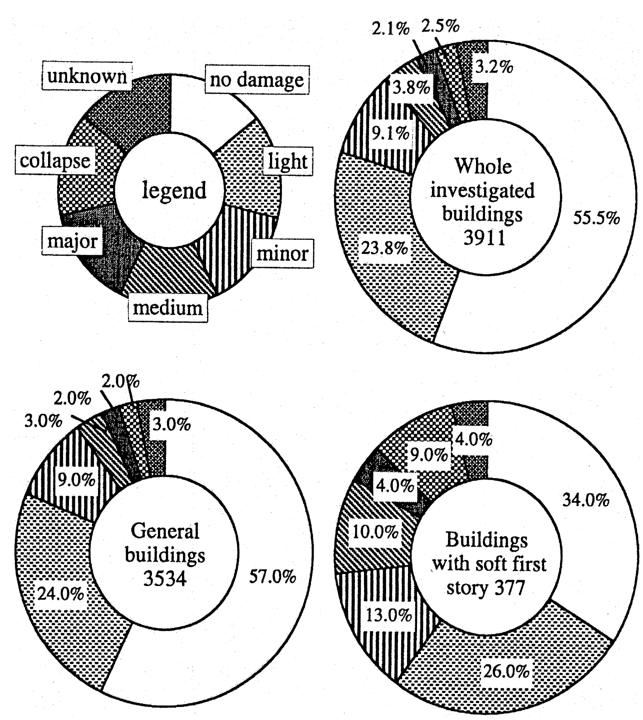

Fig. 1. Damage to concrete buildings by the Hyogoken-Nanbu Earthquake at JMA seismic intensity "7" area in Kobe city.

In order to promote seismic retrofit of pre-code revision buildings, the "Standards for Evaluation of Seismic Capacity and Guidelines for Seismic Rehabilitation of Existing Reinforced Concrete Buildings" [5] were developed by the Japanese Government and published from the Japan Building Disaster Prevention Association in 1977. However, they have been applied only to a limited number and limited types of buildings in a limited areas excluding the Kobe area even though the necessity of seismic retrofit had been pointed out before the Hanshin-Awaji Earthquake Disaster. The reasons could be summarized as follows:

1. The seismic strengthening is less attractive for owners, architects, engineers, researchers, constructors, administrators and politicians than new building construction.
2. Since a return period of a big earthquake is usually long, owners are apt to hesitate to spend money in seismic retrofit of existing buildings.
3. Since a seismic retrofit is more complicated than construction of new buildings, it is usually troublesome for architects and engineers, and less paid.
4. Since the Japanese Building Code is not retroactive, a seismic retrofit is not enforced by law.

2.2. Response to the lessons from the Great Hanshin-Awaji Earthquake Disaster

Since the Great Hanshin-Awaji Earthquake Disaster was a great shock to Japanese people, various responses have been quickly taken to upgrade the seismic capacities of pre-code revision buildings all over Japan. In order to promote the seismic retrofit, it is necessary: (1) to develop methodologies to evaluate seismic capacities, (2) to develop techniques to strengthen existing buildings, (3) to train engineers, and (4) to prepare subsidies, low-interest loan, tax exemption and so on, to increase public incentive for seismic rehabilitation. In the following, the activities of the Network Committee, the Law for Promotion of Seismic Retrofit of buildings, and the Method for evaluation of seismic performance of existing reinforced concrete buildings are briefly described.

2.2.1. Network Committee for promotion of seismic rehabilitation of buildings

Network Committee for promotion of seismic retrofit of buildings was established in April 1995. This committee consisting of 76 organizations related to the design and construction of buildings and houses including associations for academic people, for architects, for engineers, for consultant offices and for building owners. Major activities of the committee are: (1) to exchange information on seismic retrofit, (2) to organize seminars to train engineers, (3) to support local governments and groups of engineers to establish local centers for promoting seismic retrofit, and so on. One of the major activities of such local centers is to organize committees to review the results of seismic capacity evaluation and retrofit design by engineers, which may also contribute to improve the level of engineers.

2.2.2. Law for promotion of seismic rehabilitation of buildings

Law for promotion of seismic rehabilitation of buildings was enforced in December 1995. The objectives of the law are to enforce the seismic rehabilitation on the owners of the specified occupancy and/or large occupants buildings and to prepare the incentives to implement seismic rehabilitation of other buildings and houses. For this purpose, the law identifies the important buildings such as schools, hospitals, department stores, theaters, office buildings and so on, which accommodate a large number of inhabitants and visitors, and enforces the owners to make seismic rehabilitation. If the building officials approve the retrofit plans of such buildings, the owners are eligible to apply for lower interest loan, tax exemption, and exemption from regulations for land use and fire protection codes.

2.2.3. Evaluation of seismic capacity of existing buildings

It is assumed that there are about 18 million wooden houses and more than 2 million buildings, which were designed and constructed by the previous seismic codes. Considering the damage due to past earthquakes including the Hyogoken-Nanbu Earthquake, about 20% of wooden houses and 10% of buildings are assumed vulnerable. Therefore, many retrofit works have been going on around the country since the Great Hanshin-Awaji Earthquake Disaster. In order to evaluate the seismic capacity and to rehabilitate the existing reinforced concrete buildings, the Seismic Capacity Evaluation Standards and Rehabilitation Guideline [5] have been widely used since 1977 as the guidelines of seismic diagnosis.

In this seismic capacity evaluation procedures, the seismic capacity of a building is measured by the seismic index, I_s, which is defined as the following equation:

$$I_s = E_0 \times S_D \times T, \quad (1)$$

where I_s is the seismic index, E_0 is the basic seismic index, S_D is the structural design index, and T is the time index.

Basic seismic factor E_0 is evaluated as a function of strength index, C, and ductility index, F:

$$E_0 = C \times F. \quad (2)$$

For example, if a story is idealized as a series of vertical members such as in Fig. 2, the load deflection relationship for the story under a monotonic loading could be

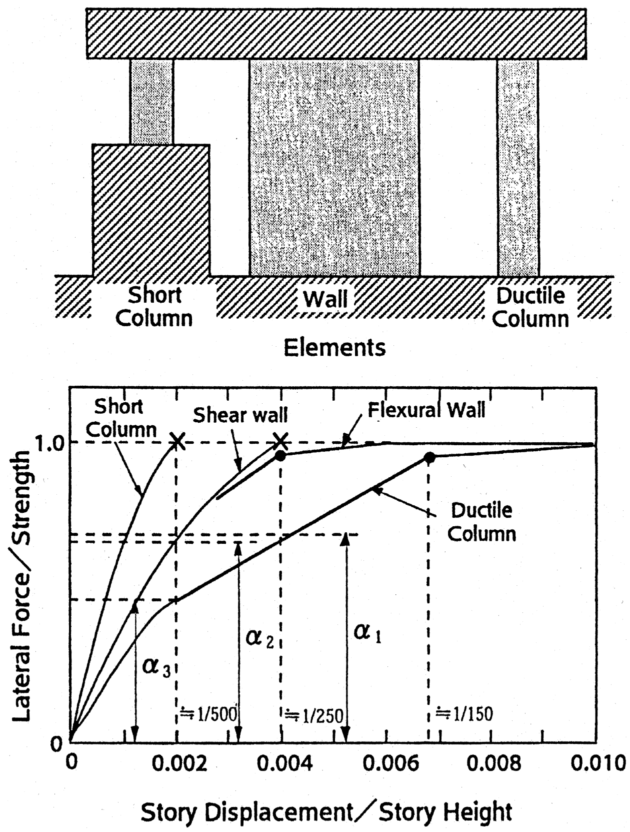

Fig. 2. Ideal load–displacement relationships of elements.

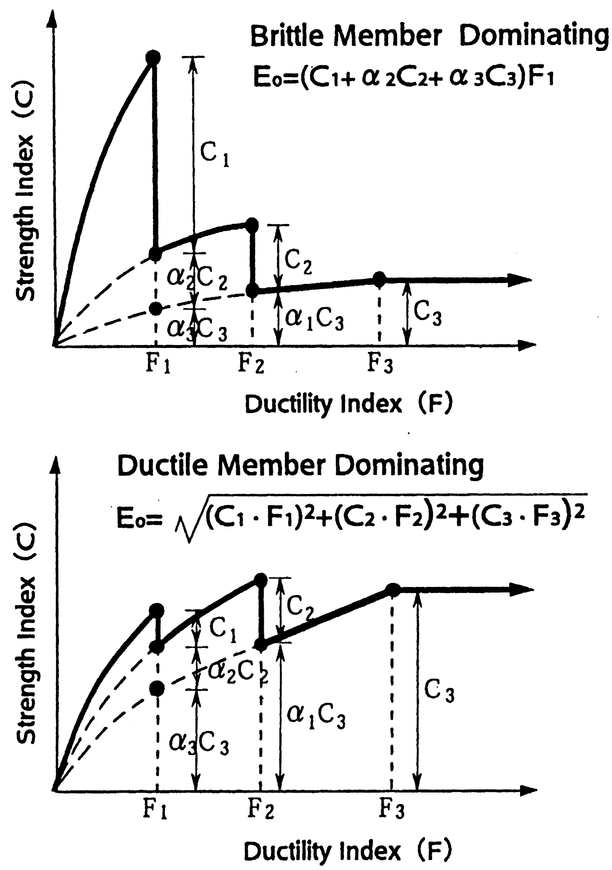

Fig. 3. Basic seismic index.

represented by the curves in Fig. 3. The idea of the seismic index, I_s, is to evaluate the capability of energy consumption of the story. There are three levels of procedure to evaluate the basic seismic index, E_0, depending on its simplicity. The first level procedure is a simple procedure but useful for buildings with considerable amounts of walls, where the strength index C is calculated based on section area and unit strength of columns and walls. The second level procedure requires the calculation of the ultimate strength of columns and walls with consideration of reinforcing bar arrangement. In the third level procedure, it is required to calculate the ultimate strength and ductility of beams as well as columns and walls.

