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A seismic retrofitting method for existing reinforced concrete structures using CFRP

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Abstract—Carbon fiber with high strength, light weight, and high durability has been used for the seismic rehabilitation and strengthening of a number of existing reinforced concrete structures. The authors have been investigating the seismic retrofitting methods using carbon fiber and those effects for improvement of earthquake resistance capacity since 1984. We have developed three types of seismic retrofitting methods, namely for building columns, chimneys, and bridge columns. After the 1995 Great Hanshin-Awaji Earthquake Disaster, the amount of seismic retrofitting work using CFRP has significantly increased.

This paper consists of 7 sections: Section 2 introduces carbon fiber used and the product forms; Sections 3 through 6 describe the seismic retrofitting methods by CFRP; Section 3 is an overview of the methods; Section 4 describes construction procedure of retrofitting; Section 5 gives an outline of research and development; and Section 6 discusses utilization and construction records.

Keywords: Seismic retrofit; carbon fiber; reinforced concrete structure; shear strengthening; flexural strengthening; retrofitting method.

1. INTRODUCTION

The development of seismic design methods has advanced incrementally as lessons were learned from the damage caused by major earthquakes. In building, the massive revision of the Building Code which took effect in 1981 enforced a new seismic proof structural design method called 'new seismic design' which incorporated the lessons learned from the Tokachi Oki Earthquake (1968) and the Miyagi-ken Oki Earthquake (1978). In the meantime, the Earthquake Resistant Design Guideline of Road Bridge was enforced in 1980. The necessity of implementing seismic retrofitting for so-called 'pre-code revision structures' that were built before the revisions of these standards has long been pointed out but not much has been done.

Many structures suffered damage from the Hyogo-ken Nanbu Earthquake in 1995. It was these many pre-code revision structures that suffered most serious damage such as collapse. Social demands to consider seismic retrofitting counter-measures for such structures are on the rise triggered by this earthquake. Seismic retrofitting for existing buildings is essential for effective disaster prevention. In the conventional seismic retrofitting methods, reinforced concrete or steel (steel frames or steel plates) were commonly used. Addition of reinforced concrete walls or steel-framed braces, steel jackets or gluing of steel plates have been used in the conventional methods. Building columns, bridge columns, chimneys, building beams and bridge columns have been retrofitted using these methods.

In the conventional retrofitting method using reinforced concrete, not only is the work required very time-consuming but also the weight of such a structure tends to increase due to the strengthening. Retrofitting by steels requires welding work for which special skills may be needed and the retrofitting work is complex as resin must be poured. It is further accompanied by higher construction cost. For this reason, seismic retrofit methods using CFRP were devised. Carbon fibers have higher tensile strength than steel and the strengthening structures are lighter and more durable.

The seismic retrofitting methods using CFRP have been drawing attention since the Great Hanshin-Awaji Earthquake Disaster. Seismic retrofitting using these methods was first applied to buildings and bridge columns which were damaged by the earthquake and was later adopted to pre-code revision structures. As a result, the amount of seismic retrofitting work by CFRP has significantly increased. One such method is called the CRS method (Carbon Fiber Retrofitting System). Although many other methods under different names exist these days, they are basically identical except for differences in manufacturing companies of carbon fiber materials and companies or organization for development methods and actual construction work. In this report, several examples using the CRS method are introduced for seismic retrofitting of typical building columns, chimneys and bridge columns.

2. CARBON FIBERS USED AND PRODUCT FORMS

Figure 1 shows the relationship between the tensile stresses and the extensions (strains) for carbon fibers compared with Aramid fibers, glass fibers and steels. The mechanical characteristics of carbon fibers are such that their tensile strength is extremely high compared with steels (10 times that of steel) while their elastic moduli are almost the same as steels which are still higher than other materials. Carbon fibers exhibit no yielding found in steels and their extension is extremely small. The functional characteristics of carbon fibers are such that their weight is lighter than steels (a quarter of steel) and they do not rust so they excel in durability and flexibility. The elastic moduli of carbon fibers are larger than those of Aramid fibers so that the confined forces of wound carbon fibers around concrete is larger than those of Aramid fibers. For these reasons, almost all fibers used for seismic retrofitting are carbon fiber, although the use of Aramid fibers began to appear lately.

The strength of carbon fibers can be best exhibited when they are in CFRP state where epoxy resin is poured and cured. Although a retrofitting work method in CFRP state has been developed, most methods used now are performed in carbon fiber state which is more flexible.

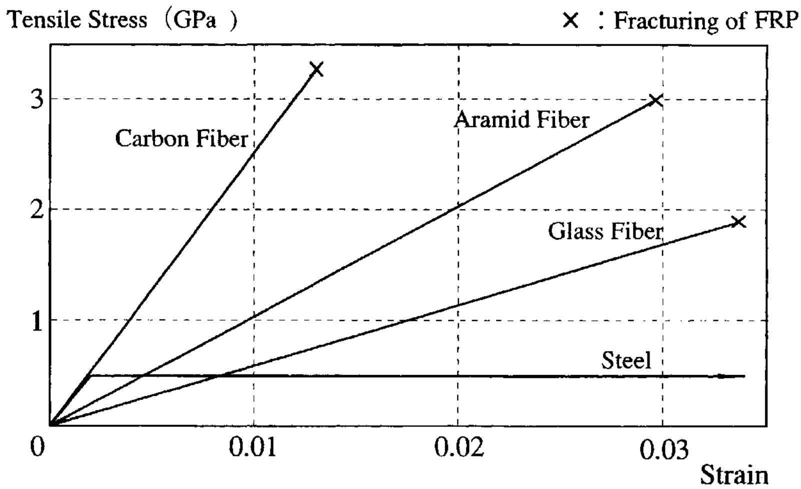

Figure 1. Comparison of stress strain relationships.

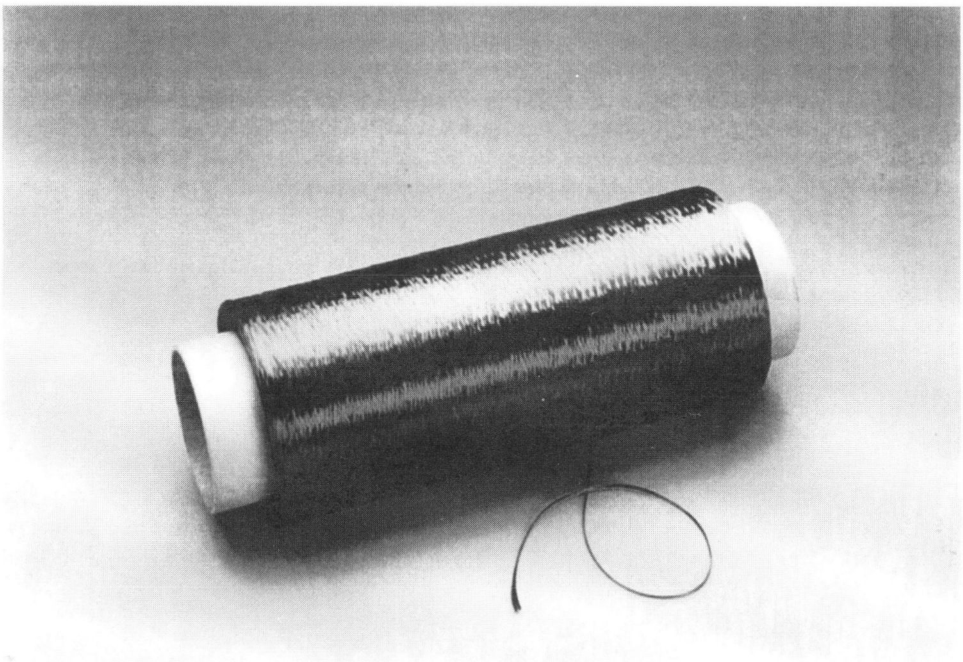

Figure 2. Carbon fiber strand (bobbin).

