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Seismic Strengthening of Reinforced Concrete Buildings in Japan

Renforcement contre les séismes de bâtiments en béton armé au Japon

Seismische Verstärkung von Stahlbetonbauten in Japan

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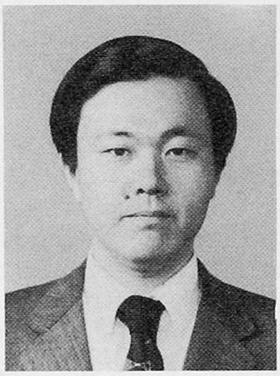

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SUMMARY

Available data on existing reinforced concrete buildings, strengthened against severe earthquakes as well as test data relevant to seismic strengthening of existing structures have been integrated and reviewed. The knowledge obtained from the review was described with respect to the effect of strengthening on the overall behaviour of structures, and to design criteria, seismic evaluation and construction techniques for the strengthening.

RESUME

Les données disponibles relatives à des bâtiments existants renforcés en béton armé contre les grands tremblements de terre, ainsi que les données d'essai applicables au renforcement contre les séismes ont été complétées et révisées. Les connaissances obtenues lors de cette révision sont décrites selon les effets des renforcements sur le comportement général des ouvrages, et selon les critères de conception, l'évaluation sismique et les techniques de construction pour le renforcement.

ZUSAMMENFASSUNG

Die vorhandenen Daten existierender, gegen starke Erdbeben verstärkter Stahlbetonbauten sowie Versuchsangaben über Verstärkungen für bestehende Bauten sind vervollständigt und überspprüft worden. Die aus der Ueberprüfung erhaltenen Erkenntnisse werden hinsichtlich der Wirksamkeit von Verstärkungen auf das Verhalten der Gesamtstruktur, der Bemessungskriterien, der seismischen Beurteilung und der Bauverfahren für Verstärkungen dargelegt.

1. INTRODUCTION

A number of reinforced concrete buildings, damaged by recent severe earthquakes in Japan, required extensive repair and also strengthening. The Tokachi-oki Earthquake of 1968 heavily damaged a large number of low-rise buildings. Some of these were strengthened by the addition of structural walls. Because of the lack of guidelines, the design as well as the construction for strengtheening was based on engineering judgement alone. This was practically the first experience for Japanese engineers to extensively strengthen existing buildings against severe earthquakes. The destructive 1978 Miyagiken-oki Earthquake was also followed by the strengthening of a number of buildings. However, in this case materials and techniques for construction were specifically selected and the design was based on experimental or analytical investigations or on guidelines, where these were available [1, 2].

Current studies have indicated that there is a wide scatter in the level of seismic resistance of existing buildings. It was found that a considerable number of low to medium-rise buildings, designed and constructed in accordance with previous building codes, may need strengthening. Consequently a number of buildings, considered hazardous, were strengthened or rebuilt [3 ~ 5]. While several experimental studies, relevant to the seismic strengthening of existing structures, have been conducted to establish guidelines for design and construction [6 ~ 13]. Thus the necessity for strengthening of hazardous buildings was recognized for some time, and as a consequence an advisory committee for the Japanese Ministry of Construction prepared design guidelines [14] in 1977. These design guidelines were intended to be used in conjunction with the method of evaluation of seismic safety of existing buildings, proposed by the same committee [15]. This method was described in some detail in references 16 and 18. In a large number of cases these guidelines have been used in Japan.

Available data of the design and construction for strengthened buildings as well as existing test data relevant to the strengthening have been integrated and reviewed by a committee chaired by the authors. The committee was organized in the Japan Concrete Institute on September 1981 to provide improved guidelines for seismic strengthening based on as much up-to-date information as possible. This paper describes the knowledge obtained from the review, as of March 1983, with emphasis on 1) structural effects of the strengthening, 2) design criteria and construction techniques for the strengthening and 3) seismic resistance of strengthened buildings. As the committee has been reviewing the integrated data, further results will be presented in other opportunities.