The procedure to judge the seismic performance of existing building by the Seismic Capacity Evaluation Standards is as follows. First, the seismic index of I_s is estimated to evaluate the seismic capacity of the building, then it is compared with the judging index of I_{so}. If the I_s index is larger than the I_{so} index, the building is judged to have good seismic performance. This standard has been applied to the reinforced concrete buildings, which suffered from some previous earthquakes. From those studies, it was clarified that most buildings of which I_s indices were less than 0.3 took severe or moderate damage and the damage was slight for buildings of which I_s indices were greater than 0.6. Therefore, I_s of 0.6 has been recommended for judging criterion.

Similar study was carried out for reinforced concrete school buildings suffered from the 1995 Hyogoken-Nanbu Earthquake and it was found that the I_s index of 0.6 is considered to be the border between severe damage and moderate damage [6]. Considering these studies, the judging index of 0.6 is adopted in the Law for Promotion of Seismic Retrofit of Buildings as a standard criterion to prevent collapse or severe damage.

3. Rehabilitation strategy and techniques

3.1. Historical background

The research on seismic retrofit of existing buildings in Japan was initiated shortly after the 1968 Tokachi-oki Earthquake. A number of low-rise reinforced concrete buildings were heavily damaged by the earthquake. While many of severely damaged buildings were demolished, several damaged buildings were strengthened by the addition of structural walls along with repair. This was practically the first experience for Japanese engineers to extensively strengthen existing buildings against earthquake. The retrofit design and construction, however, were performed based on engineering judgment alone due to lack of appropriate guidelines.

Since then a number of experimental studies were conducted to investigate the seismic behavior of retrofitted buildings. Early studies were reflected to the "Guidelines for Seismic Rehabilitation Design of Existing Reinforced Concrete Buildings" [5] prepared by the Japanese Government in 1977. They were intended to be used in conjunction with the "Standards for Seismic Capacity Evaluation of Existing Reinforced Concrete Buildings" [5] prepared also by the government in the same year. These guidelines and standards have been widely used by Japanese engineers. In 1990, they were revised reflecting cumulative data of both research and design of over 15 years.

3.2. Rehabilitation strategy

As shown in Fig. 4, 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. 5). General approach to upgrade original performance is to strengthen existing structure by the methods described in the following section. To reduce large response displacement, a building may 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 damping of building and as a result to reduce seismic response.

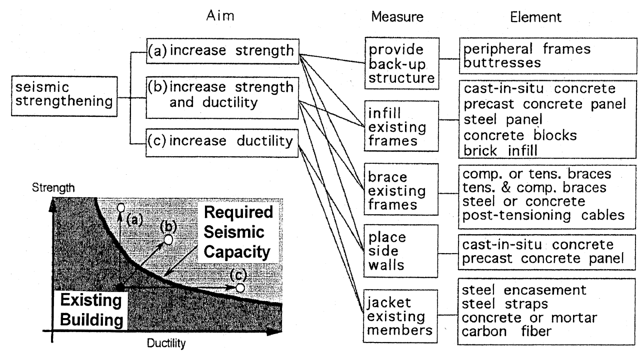

Fig. 5. Typical strengthening methods.

Another concept to reduce seismic response is to isolate existing structure from the ground excitation for increasing the fundamental period of building (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, this is particularly an effective approach. Schematic concept of seismic strengthening, seismic isolation and energy dissipation is shown in Fig. 6.

3.3. Strengthening techniques

3.3.1. Conventional technique

Many approaches and techniques have been studied and practiced for recent 20 or more years to strengthen existing structures. Some of them include to stiffen existing structure and/or to improve irregularity or discontinuity in distribution of stiffness or strength 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. 5). The required performance is evaluated in terms of strength and/or ductility. The combination of strength

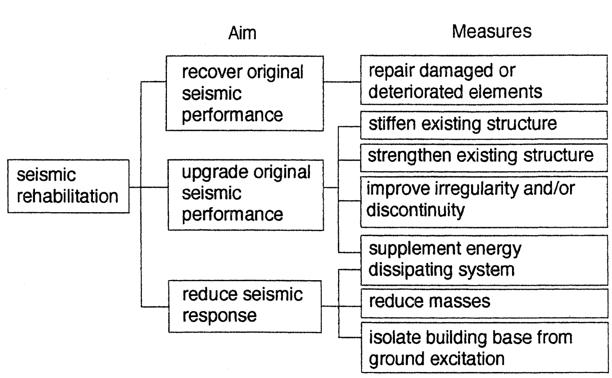

Fig. 4. Seismic rehabilitation strategy and measures.

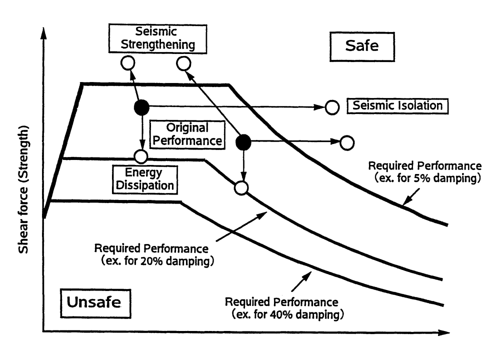

Fig. 6. Seismic strengthening, seismic isolation and energy dissipation.

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 prevent excessive inelastic displacement. To increase ductility spandrel walls may be separated from a column to eliminate "captive column".

Typical strengthening techniques are summarized in Figs. 7–14. New elements are added to existing frames to provide increased strength (Fig. 7), or existing framing elements are reinforced with additional materials to increase flexural capacity and/or to improve ductility (Figs. 9–11).

The typical elements to strengthen existing frames are infill walls, braces and side walls. Buttresses and additional peripheral frames also increase the lateral resistance of existing frames. Infill walls and side walls are cast-in situ or precast wall elements to be attached to frames or to columns. Generally, walls are of cast-in situ concrete infilling existing bare frame. Steel panel may also be an element to infill existing frame. It is necessary

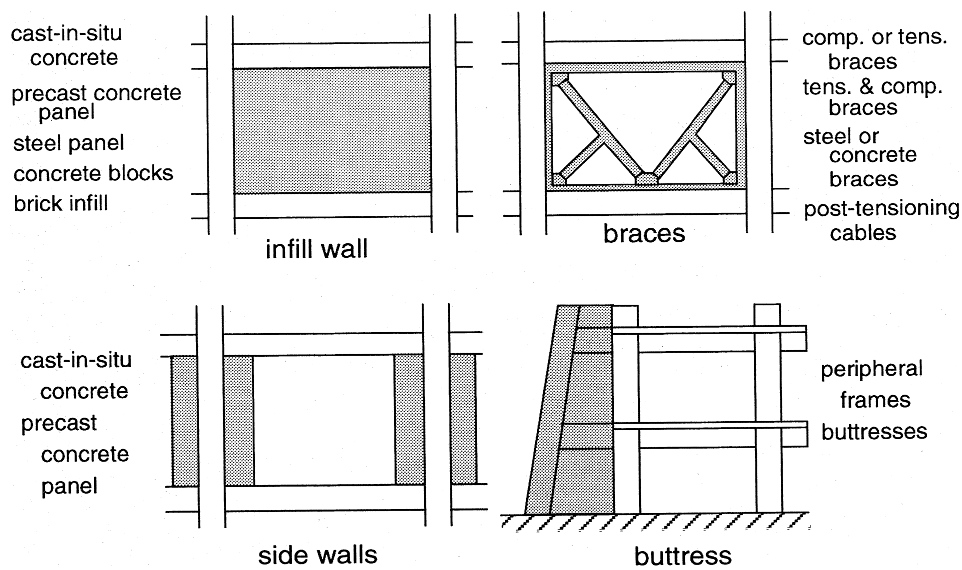

Fig. 7. Typical frame strengthening techniques.

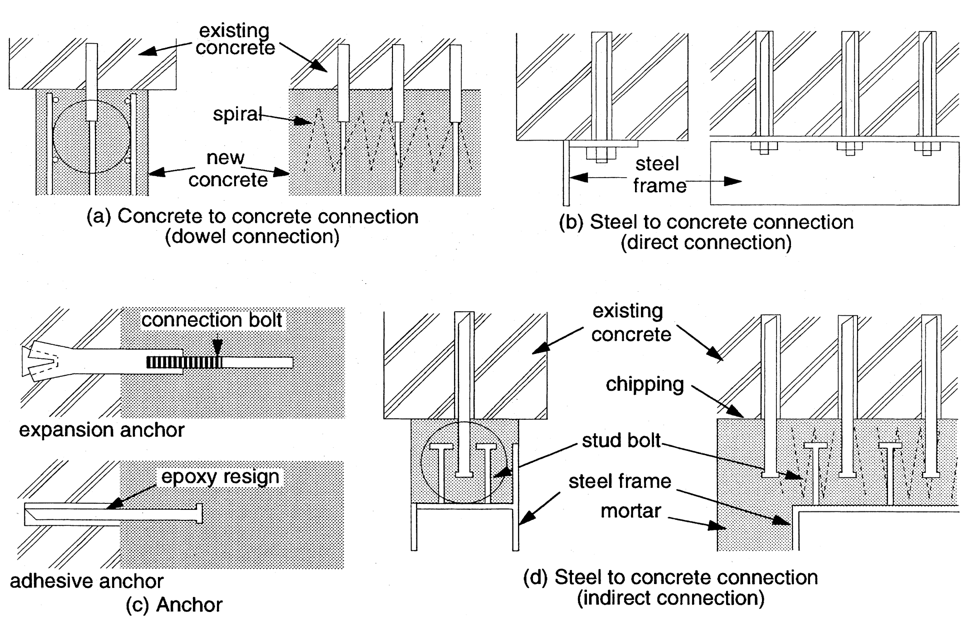

Fig. 8. Connections in frame strengthening.

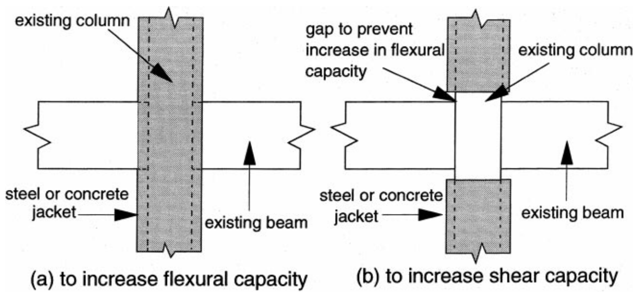

Fig. 9. Column jacketing.