As shown in Figs 2 and 3 the following two types of carbon fibers are used in seismic retrofitting:

(1) Carbon fiber strand: bundled carbon fiber monofilaments.

(2) Carbon fiber sheet: unidirectionally arranged carbon fiber strands in sheet form.

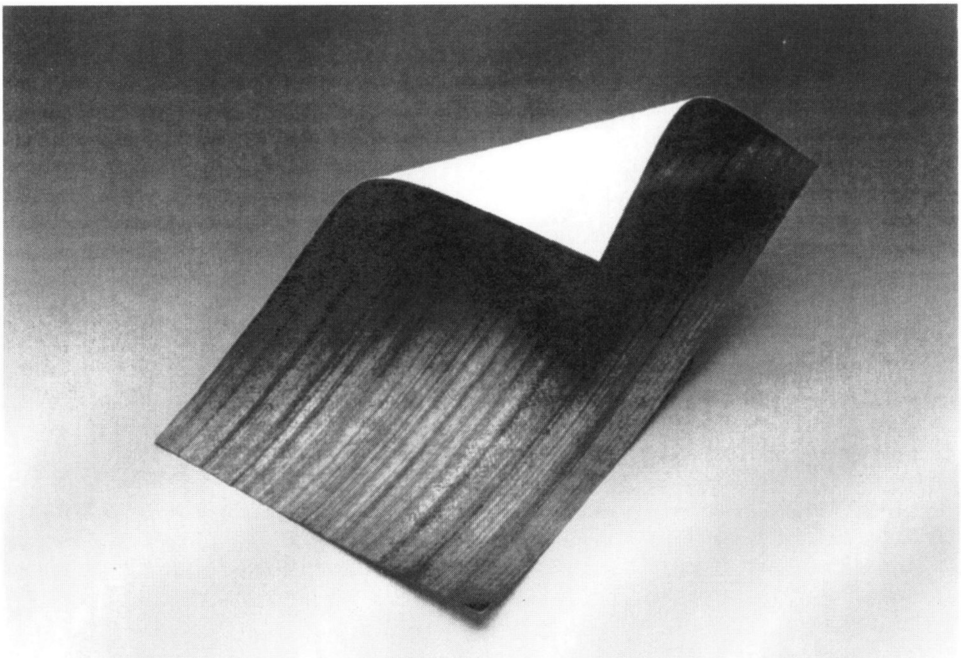

Figure 3. Carbon fiber sheet.

The carbon fiber strand used a bundle of 12 000 monofilaments with a cross section of 0.46 mm^2. The density of carbon fiber sheets is 200 g/m^2 (thickness of 0.111 mm) or 300 g/m^2 (thickness of 0.167 mm). Carbon fiber sheets are used more than carbon fiber strands in general.

3. OVERVIEW OF SEISMIC RETROFITTING METHOD

The following are two retrofitting methods for existing structures using CFRP.

(1) Shear strengthening: carbon fiber strands or carbon fiber sheets are wound in the shear reinforcement direction of concrete surfaces to enhance shear strength. In this strengthening, the wound CFRP confines the concrete to improve the concrete compressive strength as well as the ductility, resulting in improvement of compressive performance.

(2) Flexural strengthening: this method uses carbon fiber sheets only. By gluing carbon fiber sheets in the direction of flexural reinforcement of concrete surfaces, the effect of flexural reinforcement is enhanced and the flexural strength can be improved.

Actual seismic retrofitting uses shear strengthening or flexural strengthening individually or in combination. The amount of CFRP reinforcement is determined by the winding interval for carbon fiber strands and by the number of stacking sheets for carbon fiber sheets.

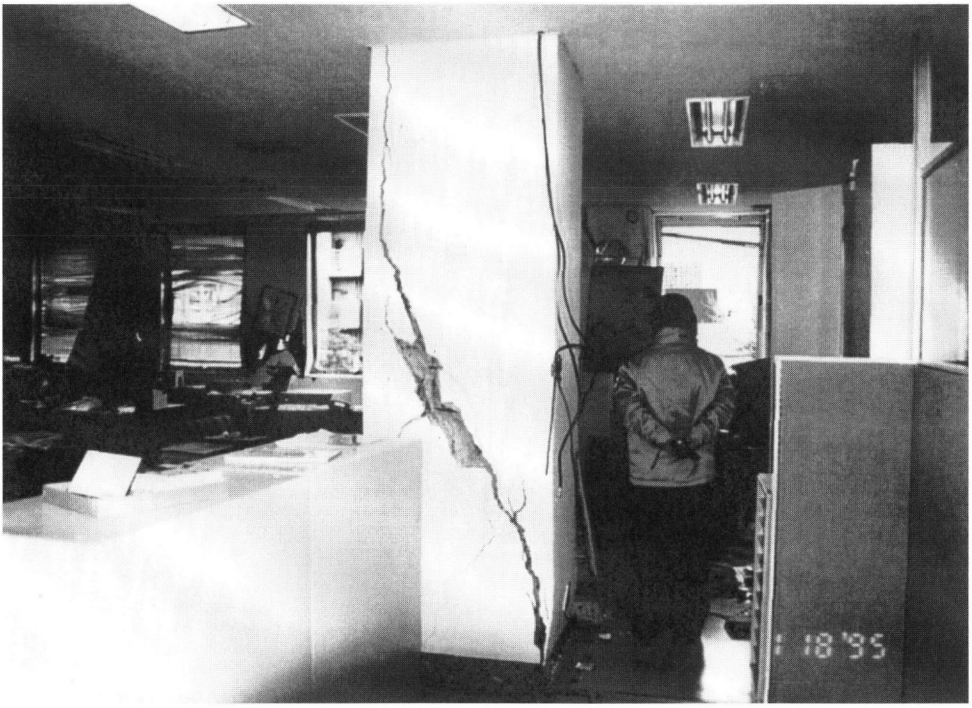

Figure 4. Shear cracks in building column.

3.1. Seismic retrofitting for building columns

Columns exhibit brittle shear failure as shown in Fig. 4 when the amount of hoop (shear reinforcement) is relatively little. Figure 5 shows a concept of the seismic retrofitting method to prevent such failure. In this method, shear reinforcement around the external surface of columns is increased by winding carbon fiber strands while impregnating strand with epoxy resin or wrapping carbon fiber sheets using epoxy resin. In this method, seismic retrofit is achieved by the above mentioned shear strengthening to prevent shear failure, by causing flexural failure at the both ends of the column and by causing large deformation to increase the strength.