2. GENERAL PRINCIPLES OF SEISMIC STRENGTHENING

2.1 Aims of Seismic Strengthening

The aims of the strengthening are to provide (1) increased strength with respect to lateral loading, or (2) increased ductility, or (3) a proper combination of these two features. These concepts are illustrated in Fig. 1. To provide increased strength is considered as being the most promising approach in the strengthening of low to medium-rise buildings. Even if ductility is provided, increased strength is expected to reduce the magnitudes of inelastic displacements. It is considered to be also important to reduce eccentricities resulting often from the irregular distribution of stiffness within a story or throughout the entire structure.

2.2 Construction Techniques

Typical strengthening methods are assembled in the chart of Fig.1. Examples of construction techniques to meet both criteria for strengthening, the increased strength and increased ductility, are given in Fig.2. Generally new elements may be added to existing structures to give increased strength, or existing framing elements may be reinforced with new materials to improve their ductility. Infilled walls and side walls, shown in Fig.2(a), are cast-in-situ or precast wall elements which are attached to frames or to beams, as appropriate. In the process of increasing the ductility of existing columns, such as shown in Fig.2(b), the aims is to increase their shear strength. This is achieved by wrapping techniques shown in these illustrations. A narrow gap at the ends of the encasement is provided to avoid the undesired increase of the flexural strength of the member at that section.

For the systems shown in Fig.2(a), cast-in-situ or precast concrete is commonly used with the various connection techniques. Typical details for such connections are given in Fig.3. Careful attention must be paid to connections, because they will strongly affect the behavior of the strengthened structures. High pressure pumping of the fresh concrete or nonshrink material may be necessary to avoid the formation of cavities between the new and existing elements.