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 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. 8. Dowel connections in Fig. 8(a) are used for infill walls and side walls. The expansion and adhesive type anchors for dowel connection are illustrated in Fig. 8(c). Steel elements may be simply attached to the existing concrete through mortar fill, as shown in Fig. 8(d), while they may be directly attached to the frames by bolting (Fig. 8(b)). Steel systems of braces and panels with peripheral frame were studied by Yamamoto [7] (Fig. 16) using the connection in Fig. 8(d). 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 with 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.

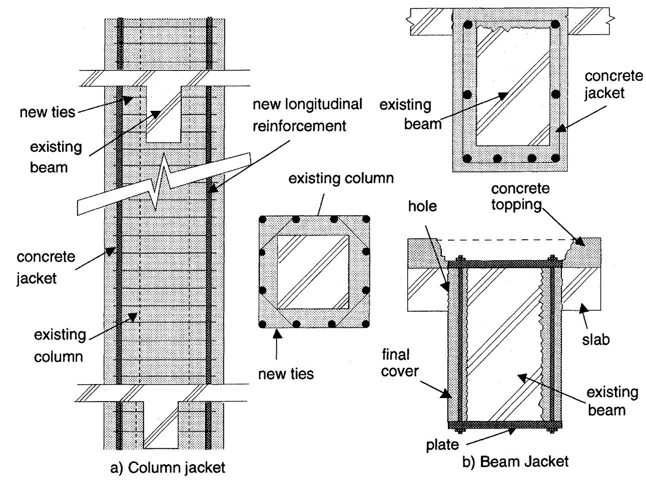

Fig. 11. Jacketing to increase flexural capacity.

Flexural capacity of frames may be increased with concrete or steel jacket shown in Fig. 11 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 (Fig. 12), though the construction is not easy. Column ductility may be improved with jacketing techniques shown in Figs. 9 and 10. 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.

3.3.2. New approaches in seismic rehabilitation [8]

Recently seismic isolation has been adopted for rehabilitation of critical or essential facilities, buildings

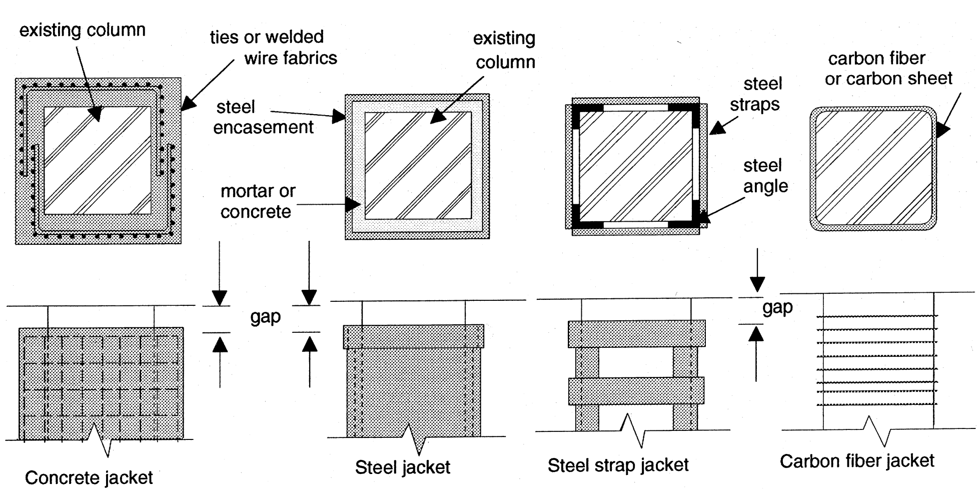

Fig. 10. Jacketing to increase column shear capacity.

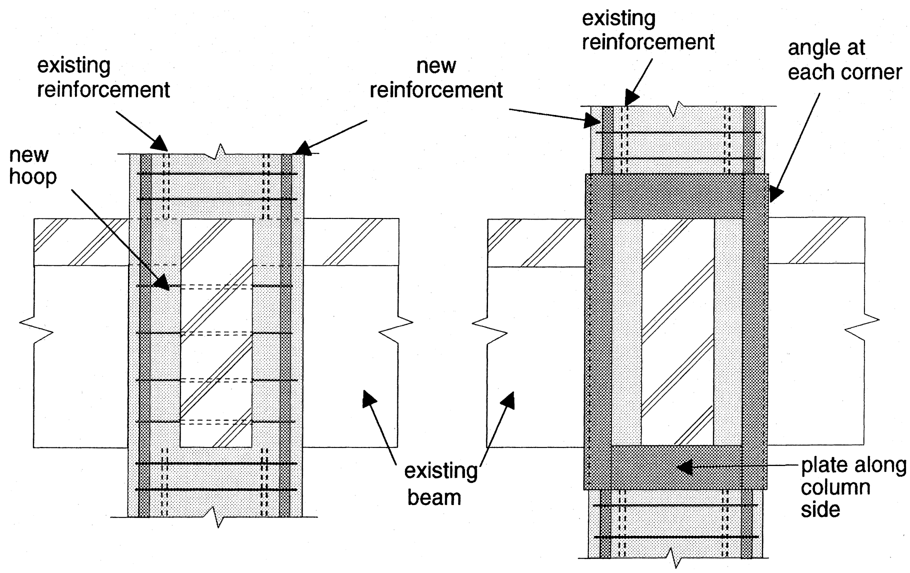

Fig. 12. Joint confinement steel.

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 by increasing the fundamental period of buildings. For isolation bearings, elastomeric systems (high-damping rubber and lead core rubber) or friction pendulum system are presently available (Fig. 13). In other cases, rubber bearings accompany damping element such as viscous damper. These damping elements are required for seismic isolation system to reduce the relative deflection between superstructure and ground. The locations for establishing isolation are, under the foundation girders, on the foundations, middle of columns or top of columns in a middle story of building. It is necessary to take into account the flexural deflection of isolators installed into the middle story columns.

The merits of the seismic isolation system are summarized as follows:

1. Construction part of building is less than that of other rehabilitation methods,
2. Trouble put to the users is decreased since building function can be operated during the construction for rehabilitation, and
3. Building style can be preserved.

However, because of the difficulties in design and lack of design procedure for rehabilitation with seismic isolation system, application of this system for rehabilitation is not so much though that for new construction is increased drastically. The rehabilitation of buildings with seismic isolation system means developing a new structural system. Then careful considerations of design criteria, structural planning and verification of performance are required. For these purposes, performance based design system, which has been developing in present for new construction buildings, are required also for the rehabilitation design.

Energy dissipation devices have recently been also adopted as vibration control elements for existing buildings to reduce inelastic deformation demand by increasing the damping of structures. Many ideas are proposed for new buildings; however, shear yielding damper, friction damper, rheological fluid damper and viscoelastic damper elements are presently available for seismic rehabilitation (Fig. 14). These devices may be installed into braces, wall panels or between braces and beams.

The merits of the energy dissipation system are large effect on reducing response and easy installation, which can reduce the trouble put to users and functional limitation of buildings during the rehabilitation. Because of the same reason as seismic isolation, application of this system for rehabilitation is not so much.

Application of continuous fiber sheet wrapping technique has been increased drastically because of its excellent workability and cost effectiveness. This newly developed technique is described in the later section.

4. Behavior of rehabilitated structures

4.1. Research on rehabilitated structures

The earliest tests in rehabilitation research were aiming at repair of damaged structure and the im-

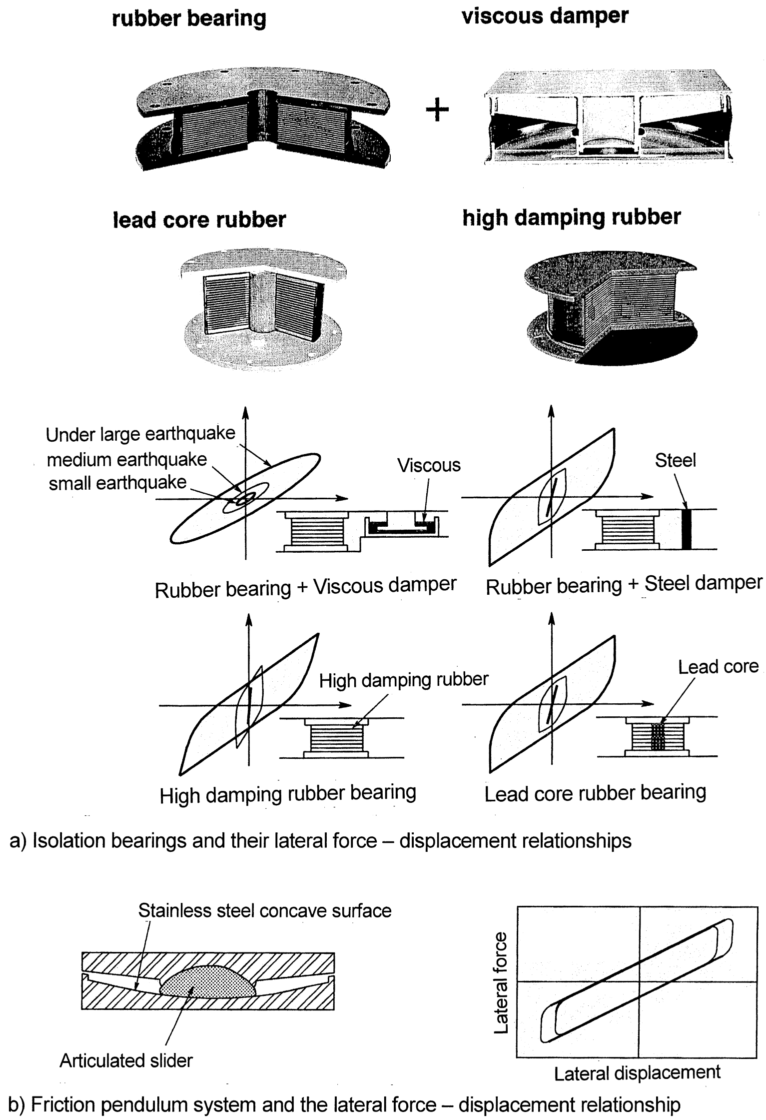

Fig. 13. Isolation bearings used for seismic rehabilitation [8].

provement of column ductility by jacketing with steel encasement, steel straps or welded wire fabrics. They were also aiming at the boosting of the strength of frames by the addition of precast or cast-in situ walls. In addition, one-story infilled frames with various connection details and bracing systems were examined. Three-story frames, strengthened by infilling and bracing techniques, were also tested. Further tests were those for infiill walls, steel bracing systems and jacketed columns with steel straps, with concrete, with steel encasement and with continuous fibers such as carbon fiber and aramid fiber. Beam-column joints of jacketed frames were also tested.