3.2. Seismic retrofitting for chimneys

Chimneys fail by flexure at around 2/3 of the height from the ground as shown in Fig. 6 when the amount of flexural reinforcement is insufficient. Figure 7 shows a concept of the seismic retrofitting method to prevent such failure. In this method, flexural reinforcement is enhanced by gluing carbon fiber sheets in the height direction of the external surface of chimney using epoxy resin. In addition, carbon fiber strands or carbon fiber sheets are wound in the horizontal direction outside in the same manner as columns. This retrofit method can resist earthquake forces by improving own flexural resistant capacity through the above mentioned flexural strengthening on the sections where flexural reinforcement is not sufficient.

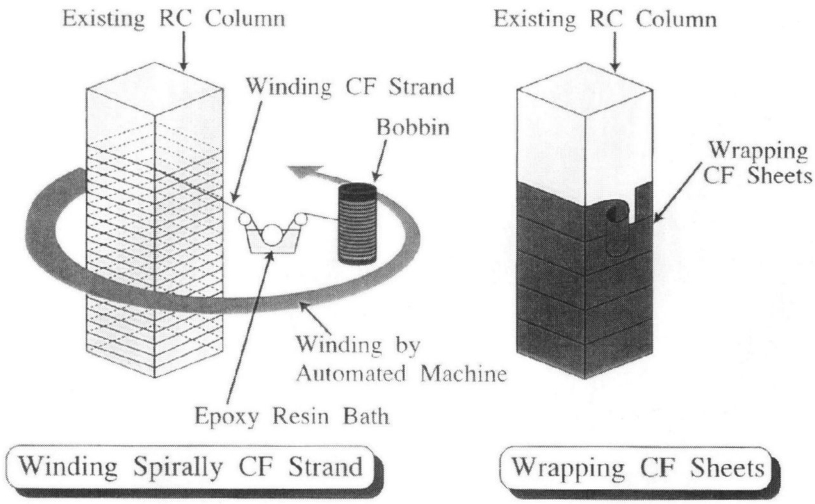

Figure 5. Seismic retrofitting method for columns.

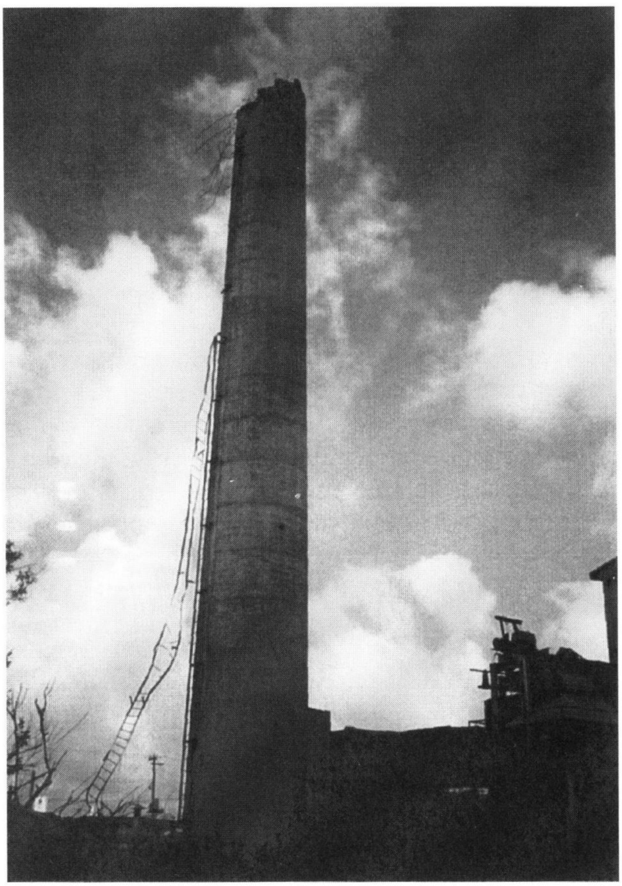

Figure 6. Flexural failure of chimney.

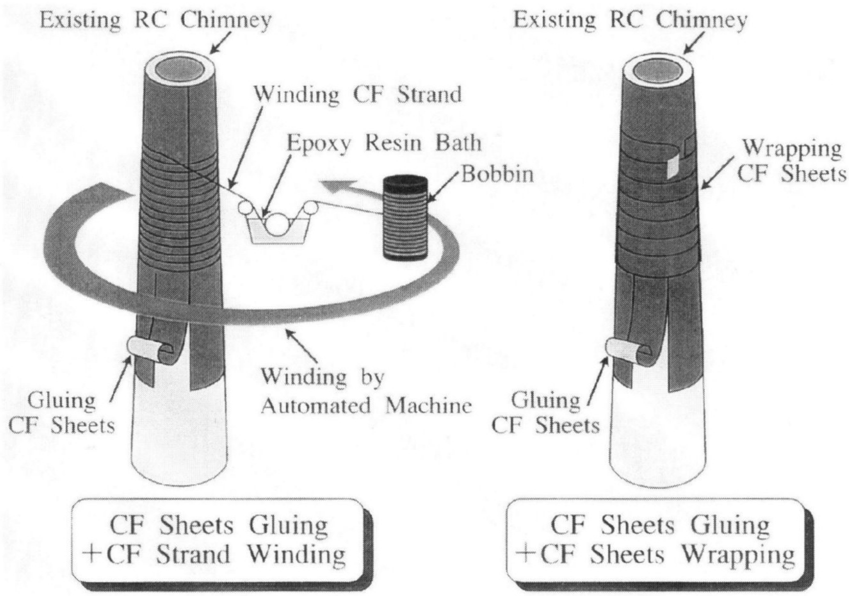

Figure 7. Seismic retrofitting method for chimneys.

As it is very rare that the shear strength in chimneys is insufficient, the wound CFRP can improve bond strength between the glued CFRP sheets and the concrete and can constrain thermal stresses.

3.3. Seismic retrofitting for bridge columns

Some bridge columns have sections where the amount of flexural reinforcement is insufficient for economical considerations (called rebar cut-off sections). When the length of cut-off rebar at rebar cut-off sections is short or when the amount of hoop (shear reinforcement) is insufficient, the rebar cut-off sections fail as shown in Fig. 8. Figure 9 shows a concept of the seismic retrofitting method to prevent such failure. In this method, flexural reinforcement is enhanced by gluing carbon fiber sheets in the direction of cut-off rebar of concrete surfaces of rebar cut-off sections using epoxy resin. Shear reinforcement is also enhanced by winding carbon fiber sheets or carbon fiber strands in the shear reinforcement direction of rebar cut-off sections and column bases similar to building columns. This retrofit prevents flexural failure by constructing the above mentioned flexural strengthening at rebar cut-off sections. In addition, shear failure can also be prevented by the above mentioned shear strengthening at rebar cut-off sections and column bases. Using these methods, the strength can be improved by causing flexural failure at column bases and earthquake forces can be resisted by large deformation of columns.

In this retrofit, the wound CFRP confines concrete resulting in improvement of the compressive strength of concrete thus preventing failure shown in Fig. 10.