Shear transfer at the connection between new and existing elements was another issue in strengthening. The behaviors of fasteners and connections were investigated.

4.2. Behavior of strengthened frames

Examples of the behavior of strengthened frames with various construction techniques are shown in Fig. 15 [9]. Infill walls 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 ductile 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. 16 [7]. 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 also indicated significantly improved both strength and ductility of original frame. Note that even a steel peripheral

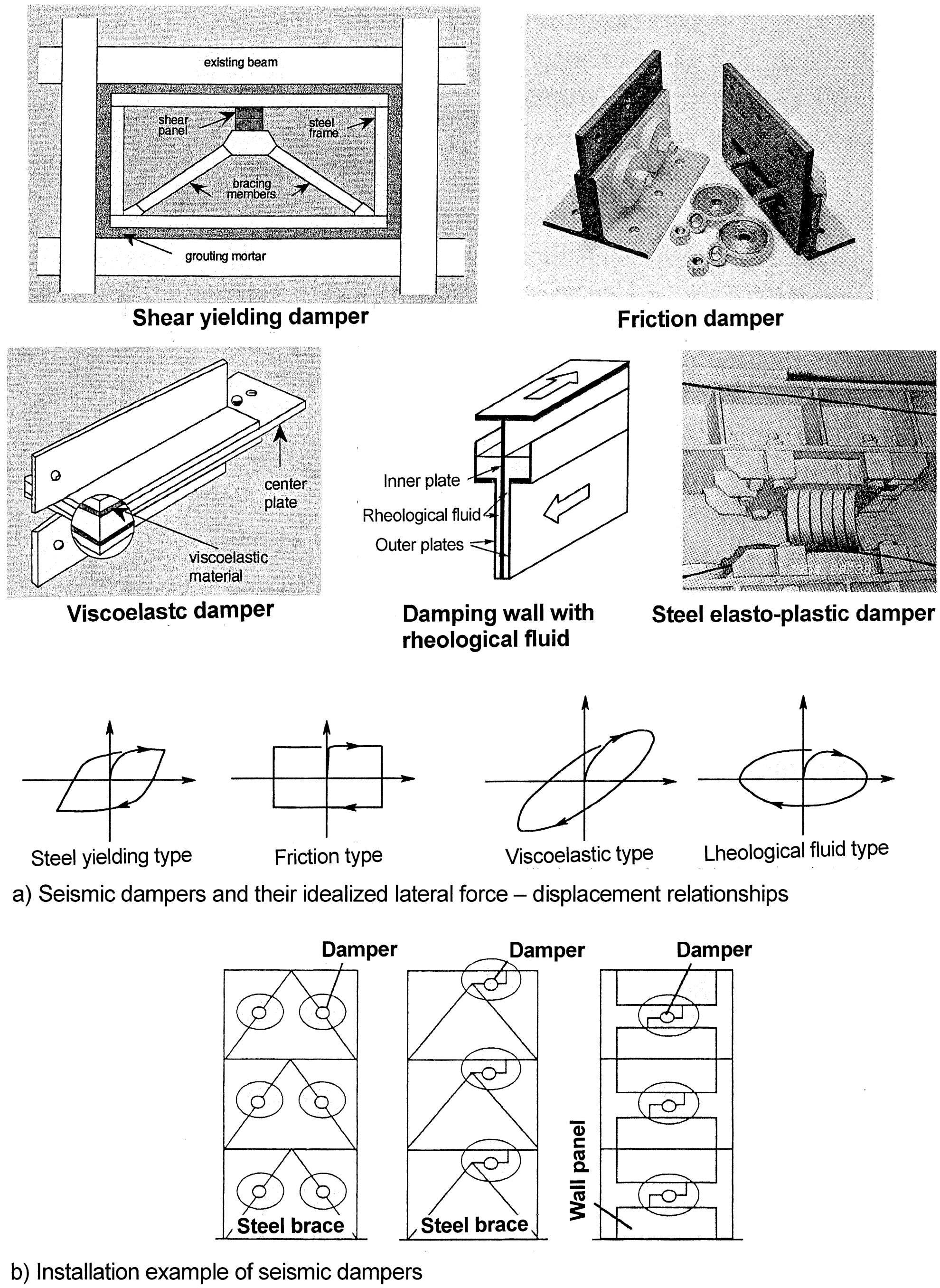

Fig. 14. Seismic dampers used for rehabilitation [8].

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 [10] (Fig. 14) 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. 17 [11,12]. This is only qualitative indication of the order of strength and ductility that might be attained using different techniques. The findings from the figure are 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.

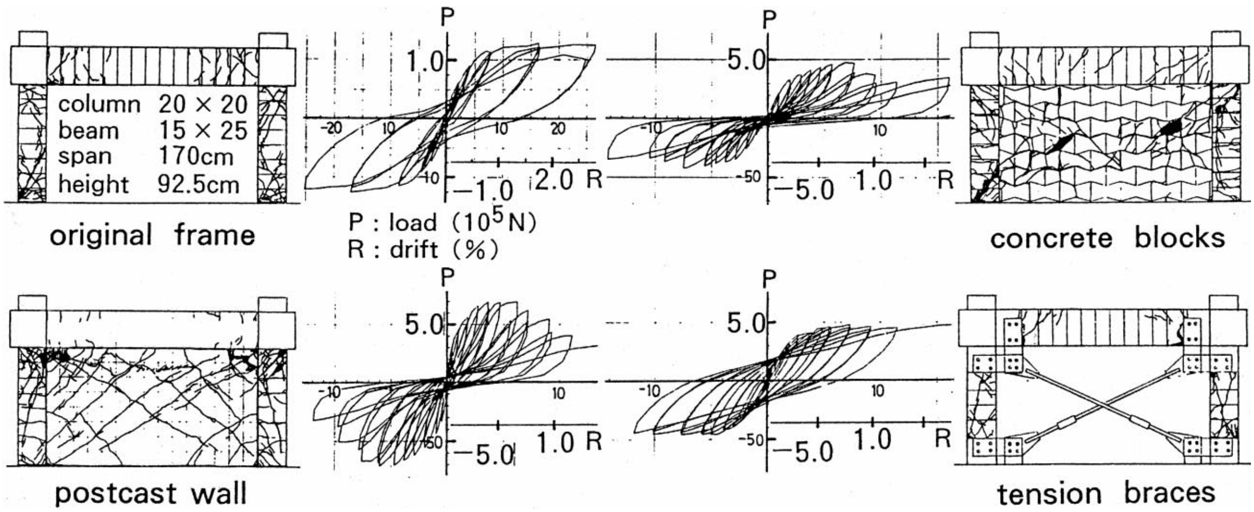

Fig. 15. Hysteretic behavior of strengthened frames with various techniques [9].

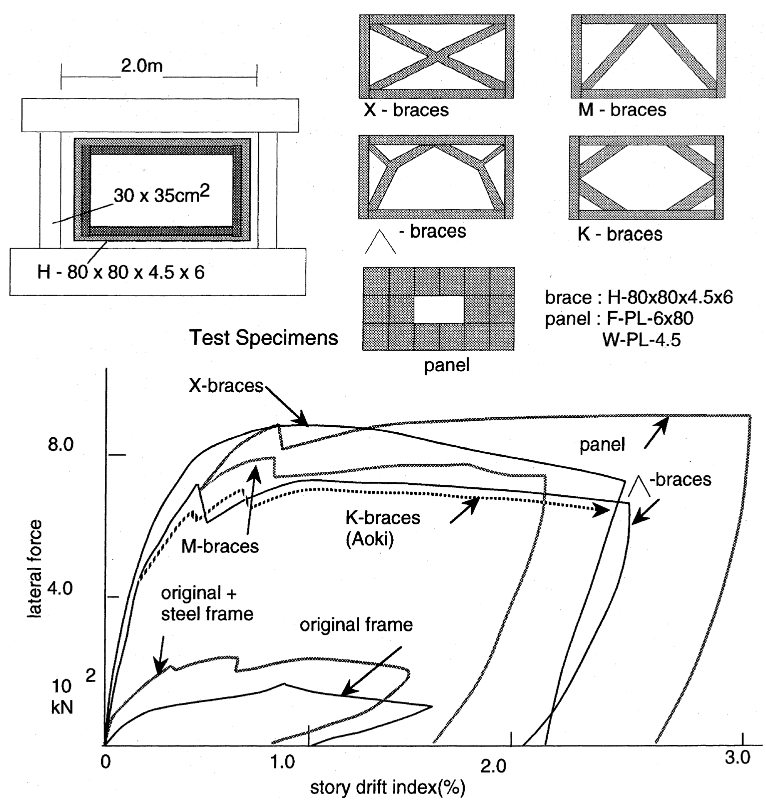

Fig. 16. Behavior of stregthened frames with steel systems [7].