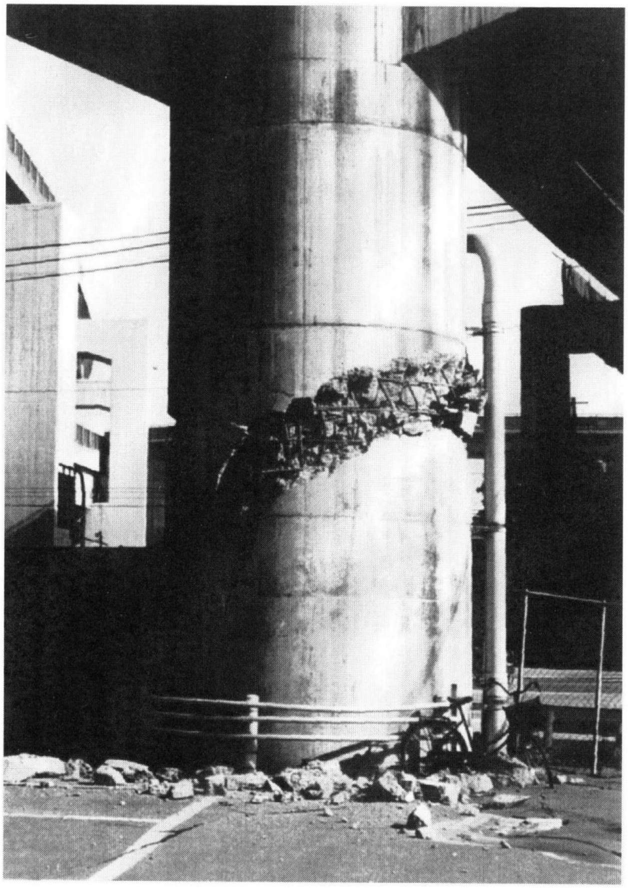

Figure 8. Damaged bridge column at rebar cut-off section.

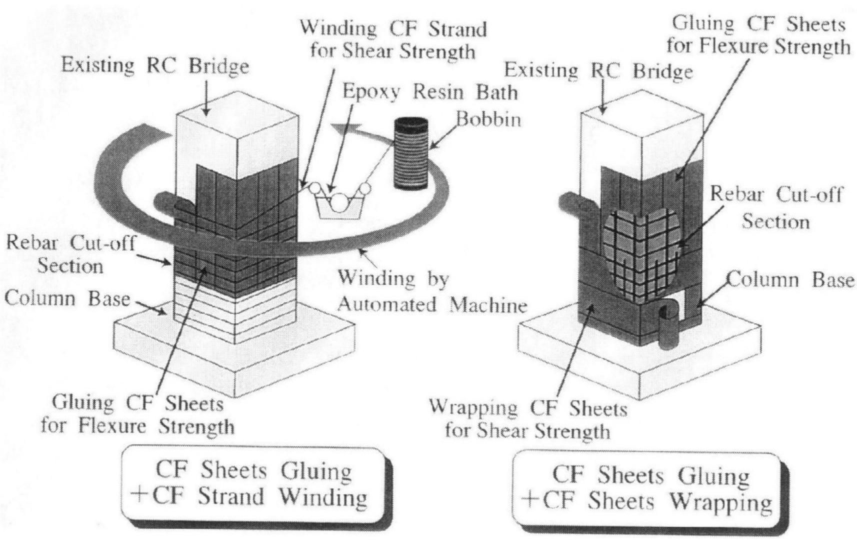

Figure 9. Seismic retrofitting method for bridge columns.

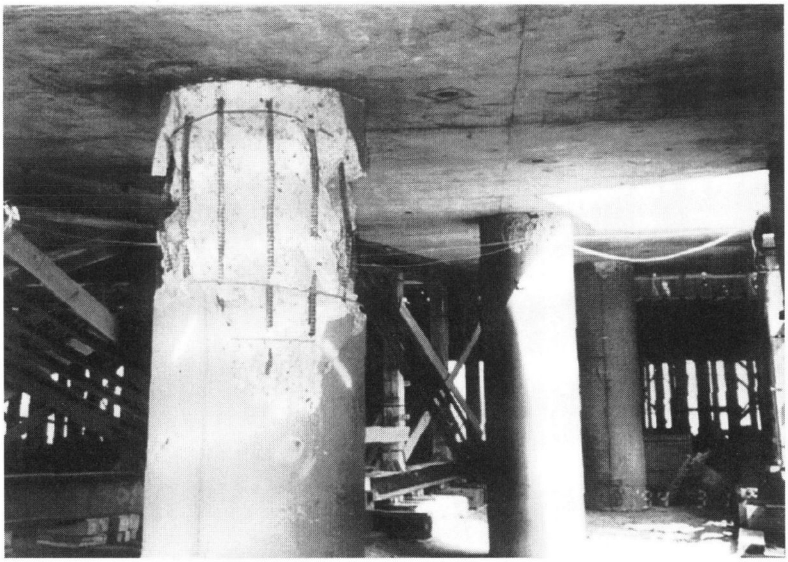

Figure 10. Damage at top of bridge columns.

3.4. Characteristics of seismic retrofitting methods

The following are the characteristics of the seismic retrofitting method using CFRP compared with conventional methods:

(1) Weight increase due to strengthening is small.

(2) External view is not spoiled as work space is not divided.

(3) Retrofitting work is easy and reliability is high.

(4) No special skill or qualification of workers is required.

(5) No increase of column cross sections due to retrofitting.

(6) Durability is improved because of non-rusting strengthening material.

(7) Retrofitting work period is short.

(8) No heavy equipment is needed and work is possible even in limited space.

(9) Operations of chimneys do not have to be interrupted during retrofitting work.

4. CONSTRUCTION PROCEDURES FOR SEISMIC RETROFITTING METHOD

The following are the basic procedures for application of the seismic retrofitting method using CFRP although details may vary for building columns (shear strengthening), chimneys (flexural strengthening) and bridge columns (flexural and shear strengthening).

(1) Removal and transfer of existing finishing and obstacle to retrofit.

(2) Concrete repair and surface treatment. For rectangular cross sections, smoothing of corners (chamfering) must be performed.

(3) Primer plastering on concrete surface.
(4) Gluing of carbon fiber sheets (flexural strengthening).
(5) Winding of carbon fiber strands or carbon fiber sheets (shear strengthening).
(6) Finishing of CFRP surfaces.
(7) Restoration of obstacles temporarily removed for retrofitting.

The following are the works of ordinary construction.

4.1. *Surface treatment work*

Concrete surfaces must be adjusted so that CFRP can exhibit its intended strength. As CFRP tends to be broken easily when contacting sticking objects, convex sections need to be smoothed out. Weathered sections of the surface need to be removed and concave sections need to be filled with mortar for smoothing. Cracked and raised concrete and rusted reinforcement must be repaired.

4.2. *Chamfering of corners*

CFRP wound around acute corners may fracture before exhibiting its full tensile strength. For this reason, chamfering needs to be performed at corners of the rectangular cross section of columns in buildings or bridges. The chamfering radius must be more that 3 cm for building columns and more than 5 cm for bridge columns. When carbon fiber sheets are wound, it is important to have precise vertical chamfering. Figure 11 shows its work for building columns.

Figure 11. Rounding work of corners.

4.3. Primer plastering work

Primer needs to be applied on concrete surfaces in order to strengthen concrete surfaces and improve adhesive strength between concrete and carbon fiber sheets for flexural strengthening. Concrete surfaces must be sufficiently dried.

4.4. Gluing of carbon fiber sheets (flexural strengthening)

A necessary number of carbon fiber sheets are glued manually one by one for lamination using resin whose major component is epoxy resin. The resin functions as a fiber gluing agent by impregnating inside carbon fiber sheets to form CFRP and as an adhesive to glue sheets with concrete surfaces. When gluing, it is important not to leave air bubbles on the adhesive surface of carbon fiber sheets and not to make wrinkles. To facilitate the gluing work, the width of carbon fibers is set at about 30 cm in many cases. Figure 12 shows chimney construction and Fig. 13 shows bridge column construction.

4.5. Winding of carbon fibers (shear strengthening)

Winding of carbon fiber strands can be performed using the newly developed automated winding machine. A winding machine with a gondola is used for all chimneys. Figure 14 (building columns) and Fig. 15 (chimneys) shows such construction. The advantages of the automated winding machines include easy quality control, labor saving, shortened construction periods and cost reduction. When carbon fiber sheets are wrapped, the same resin as in flexural strengthening work is used and a necessary

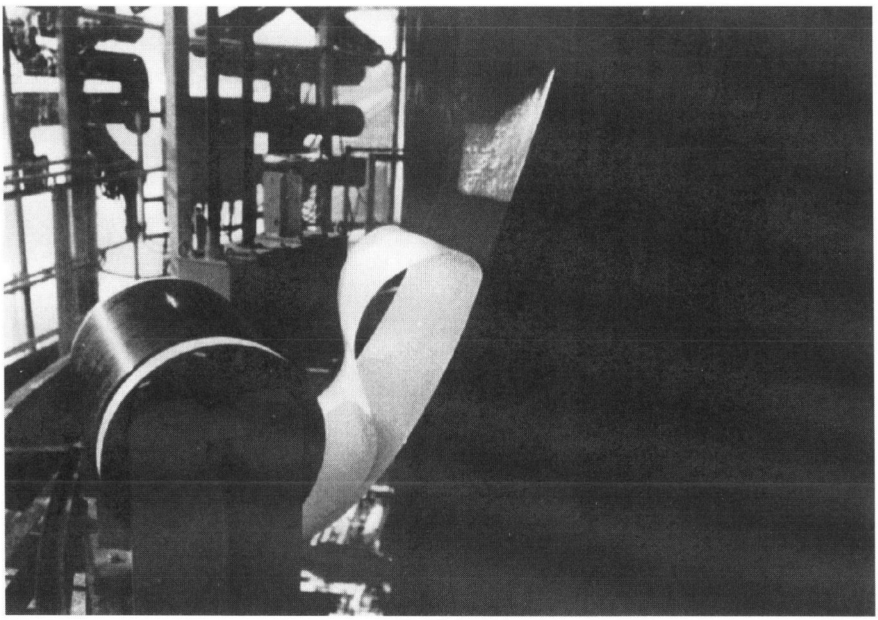

Figure 12. Automatic gluing of carbon fiber sheet for chimny.

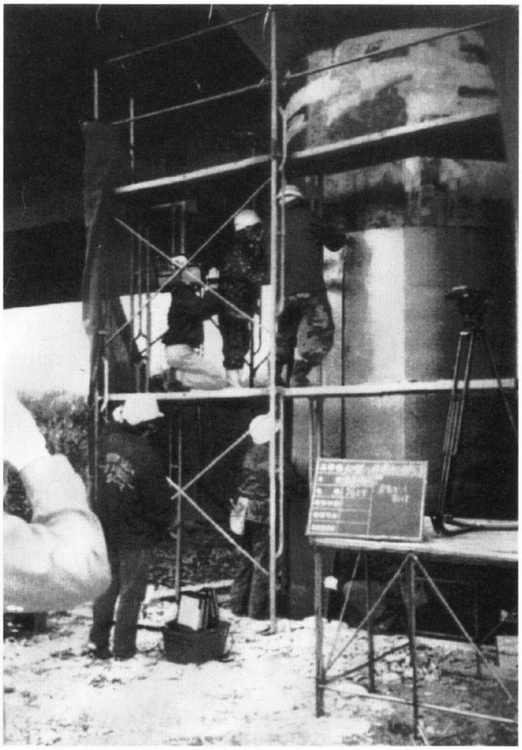

Figure 13. Gluing work of carbon fiber sheet for bridge column.

number of carbon fiber sheets must be wrapped as in gluing. Figure 16 shows construction for building columns. The advantages of carbon fiber sheets are that heavy equipment is not necessary as work is done manually and that work in limited space is possible.

4.6. Finishing work

Surface finishing needs to be performed as epoxy resin in CFRP is flammable if a fire breaks out as well as from the standpoint of protection and finishing. In particular, it is necessary to have covering to ensure 'fire protecting performance' or 'fire resistance efficiency' for building columns. Fire preventive covering to prevent spread of fire and fire resistive covering to protect CFRP in case of fire must be constructed.

5. OUTLINE OF RESEARCH AND DEVELOPMENT OF SEISMIC RETROFITTING METHOD

5.1. Issues to be investigated

The following is a list of R&D topics for establishing and constructing seismic retrofitting methods by CFRP.

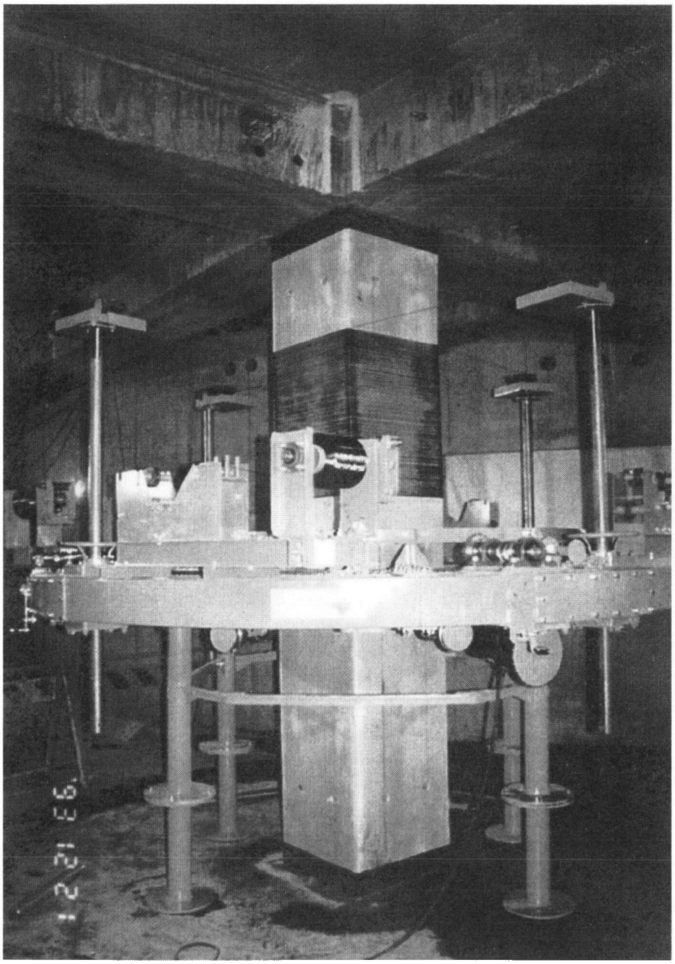

Figure 14. Automated winding machine of carbon fiber strand for building column.