3. The predominance of flexural behavior in three stories 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.

4.3. Behavior of reinforced members

Fig. 18(a) shows the dramatic improvement of ductility attained by a column using welded wire fabric wrapping and mortar [13]. 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

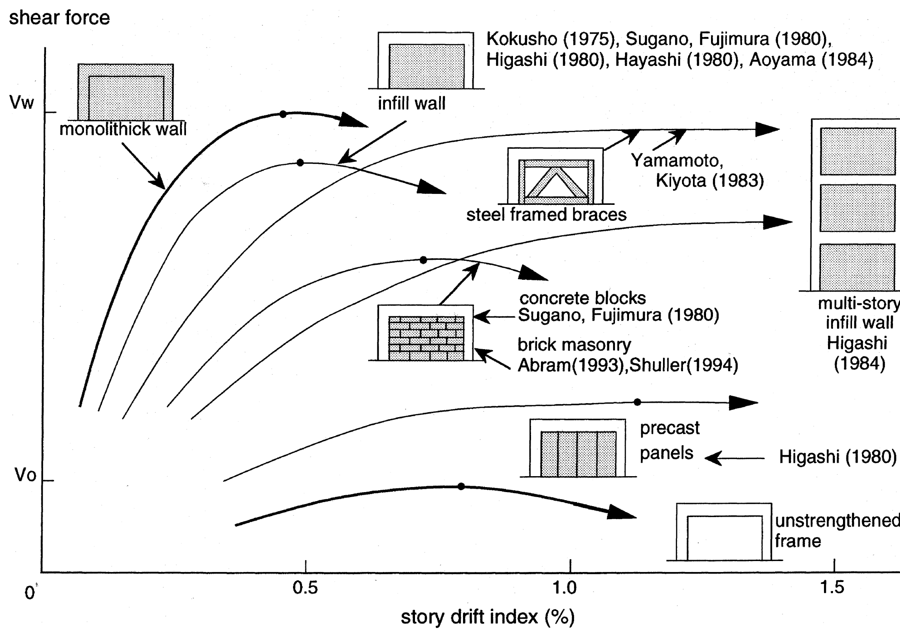

Fig. 17. Typical load–displacement relationships of strengthened frames with various techniques [11].

destructive earthquakes. Displacement ductility larger than 6 could be attained in this case. Also the significant improvement of ductility by steel encasement is shown in Fig. 18(b) [14]. 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. 19 [11,12]. 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 ductility, though higher strength was obtained.
4. Separation of spandrel walls considerably increased ductility while the strength was significantly reduced.

5. Continuous fiber wrapping technique [15]

5.1. Background

The repair and seismic strengthening by continuous fiber sheet wrapping method (Fig. 20), using carbon, aramid or glass fibers, is a relatively new retrofitting method developed firstly in Japan, whose research was first carried out in 1979. The wrapping method is characterized by its excellent constructional workability in addition to the characteristics of the construction materials, which exhibit high levels of anti-corrosion, high strength and lightweight. With these features, it is considered to be one of the most effective rehabilitation methods today. Until the Hyogoken-Nanbu Earthquake in 1995, this method had been studied only by a handful of organizations and employed by a few construction projects. After assessing the damage caused by the earthquake, however, various agencies have initiated research on this method and guidelines as for the design and construction have been established. The number of construction projects adopting this retrofitting method has also increased drastically in recent years.

5.2. Materials

In this section, fiber material is referred to as "fiber", the former materials that are transformed into pre-impregnated sheets or fiber fabrics "(continuous fiber) sheets," and fiber sheets that are hardened by impregnated resin "FRP (fiber reinforced plastic) sheets".

The continuous fiber is a generic term for extremely minute continuous fiber, which is approximately 5–20 μm in diameter and is characterized by high strength, high corrosion resistance, light-weight and non-magnetism. Continuous fibers are classified into various types of fibers including carbon fibers, aramid fibers and glass fibers. However, continuous fibers that are considered appropriate as reinforcing materials for buildings are represented by the above-mentioned three types of fi-

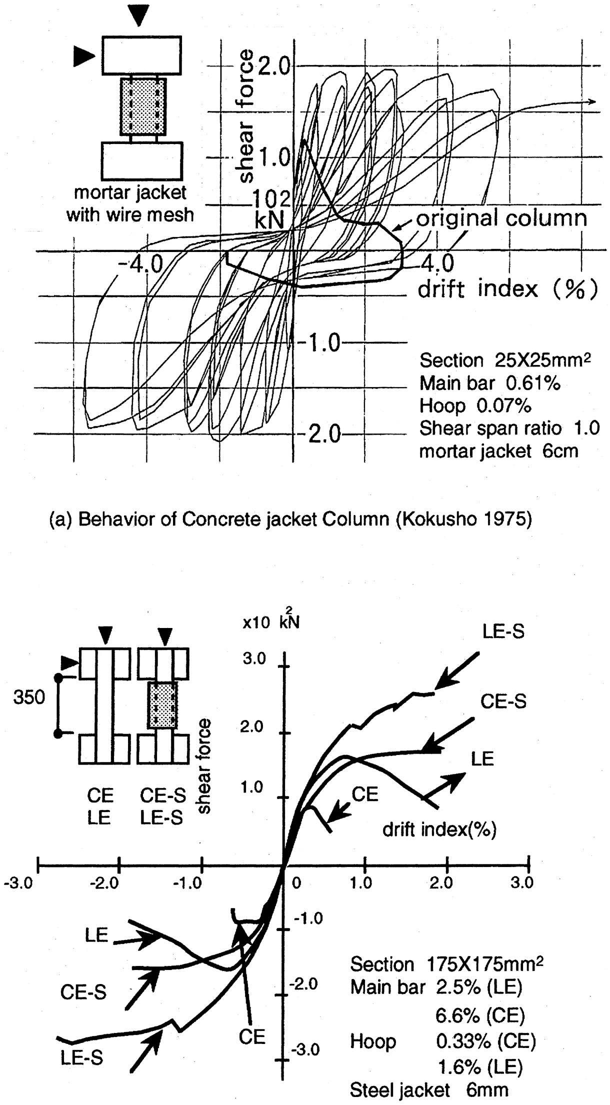

Fig. 18. Behavior of jacketed columns [13,14].

bers. These fibers are already used extensively in the field of sporting goods and aircraft. Therefore, their reliability as materials has already been verified.

5.2.1. Fibers

Fiber types used for seismic rehabilitation as fiber sheets in present are shown in Fig. 21. Fibers being used are carbon fibers, aramid fibers and glass fibers. Commercially used carbon fibers consist of both the PAN-type fibers and the pitch-type fibers. However, only one type of fiber belongs to the pitch-type fiber and the rest of the carbon fibers are of the PAN-type in its origin. The PAN-type carbon fibers are further divided into two types of fibers: high strength type and high elasticity type. Aramid fibers are classified into two types of fibers: whole-aroma-family polyamide fibers and aroma-family polyetherialamide fibers. Glass fibers only have one classification known as E-glass fibers. The tension characteristics of each fiber are shown in Table 1.

5.2.2. Fiber sheets

The classification of sheet form and weight per unit is indicated in Fig. 22. Shapes of the sheets are classified into one-way or two-way fabric, one-way prepreg that is pre-impregnated resin sheet, and one-way sheet. In the two-way fabric, fibers are arranged in both the lateral and transverse directions. In the other cases, fibers are arranged in one direction. Since one-way sheet does not expect the fibers being directed perpendicular to the reinforced fibers to have any strength or durability, low-cost fibers, i.e., glass fibers and nylon fibers, are used.

The weight per unit indicates the amount of reinforced fibers contained in the fiber sheets and is defined in weight of only fibers per 1 m^2 sheet. The weight per unit that is currently used ranges from 200 to 415 g/m^2.

5.2.3. FRP sheets

The tension characteristics of fiber sheets are determined based on the results of the tensile test of FRP sheets [15]. The cross-section areas used in calculating the tensile strength and the modulus of tensile elasticity are the sectional areas, solely consisting of fibers. The reason why the cross-section of fiber areas is singularly used is the possible fluctuation of the tensile strength and the modulus of tensile elasticity depending on the resin content if resin is included in the cross-section areas. There are large variations in resin content at the time of actual construction due to difficulty in controlling the maximum amount of resin.

In the tensile tests for the FRP sheet, fibers, as a congregate body, are to resist tension. Therefore, in general, the strength of FRP sheets is smaller than that of fibers. The relationships between tensile strength and Young's modulus of FRP sheets available in Japan are shown in Fig. 23.

5.2.4. Characteristics of materials

Characteristics of continuous fibers and resins as materials are discussed below:

(1) *Specific gravity*. The specific gravity of continuous fiber is 1.8–2.1 for carbon fibers, 1.4 for aramid fibers and 2.6 for glass fibers. All these values are far smaller than that of steel, which measures 7.74. Further, the specific gravity of resins also indicates a small value ranging approximately from 1.1 to 1.4. The data show that these materials provide enormous advantages in transportation and construction.

(2) *Tensile strength*. The tensile strength of continuous fibers, approximately 2900–4600 MPa, exceeds the general yield strength and the tensile strength of steel, approximately 300–600 MPa. This is a great advantage

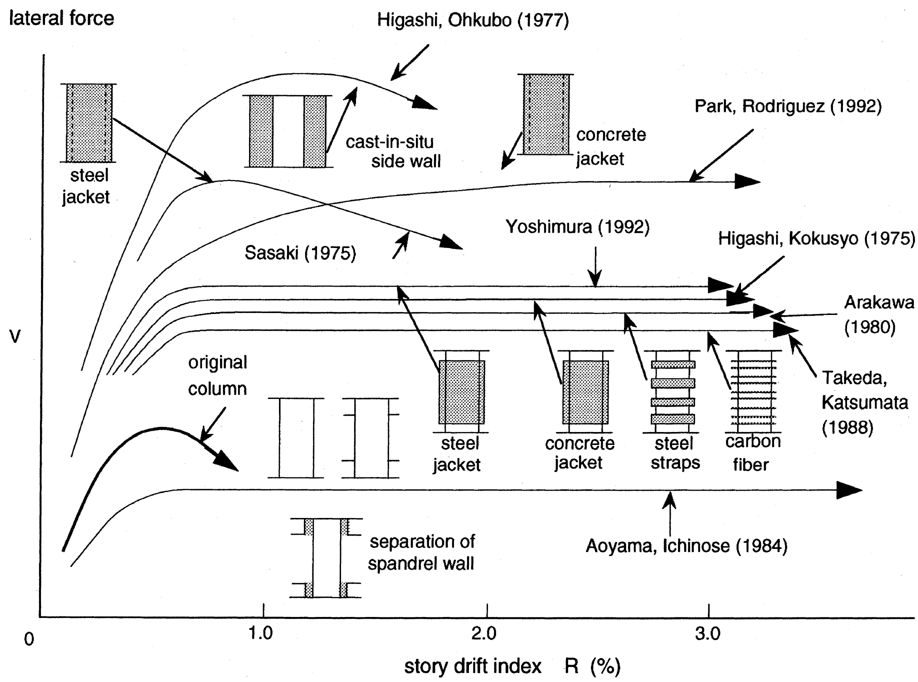

Fig. 19. Typical load–displacement relationships of columns reinforced with various techniques [11].