(1) Research on material properties of CFRP.

Tensile properties of CFRP strands and sheets.

Adhesive strength between CFRP sheets and concrete.

Lap length of CFRP sheets.

Durability of adhesive strength between concrete and CFRP sheets and CFRP.

(2) R&D on structural performance of retrofitted members.

Shear strength of members retrofitted by CFRP strands or sheets.

Flexural strength of members retrofitted by CFRP sheets.

Compressive strength of concrete wound by CFRP strands or sheets.

Design method for shear and flexural strengthening by CFRP.

Fire resistance efficiency and design method of columns reinforced by CFRP.

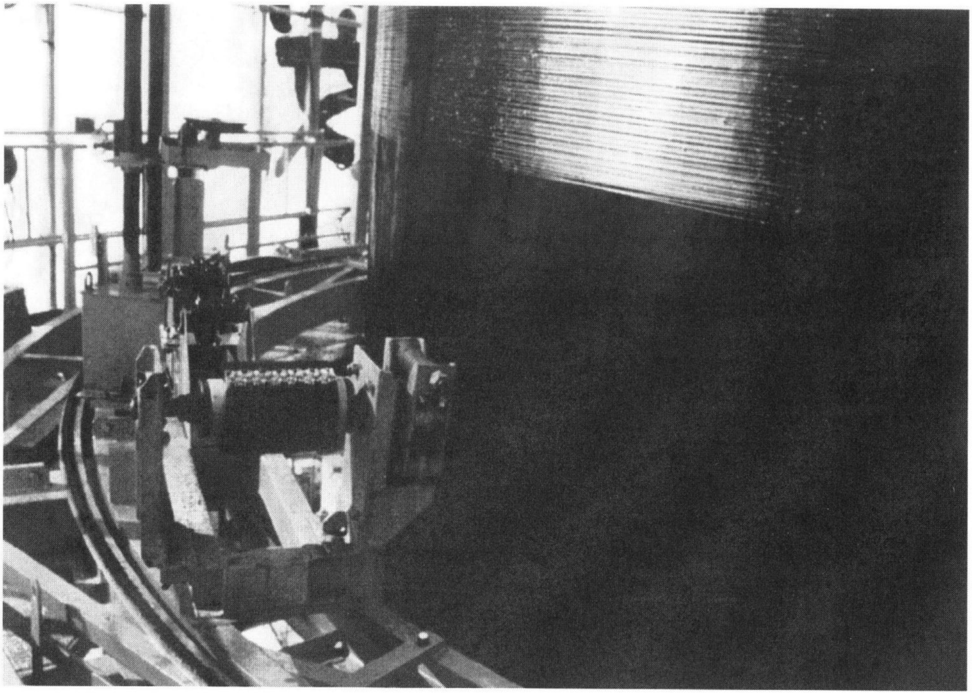

Figure 15. Automatic winding of carbon fiber strand for chimny.

Figure 16. Wrapping work of carbon fiber sheet.

(3) R&D of construction method.

Development and method of automated winding machine for carbon fiber strands.

Construction and quality control methods of carbon fiber sheets.

Finishing method of CFRP surfaces.

(4) Establishment of design and construction guidelines.

(5) Technology evaluation and authorization by public organizations.

More than 40 technical papers have been published that reported the results of these research and development efforts on the subjects above. Some of the major papers are listed in the References.

5.2. Outline of research and development

Research and development of seismic retrofitting methods using CFRP began in 1984. A retrofitting method with winding of carbon fiber strands was devised first and a patent was applied for. Beginning the following year, joint research with Mitsubishi Chemical Corporation began on research and development of seismic retrofitting of columns. The major revision of the Building Code was enforced in 1981 and the social needs of seismic retrofitting for pre-code revision buildings prompted the research and development efforts. The research and development on seismic retrofitting for chimneys began in 1986 based on the results on columns. The research and development on seismic retrofitting for bridge columns began in 1989 based on the result of columns and chimneys. Beginning the following year, joint research with Japan Highway Public Corporation on research and development of seismic retrofitting for bridges that have rebar cut-off sections began.

In the research on material properties of CFRP, the quality standard and quality control method were established on carbon fibers and CFRP by material testing. In the research on structural performance of retrofitted members, the seismic retrofitting effect was investigated by experiments and the design method for shear and flexural strengthening was specified. Specifications to ensure fire prevention and resistance were established by carrying out fire resistance tests. In the research on construction method, carbon fiber strand automated winding machines (Fig. 14) were developed in 1987 and they were improved in 1995 (Fig. 17). Construction methods of retrofitting and finishing methods were investigated through test construction. Based on these results, the design and construction guidelines were established.

Obayashi Corporation has obtained technical evaluation and assessments by public organizations on the seismic retrofitting methods for building columns and chimneys using the CRS method. Technical evaluations by the Japan Building Disaster Prevention Association were obtained in 1991 for carbon fiber strands and in 1995 for carbon fiber sheets. Technical evaluation by the Building Center of Japan was obtained in December, 1996 and the authorization based on this evaluation by the Construction Minister on the 38th clause of the Building Code (new materials and new building construction) is expected to be obtained in February, 1997.

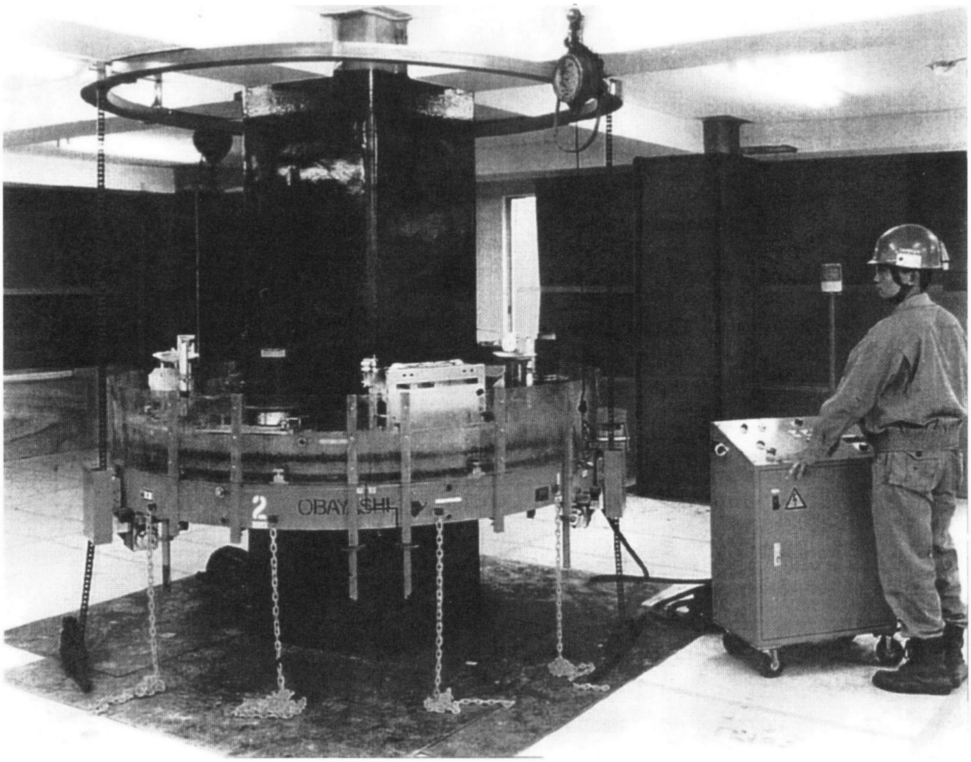

Figure 17. Retrofitting work for building column using carbon fiber strand.