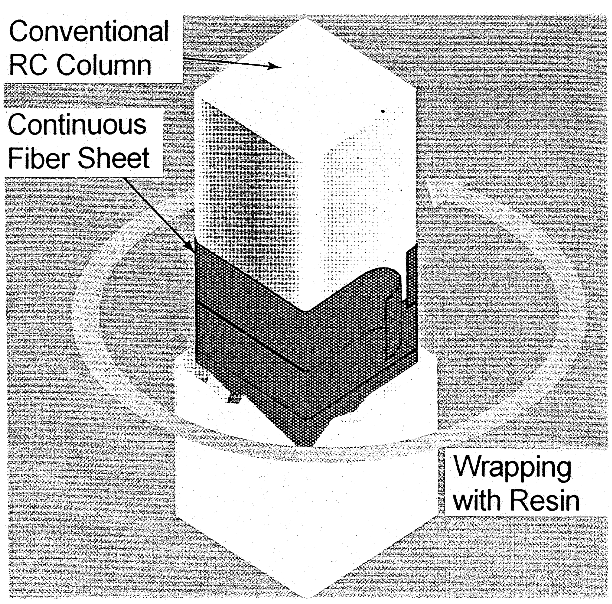

Fig. 20. Continuous fiber sheet wrapping method.

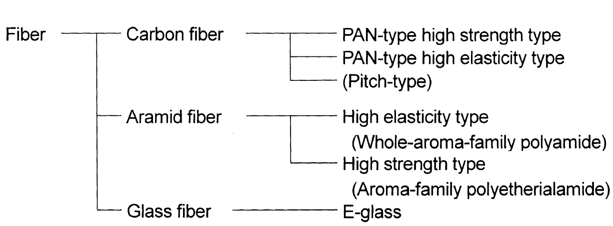

Fig. 21. Classification of fibers used.

when used as structural materials. However, performance of structural members reinforced with continuous fibers can be largely reduced when the concrete materials are failed in compression. Therefore, in evaluating the structural performance, a thorough investigation must be conducted on the failure mechanism of structural members and on the reinforcing effects of continuous fibers.

The tensile strength of continuous fiber sheets that are impregnated with resins can be lowered if the impregnation of resins between fibers is insufficient. This arises from the tension destruction of individual fiber being burdened with large stress due to the unequal stress among the fibers. Therefore, in order to spread the amount of stress almost equality to each continuous fiber, it is necessary to harden continuous fibers after impregnating resins fully among them.

(3) *Ductility performance.* Since continuous fibers are perfect elastic bodies and do not indicate any yield phenomenon, ductility design, which relies on the elongation of reinforcing bars as in conventional reinforced concrete structures, is not applicable when reinforced against bending. This should be well noted in designing reinforcement. In reinforcement against stress other than bending, the rupture of continuous fibers often leads to brittle failure of structural members. Therefore, it is important to properly understand the safety allowance ratio against rupture of fibers.

The typically observed Young's modulus values are between 230 and 640 GPa for carbon fibers, 74–111 GPa for aramid and glass fibers. In comparing the Young's

Table 1
Characteristics of fibers used

Classification of fibers		Tensile strength (MPa)	Modulus of elasticity (GPa)	Elongation (%)	Specific gravity
Carbon fiber	High strength type	3430–4900	230–240	1.5–2.1	1.8
	High elasticity type	2940–4600	392–640	0.45–1.2	1.8–2.1
Aramid fiber	High elasticity type	2900	111	2.4	1.45
	High strength type	3500	74	4.6	1.39
Glass fiber	E-glass	3500	74	4.7	2.6

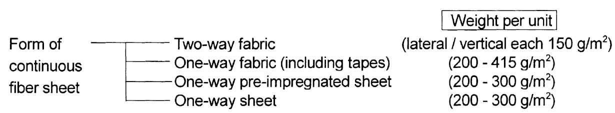

Fig. 22. Classification of fiber sheets by forms.

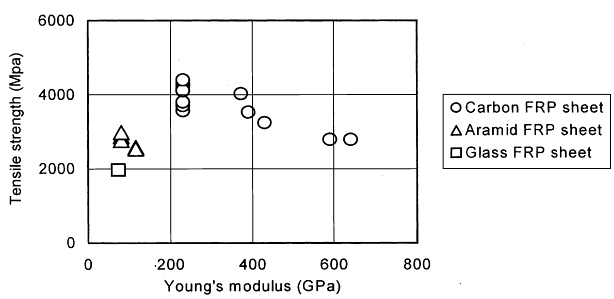

Fig. 23. Tensile strength and Young's modulus of FRP sheets used for seismic rehabilitation.

modulus with steel, 206 GPa, carbon fibers show values that are equal to or larger than the value of steel. Both aramid and glass fibers indicate around half the value of steel. Therefore, the strain of aramid and glass fibers becomes larger than that of carbon fibers when affected by the same level of stress. It must be noted that in the case of carbon fibers, elongation capability is smaller than that of aramid and glass fibers.

(4) *Durability.* Unlike steel, continuous fibers have the advantage with respect to corrosion. Therefore, from the viewpoint of anti-corrosion, continuous fibers are considered excellent materials. Regarding other durability such as chemical resistance, etc., caution must be taken in selecting fibers as different fiber may exhibit different chemical reaction. Durability of FRP sheets requires comprehensive evaluation including that of hardened resins. Establishing a testing method and accumulating data are desirable.

(5) *Adaptability to structures and molding ability.* Continuous fiber sheets are flexible materials that allow free folding. In other words, the adaptability to the shape of the structures is excellent. Furthermore, easy molding is made possible due to the nature of the sheets that can be cut with scissors and cutters. In general, widely used continuous fiber sheets have a thickness of 0.3 mm or below.

(6) *Cost.* The present cost per unit area of continuous fiber sheets is ¥6000–¥20,000/m^2 for carbon fibers, ¥6000–¥9000/m^2 for aramid fibers and ¥3000–¥4500/m^2 for glass fibers. If only the cost is considered, it is unreasonable. However, taking a look at the total cost including workability and maintenance, many cases report that the cost is lower than that of other construction methods.

(7) *Thermal resistance.* In comparison with steel, aramid fibers have less thermal resistance. However, resins are more vulnerable to heat. For instance, some epoxy resins start softening at about 80°C. When resins soften the tensile strength of the FRP sheets decreases compared with the condition of sheets at a normal temperature. To generate fire resistance when applying the retrofitting method using continuous fibers, sufficient fire resistance covering is necessary. With respect to the fire resistance of FRP sheets, accumulation of research data is desirable for the material characteristics during and after heating.

(8) *Hardening of resin.* Resin must be selected to match the temperature at the time of construction. The epoxy resin, which is widely used today, increases its viscosity and slows the hardening reaction at a low temperature. As a result, insufficient impregnation or hardening may occur. Therefore, when the temperature drops below 5°C, an appropriate treatment such as heating is required. Recently, acrylic-system resins have been developed for use at such a low temperature. Since the existence of water disturbs the hardening of epoxy resins and primers, measures must be taken to dry the concrete surfaces where rainfall and condensation are unavoidable.

5.3. Construction method

5.3.1. Overview of the construction method

The rehabilitation method using continuous fiber sheets for the existing concrete structures is a method that makes continuous fiber sheets adhered to the surface of concrete with resins, and transforms continuous

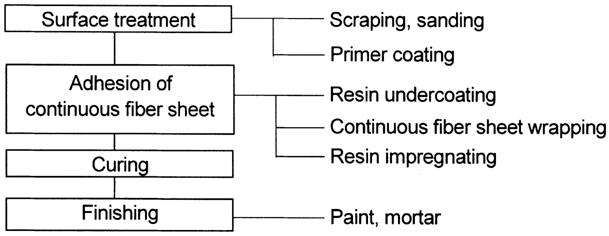

Fig. 24. Construction procedure of continuous fiber sheet retrofitting method.

fiber sheets into FRP. The general procedure of the construction method is illustrated in Fig. 24. Initially, base treatments including the adjustment of uneven concrete surfaces by scraping and primer coating are conducted. Then, continuous fiber sheets are wrapped and impregnated with resins. Finally, upon the hardening of resins, finishing work is executed:

(1) *Surface treatment of structures*. Surface treatments include cleaning and smoothing of structural surfaces by disk sanders and air blows, adjusting of unevenness by putty, and primer application in order to increase adhesion between concrete and resins. At the corners of rectangular columns and girders, the tensile strength of continuous fiber sheets may decrease. Therefore, corners must be rounded off (approximately 10–30 mm in radius). Concerning Earthquake-damaged columns, appropriate treatments, such as injection of resins into cracks, must be given. If the structural surface is moist, adequate treatments must be conducted in order not to lower the resin adhesiveness.

(2) *Wrapping of continuous fiber sheets*. First, structures are primed with resins. Then, continuous fiber sheets are pasted and air is removed with rollers after coating with resins. When wrapping multiple layers, this process is repeated. Other methods include omitting the process of resin priming, installing pre-formed FRP plates around columns and jointing the plates by continuous fiber sheets which are pasted later, and injection of shrinkage-compensating mortar into the gap between concrete and FRP plate.

(3) *Curing*. In the case of outdoor construction, curing with vinyl sheets, etc., is necessary to avoid adhesion of rain, sand, dirt and so forth. Careful attention must be paid so that sheets do not touch the construction surface. Hardening of resins is influenced primarily by the temperature.

(4) *Finishing*. Upon confirmation of dryness by touching with fingers, the finishing process can be started. The finishing is mainly done by direct painting or mortar application with tile or paint finish. A type of finishing is determined in consideration of esthetics, surface protection and, in some cases, fire resistance. Presently, the fire resistance is based on two basic ideas: a method using fire resistance covering such as mortar and a method to re-reinforce fire-damaged areas.

This construction procedure is mostly common in all the proposed methods. Construction methods other than wrapping continuous fiber sheets include a method using the strand of fibers to wrap around structures while impregnating the strand with resins.

5.3.2. Area of application and objective

The area of application varies widely. Examples for columns, beams, walls, floor slabs and chimneys are included. Objectives of the strengthening are classified into three categories: "shear strengthening", "flexural strengthening" and "compressive strengthening". The methods mentioned above possess innate abilities of anti-corrosion deriving from continuous fiber sheets and of "deterioration prevention" due to FRP layers that intercept water and gas from outside. The relationship between classification of rehabilitation objectives and the area of application is shown in Fig. 25. The shear strengthening reinforces toward at right angles to the member axis for columns and beams. An objective of strengthening columns and beams against shear is to increase ductility by raising the shear strength to exceed the flexural strength. The flexural strengthening reinforces toward the axial direction of the structural members. With regard to building columns, normally the reinforcement against flexure is barely conducted because of difficulty in executing the work. In the case of columns, compressive strength and the compressive ductility can be increased by confining the inner concrete by closely wrapping the continuous fiber sheets laterally.

5.3.3. Characteristics of construction methods

Characteristics of the retrofitting method using fiber sheets for construction are as follows:

(1) *Construction period*. The construction period differs greatly according to the construction target. In general, however, the construction period of the continuous fiber sheet method is shorter than that of the concrete jacketing or the steel plate jacketing methods.

(2) *Total cost*. The total cost of the retrofitting method using fiber sheets varies according to the types of construction. However, the total cost is normally

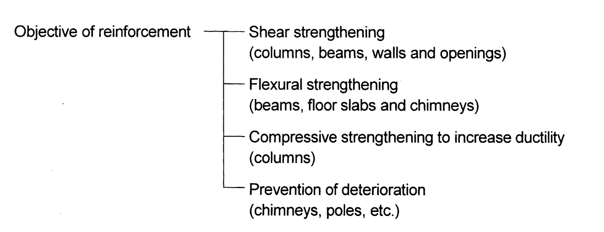

Fig. 25. Classification of rehabilitation objectives and area of application.

equivalent to or slightly higher than that of the concrete jacketing method and is often lower than that of the steel plate jacketing method.

(3) *Constructional workability*. The concrete jacketing method requires chipping of surfaces to maintain continuity between the new and the old concrete, arrangement of reinforcing bars, form installation and concrete casting. The steel plate jacketing method requires various works that demand specialization and skilled workers including anchor casting, field welding of steel plates and mortar grouting. The rehabilitation method using continuous fibers requires rounding off the corners, removing of the existing finishes and smoothing the surface of concrete. However, because continuous fibers can be wrapped directly around the structural surface, works required in other methods namely chipping, bar arrangement, welding, form installation and concrete/mortar injecting, are no longer necessary. Furthermore, work can be done in small areas, showing good constructional workability compared to the concrete jacketing and the steel plate jacketing methods. However, in order to obtain the reinforcing effect that are assumed in the design, the quality of the resins and the construction at the time of impregnating must be properly controlled.

(4) *Weight.* Since the retrofitting method that uses continuous fibers takes advantage of utilizing light-weight materials such as fibers and resins, the increase in weight can be ignored in the design. In addition, the light-weight of continuous fibers can be transported in rolls, making lifting machines unnecessary.

(5) *Stiffness of members.* When reinforcing against shear, both the concrete jacketing and the steel plate jacketing methods augment stiffness of the members. Therefore, an increase of stress on structural members during earthquakes must be taken into consideration. In contrast, the rehabilitation method using continuous fibers does not change stiffness of the members. Consequently, rehabilitation work is carried out without influencing the balance of the structural members of the buildings.

(6) *Maintenance.* Since continuous fibers are superior materials against corrosion, maintenance, such as regular painting, is barely required.

(7) *Impacts on construction workers and surrounding people*. The continuous fiber sheet method may produce noise, dirt and vibrations slightly during the process of base treatment. However, during other processes, the method scarcely causes any effect that could harm the residents or surrounding people.

5.4. Research and evaluation

Many researches on continuous fiber sheet wrapping technique have been conducted, especially after the Hyogoken-Nanbu Earthquake in 1995. Evaluations of shear strengthening effect and ductility improvement are the main target of these researches. Other researches on strengthening effect of compressive ductility, flexural strengthening, damaged columns by earthquake or corrosion, columns with round longitudinal bars, columns with side walls, columns without removing finish, steel encased reinforced concrete columns, walls and beams with slab have also been conducted.

These researches were reflected to the guidelines for "Seismic Rehabilitation Design and Construction of Concrete Buildings by Continuous Fiber Wrapping", which was published from the Japan Building Disaster Prevention Association in September 1999.

5.5. Field application

Fig. 26(a) illustrates the use of carbon fiber sheets since 1993. Consumption increased annually from the 6 ton level in 1993 to about 125 ton in 1996 and to about 250 ton in 1997. Although aramid fiber sheets are less popular, they have also experienced steady growth due to the commercial production, as shown in Fig. 26(b).

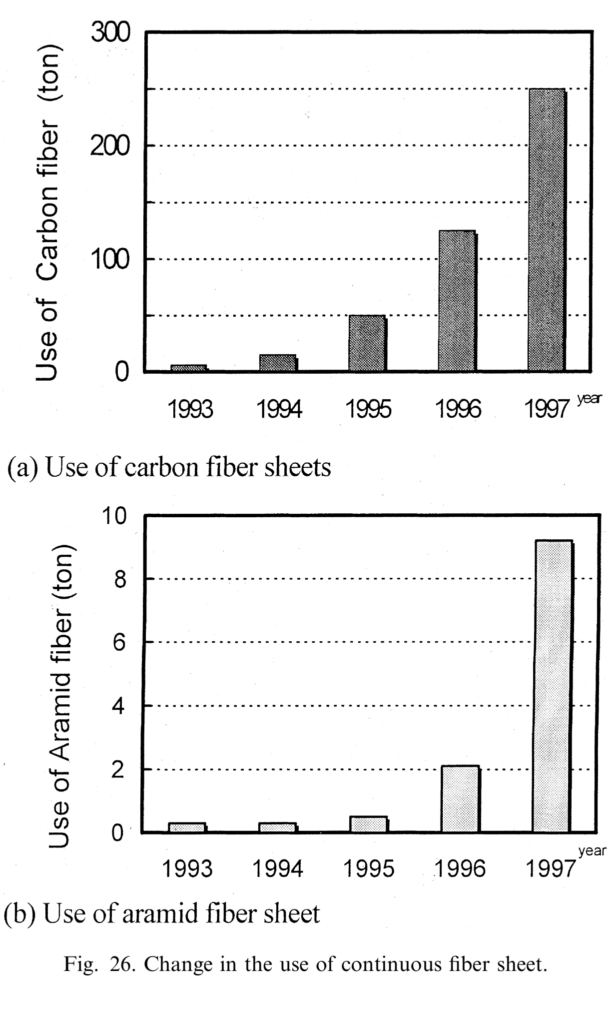

Fig. 26. Change in the use of continuous fiber sheet.

Fig. 27 shows the number of projects utilizing carbon fiber sheets for repair and strengthening. There has been rising use for bridges and buildings drastically, while application to tunnels and stacks is only just a beginning. Seismic rehabilitation is the main reason for using carbon fiber sheets. Both Figs. 26 and 27 show a sudden rise in the usage of continuous fiber sheets after The Hyogoken-Nanbu Earthquake of January 1995.

Design and construction guidelines for the repair and strengthening of structures using continuous fiber sheets (with carbon fibers and aramid fibers) are currently being developed in a joint effort of government, research institutes, and private sectors. It is, therefore, reasonable to expect a continuing rise in demand for continuous fiber sheets in the future.

5.6. Future perspective

The application of continuous fiber wrapping showed a rapid increase for the last couple of years. Therefore, it is undeniable that this method still lacks history of experience. Further propagation and application of this method to wider range of subjects are expected as studies on this method proceed. In order to achieve these goals, the following subjects must be addressed in the future:

(1) Since reinforced materials, in particular, rely their structural performance on material characteristics, further pursuit of material performance is desirable. The performance and the construction conditions required for the rehabilitation vary widely depending on target structures and members. Therefore, development of materials capable of dealing with this variety is most desired.

(2) Establishing a standard test method of continuous fiber reinforcing materials, which are new as reinforcing materials, is indispensable for evaluating the material quality and the structural performance of reinforcing materials. Information on the subject matter is considered insufficient.

(3) The social trend of the structural performance evaluation is shifting from the specification-based regulation to the performance-based regulation. The keyword to represent the future design as well as the rehabilitation design is the word "performance". Furthermore, the system must be established to allow indicating performance of repaired or strengthened structural members by means of the appropriate evaluation method.

(4) In order to achieve unfailing reinforcing effect, the quality maintenance of construction works is indispensable. Therefore, the improvement of the construction method and the enhancement of the construction management method are desired for achieving the stable quality in easier and more dependable manners. In addition, it is essential to establish quality inspection methods that are easy and effective.

(5) It is desired to establish the educational system for engineers and technicians of structures, materials and constructions concerning the rehabilitation using continuous fibers.

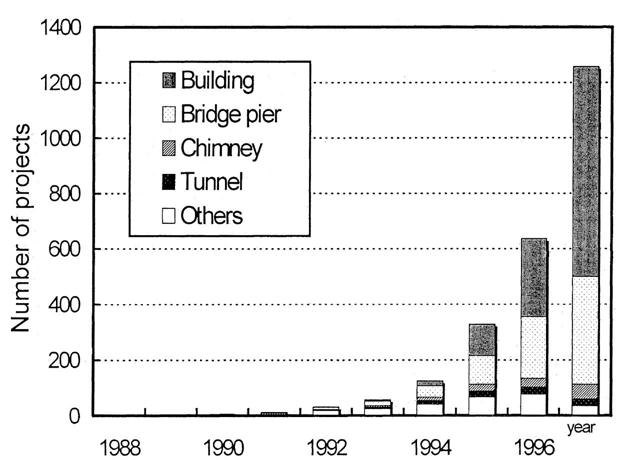

Fig. 27. Change in the number of rehabilitation projects using carbon fibers.

6. Seismic rehabilitation of existing buildings

6.1. Post-earthquake rehabilitation

Recently over 25 years, many buildings were rehabilitated after the damage by destructive earthquakes using various types of techniques. The criteria for how to restore a damaged building depend on the level of its damage and the intensity of the earthquake which caused the damage. 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 variety. In early cases, mostly concrete shear walls were selected because they were capable of providing large lateral resistance. The shear wall strengthening, however, takes disadvantages due to increased weight of the building, and separation of space. Diagonal steel bracing is another solution to provide large lateral resistance and possible large displacement capacity of a building, in addition, large opening for lighting without largely increased weight followed by the rehabilitation. Buttress is another solution to increase lateral resistance largely. It does not disturb interior building space and function; therefore, it is effective method when outer space is sufficiently provided.