5.3. Confirmation experiments of seismic retrofitting effect

In this paragraph, typical experiments are introduced to verify the retrofitting effect by the seismic retrofitting method using CFRP. Scale models based on columns in pre-code revision-buildings were fabricated and retrofitted test specimens and un-retrofitted test specimens were examined for comparison. The test specimens were retrofitted using carbon fiber strands and were separated into those with a small amount of wound carbon fibers to strengthen and those with a large amount. Figure 18 shows crack and failure patterns of the test specimens and Fig. 19 shows the relationship between the load (P) and the relative displacement (δ) of the upper and lower ends of the column.

Improvement of the seismic performance by the retrofitting effect can be evaluated by using the maximum load and the ultimate displacement as indices. The specimen un-retrofitted failed under lower loads and ultimate displacement was smaller thus exhibiting poor earthquake resistant capability. The specimen retrofitted by winding CFRP strands had higher maximum loads and the ultimate displacements were also increased. The maximum load for the specimen slightly retrofitted was higher than that for those un-retrofitted at all and their ultimate displacement increased, but their eventual failure was caused by CFRP strands which were broken. The maximum

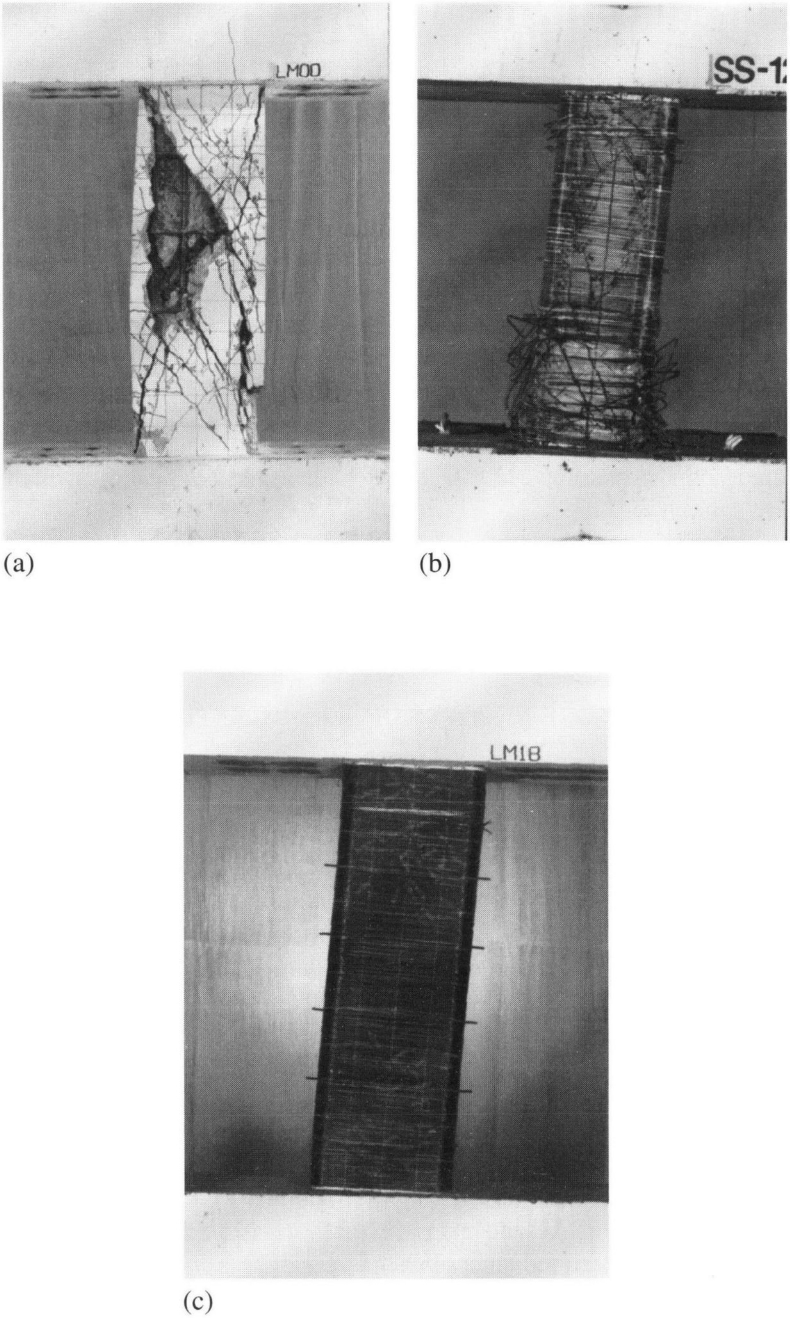

Figure 18. Crack and failure pattern at end of test: (a) unretrofitted column; (b) slightly retrofitted column; (c) heavily retrofitted column.

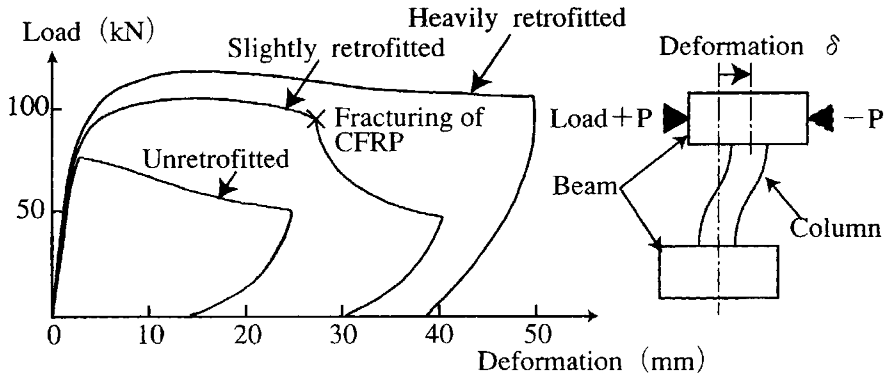

Figure 19. Load-deformation relationships.

load for the specimen heavily retrofitted was even higher than that for those slightly retrofitted and their ultimate displacement increased significantly, which did not accompany column failure.

From these results, it can be concluded that columns retrofitted by winding carbon fiber strands can improve their earthquake resistance performance due to their retrofitting effect.

6. UTILIZATION AND WORK RECORDS OF SEISMIC RETROFITTING METHODS

As mentioned before, the research and development on seismic retrofitting method by CFRP for existing reinforced concrete structures began in 1984. The first utilization of the method was in 1988 for chimneys, 1993 for building columns and 1994 for bridge columns. Utilization for chimneys was made possible earlier as there was less restriction by code on chimneys compared with building columns. A test construction was carried out in 1987 and the first utilization was in 1988 when seismic retrofit was applied to a factory chimney. Those chimneys damaged by the Hyogo-ken Nanbu Earthquake were also subjected to seismic retrofit.