6.2. Restoration of damaged buildings in Kobe

A large number of restoration works of damaged concrete buildings were carried out during these five years after the Hyogoken-Nanbu Earthquake. Then, in appearance, it is hard to find the trace of the disaster in the suffered area today. Many damaged buildings needed repair for reuse while collapsed or some of severely damaged buildings were demolished. The criteria for restoration depend on damage level and the intensity of the earthquake which damaged the buildings. Table 2 shows proposed criteria for restoration [16]. In the areas which reported seismic intensities "6" (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. Fig. 28 shows examples of recommended repair techniques for reinforced concrete buildings.

6.3. Pre-earthquake rehabilitation

Since the publication of the "Standards for Seismic Capacity Evaluation of Existing Reinforced Concrete Buildings" [5] in 1977, a large number of existing buildings have been evaluated in a limited area. Particularly, several agencies, i.e., Shizuoka Prefecture, Yokohama City and the Tokyo metropolis, in charge of administration of a number of public buildings, have performed the evaluation as a part of seismic countermeasure program. Shizuoka Prefecture, where a magnitude 8 or more severe 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 buildings were actually rehabilitated during the period 1982–1987. The major construction technique was to use concrete infiill walls so that they may provide very high lateral resistance against the presumed huge earthquake. However, in later part of the project, steel systems were also used to avoid the increased weight of building associated with the strengthening and to provide large opening for lighting.

Since the Great Hanshin-Awaji Earthquake Disaster was a great shock to Japanese people, and the Law for Promotion of Seismic Rehabilitation of Buildings was enforced in 1995, almost every local government has been promoting the seismic rehabilitation of official buildings. Seismic capacity evaluation and seismic rehabilitation of a large number of buildings were coming out. Combinations of various techniques, which are introduced in this paper, were applied in the recent rehabilitation. One of the problems to be solved in the many conventional seismic rehabilitation techniques is that building cannot fully operate under rehabilitation construction. It is a strong social demand to solve this problem for current seismic rehabilitation to prevent inconveniences and commercially disadvantages.

Table 2
Criteria for restoration of damaged buildings [16][a]

	Damage level	Light	Minor	Medium	Major	Collapse
Seismic intensity scale (JMA)	Lower than 5	○	△	×	×	×
	5	○	○	△	×	×
	Higher than 5	○	○	○	△	×

[a] Restoration by ○ repair; △ repair or strengthening (need investigation in detail); × strengthening (need investigation in detail) or demolition.

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 mortar Jacket with steel plate and grout mortar	Jacket with concrete Jacket with steel plate and grout mortar Jacket with steel plate and vertical reinforcement and grout mortar

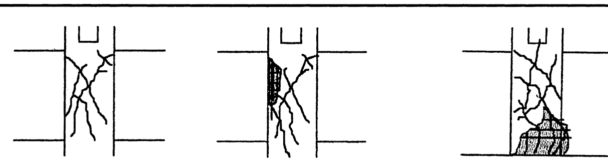

Fig. 28. Repair and strengthening of damaged concrete columns [17].

6.4. Behavior of rehabilitated buildings 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 following are the buildings in such cases.

A three-story reinforced concrete building suffered severe damage to the first-story columns due to the earthquake of 1968. The building was rehabilitated with shear walls at the damaged first story. As a result, only the unstrengthened second story columns suffered severe shear cracks due to the recent earthquake of 1994. While an adjacent building which was rehabilitated up to second story did not suffer any severe damage. Importance of balanced configuration of strengthening elements is indicated in this case [18]. It is also indicated that the building could have been badly damaged if it had been rehabilitated with repair alone and without structural walls.

The other case is an old building constructed in 1918 in Kobe City whose seismic rehabilitation was completed 10 months before the event of 1995. 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 buildings did not suffer any damage while some other buildings suffered severe damage in the same area. This is a very encouraging case to indicate the effectiveness of pre-earthquake rehabilitation.

7. Subjects to be considered in the future

7.1. Performance-based engineering

One of the lessons from the Great Hanshin-Awaji Earthquake Disaster is that most new buildings designed and constructed according to the present seismic codes showed fairly good performance for preventing severe structural damage and/or collapse. However, the problem was that the seismic performance of buildings ranged widely from the level of collapse preventing to function keeping, which is not identified by the present seismic codes. Neither building owners nor users understood performance level of buildings. Therefore, it is strongly needed to develop more rational seismic design codes based upon the performance-based seismic design concept, where the performance of buildings including structural and functional safety during and after earthquake, and reparability after earthquake are explicitly explained.

Ministry of Construction, Japanese Government, is revising the Building Standard Low as performance-based regulations. Since the code is a minimum requirement, evaluation and indication system for the performance beyond the code requirement is also under developing. Though these actions are for the newly constructed buildings in present, a performance-based engineering system may also be applied for the seismic evaluation and rehabilitation. The objective of the application of performance-based engineering is to control damage in accordance with the type of buildings and their occupancy.

7.2. Effective rehabilitation techniques without hindrance of building operation

Since many types of seismic rehabilitation work may produce dust, noise, vibration and chemical smell generally and use fire in some cases, effective rehabilitation technique that can prevent these problems must be established in order to operate buildings even under the seismic rehabilitation. To prevent inconveniences and commercially disadvantages is a strong social demand for seismic rehabilitation techniques.

Many projects to develop new techniques to meet this requirement have been conducting. The research topics of these projects are application of easy, fast and clean methods for seismic rehabilitation.

8. 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 results of the review are summarized as follows:

1. Many typical techniques to strengthen existing structures have been well investigated with respect to their improved performance, and they have been utilized.
2. In addition to conventional seismic resistant type rehabilitation techniques, other approaches to isolate an existing structure from the ground shaking or to supplement energy dissipation devices to reduce seismic response have been adopted recently. 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 small number now; however, they will be widely used in future.
3. Rehabilitation techniques may be selected in accordance with required performance level. Generally, the seismic rehabilitation is achieved to upgrade the original performance to the current code level. However, the codes do not clearly figure out the post-earthquake condition of designed buildings. Design approaches corresponding to more detailed required performance level will be necessary.

4. A performance-based engineering system should be applied for the seismic evaluation and rehabilitation to control damage in accordance with the type of buildings and their occupancy.
5. The effective rehabilitation techniques must be established to meet the strong social demand that buildings can be operated even under the seismic rehabilitation.

It is a hard task and it takes a long time to complete the seismic rehabilitation of vulnerable buildings and houses; however, it should be implemented to mitigate disaster due to future earthquakes.

References

[1] Okada T. Promotion of seismic retrofit of buildings. In: Lecture Note for 12th IISEE Seminar on Seismology and Earthquake Engineering. IISEE Building Research Institute, May 1998.

[2] Watanabe F. Behavior of reinforced concrete buildings during the Hyogoken-Nanbu Earthquake, cement and concrete composites, vol. 19. June 1997. p. 203–11.

[3] Committee for Building Damage Investigation of Hanshin-Awaji Earthquake Disaster. Report on the damage due to Hyogoken-Nanbu Earthquake. Ministry of Construction, Japanese Government, December 1995 [in Japanese].

[4] Building Research Institute. A survey report for building damages due to the 1995 Hyogoken-Nanbu Earthquake, March 1996.

[5] Japan Building Disaster Prevention Association. Standards for evaluation of seismic capacity and guidelines for seismic rehabilitation of existing reinforced concrete buildings, 1977 revised 1990 [in Japanese].

[6] Committee for Seismic Performance of School Buildings. Report on the damage of school buildings due to the Hyogoken-Nanbu Earthquake. Architectural Institute of Japan, 1995 and 1996.

[7] Yamamoto Y. Strength and ductility of frames strengthened with steel bracing, earthquake resistance of reinforced concrete structures, a volume honoring Hiroyuki Aoyama, November 1993. p. 467–76.

[8] Japan Concrete Institute. Technique and application on seismic rehabilitation of R/C structures, August 1998 [in Japanese].

[9] Sugano S, Fujimura M. A seismic strengthening of existing reinforced concrete buildings. In: Proceedings of 7 WCEE, Istanbul, Turkey, September 1980. p. 449–56.

[10] Okada T, Nakano Y, Kumazawa F. Experimental study of 1/10 scaled R/C frames retrofitted with steel framed Y-shaped bracing system. In: Proceedings of the International Symposium on Earthquake Disaster Prevention, Mexico City, May 1992. p. 200–9.

[11] Sugano S. State-of-the-art in techniques for rehabilitation of buildings. In: Proceedings of 11 WCEE, Acapulco, Mexico, June 1996. Paper no. 2175.

[12] Sugano S. State-of-the-art in techniques for seismic rehabilitation of existing buildings. In: Lecture Note for 12th IISEE Seminar on Seismology and Earthquake Engineering. IISEE Building Research Institute, May 1998.

[13] Kokusho S, Fukuhara M. Comprehensive study on collapse prevention of R/C columns – Part 27 CR series: strengthening methods of existing R/C columns by mortar and welded steel mesh. In: Proceedings of the AIJ Annual Meeting. Architectural Institute of Japan, October 1975 [in Japanese].

[14] Yoshimura K, Kikuchi K, Iguchi K. A proposal of Seismic shear strengthening method for R/C short columns in existing building structures. In: Proceedings of 9 WCEE, Tokyo, Kyoto, 1988. p. 327–32.

[15] Japan Concrete Institute TC-952. Technical report on continuous fiber reinforced concrete, September 1998.

[16] Japan Building Disaster Prevention Association. Standard for inspection of damage degree and guidelines for restoration techniques, 1991 [in Japanese].

[17] Building Center of Japan. Damage and rehabilitation examples of RC, steel and SRC buildings. In: Seminar on Rehabilitation Techniques for Damaged Buildings, 1995.

[18] Nakano, Y. Damage to buildings due to 1994 Sanriku-Harukaoki Earthquake, building disaster, vol. 211. Japan Building Disaster Prevention Association, August 1995. p. 6–15 [in Japanese].