The first test work of seismic retrofitting for building columns was performed in 1993 for actual buildings. The first utilization of the method was for restoration of buildings damaged by the Hyogo-ken Nanbu Earthquake in 1995. Seismic retrofitting for pre-code revision buildings not damaged by earthquakes has been applied in many cases. The first test construction for seismic retrofitting of bridge columns was in 1994 for an actual bridge column. It was first adopted to a bridge damaged by the Hyogo-ken Nanbu Earthquake and many pre-code revision bridges not damaged by earthquakes has been retrofitted since then.

Obayashi Corporation has constructed 35 cases for building columns, 32 cases for chimneys and 12 cases for bridge columns. Figures 17 and 20 show examples of construction for building columns, Figs 21 and 22 show examples for chimneys and Figs 23 and 24 show examples for bridge columns. Technology transfer of the seismic retrofitting method to the US is underway and a test construction shown in Fig. 25

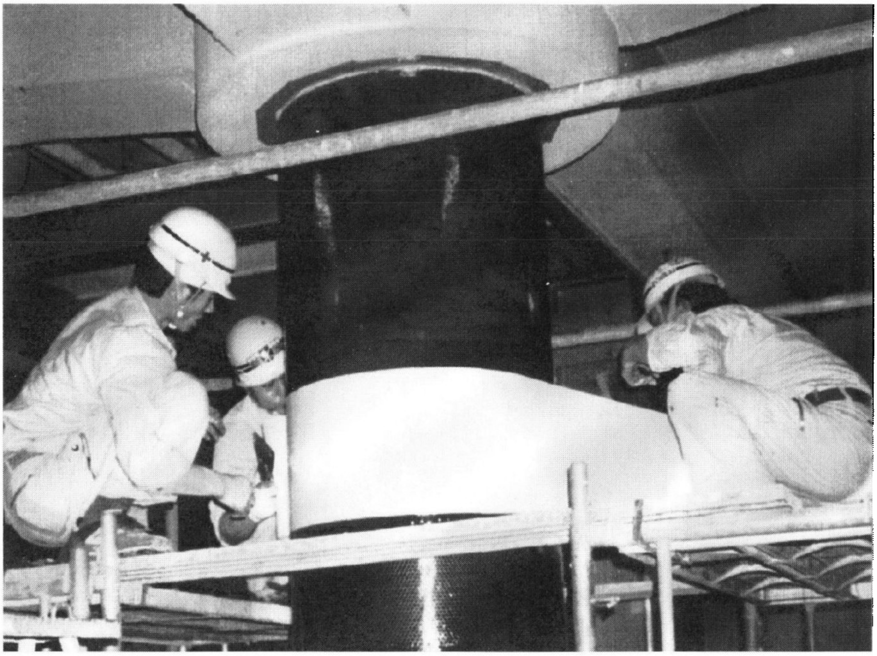

Figure 20. Retrofitting work for building column using carbon fiber sheet.

Figure 21. Retrofitting work by automated winding machine for chimny.

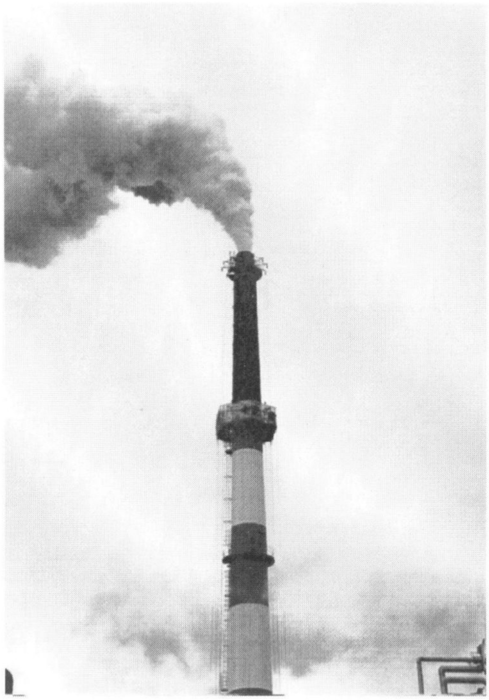

Figure 22. Retrofitting work of chimny (300 feet high).

Figure 23. Retrofitting work for bridge columns using carbon fiber sheet.

Figure 24. Seismic retrofit of railway station's columns.

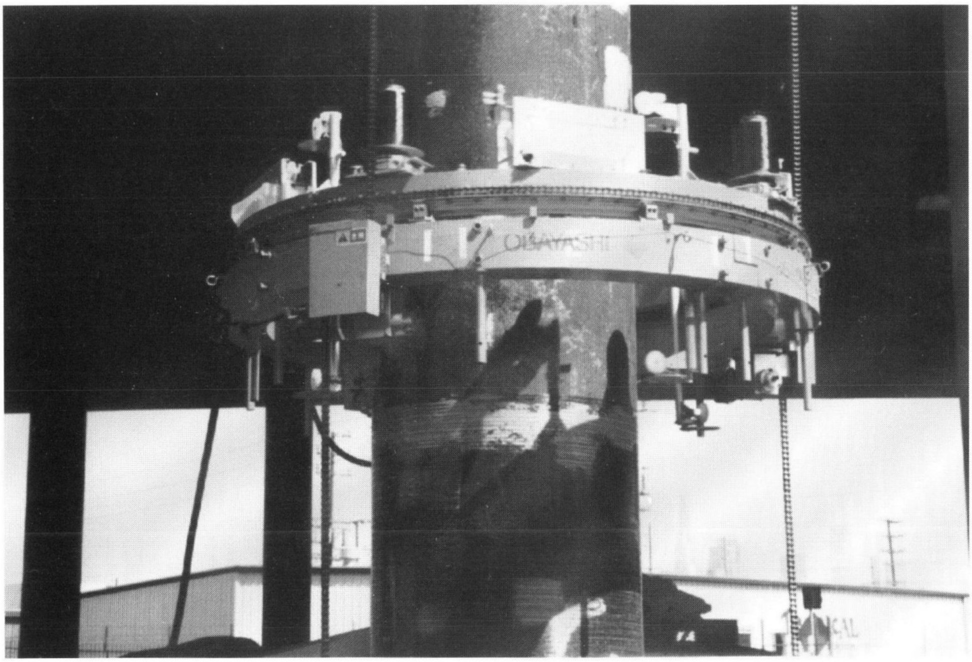

Figure 25. Retrofitting work for bridge columns using carbon fiber strand in USA.

has already been implemented. Many are under contract or planning and the number of constructions is expected to grow in the near future.

7. CONCLUSION

A seismic retrofitting method using CFRP for building columns, chimneys and bridge columns of existing reinforced concrete structures has been discussed. This method is widely applicable to retrofit bridge beams, beams and floors of buildings and structures. The retrofit work by CFRP is easy and light weight: improvement of durability can be achieved and reduced cost of maintenance can be expected. Seismic retrofitting for pre-code revision structures is a social need. The demands for the seismic retrofitting method using CFRP is expected to grow. It is necessary to conduct further research and development to improve reliability of retrofitting works and widen its applicability.

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