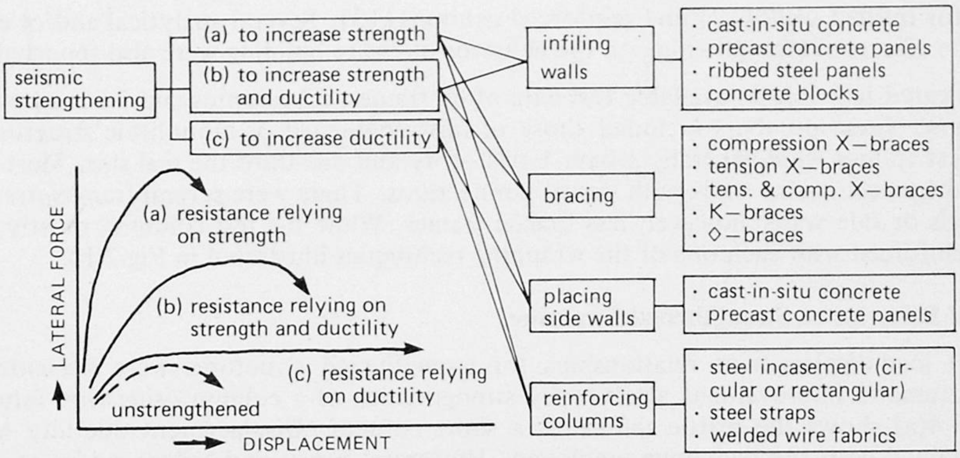

Fig. 1 Concepts of Seismic Strengthening and Strengthening Methods

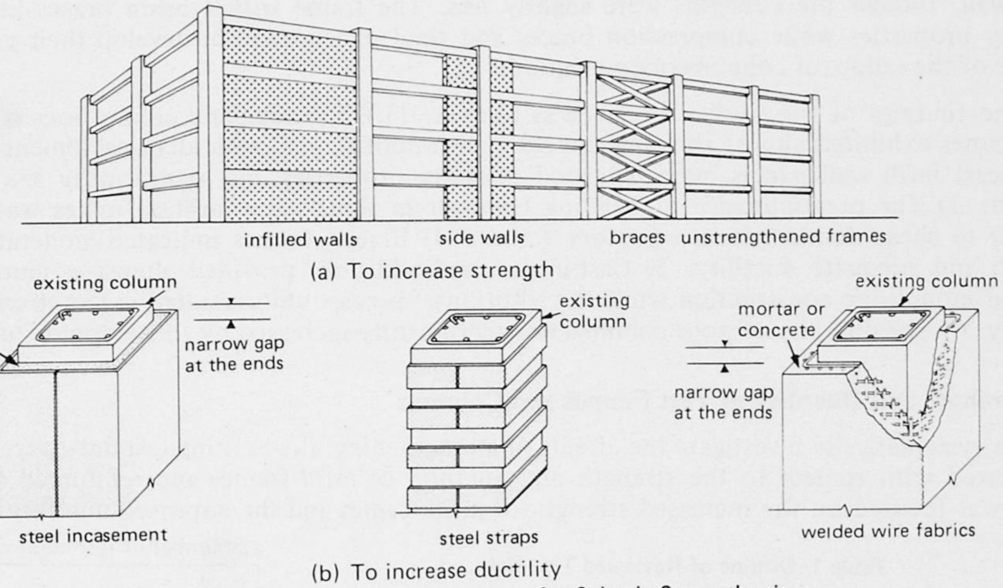

Fig. 2 Typical Construction Techniques for Seismic Strengthening

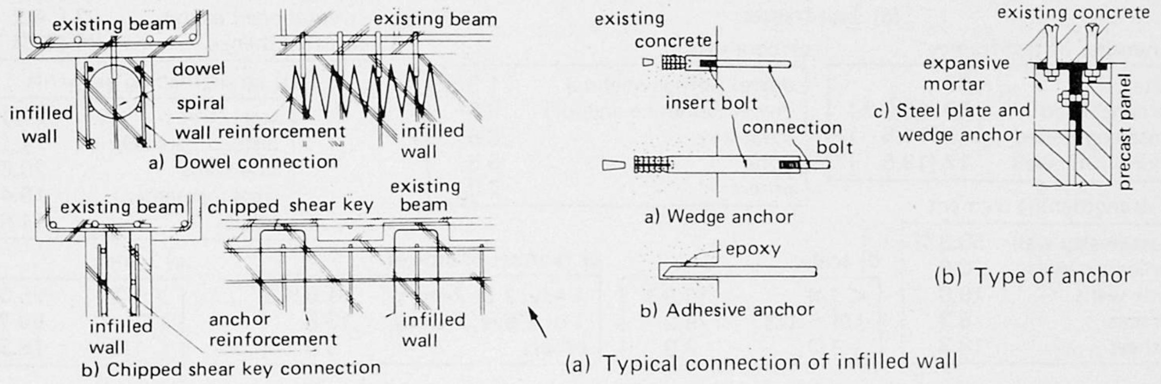

Fig. 3 Connection of Infilled Wall

3. REVIEW OF RESEARCH ON SEISMIC STRENGTHENING

3.1 Research on Seismic Strengthening and Existing Test Data

The number of strengthened structures that have been examined experimentally served as a background in formulating the design guidelines [14]. Since the proposal of the guidelines, further experimental studies have been conducted. The earliest tests, performed several years after the 1968 Tokachi-oki Earthquake, were aiming at the improvement of ductility of columns [6, 7] and at boosting the strength of frames by the addition of concrete walls [7, 8]. Subsequently one-story infilled frames with various connection details [7, 9, 11] and bracing systems [10, 11] were examined. Currently three-story frames, strengthened by infilling and bracing, were tested. Tests were also conducted for infilled walls [12] and reinforced columns [13]. Several analytical and/or experimental studies of the effects of strengthening on the behavior of entire building were also reported.

As indicated in Table 1, available test data of 87 frames, 67 columns and 5 beams were collected for the review. These numbers included those of unstrengthened or monolithic structures for reference. The test frames were generally 1-bay, 1 or 2-story and one-third the real size. Most frames were strengthened by cast-in-situ walls with dowel connections. There were several frames strengthened by precast panels or side walls, however, less braced frames. While the test columns, mostly half the real size, were reinforced with each one of the wrapping techniques illustrated in Fig.2(b).

3.2 Typical Behavior of Strengthened Structures

Typical load-displacement relationships for strengthened structures were presented. Figure 4 shows the dramatic improvement attained by strengthening of a column using wire fabric wrapping [7]. Figure 4(a) shows the brittle failure of a short column. Displacement ductility larger than 6 could be attained with the technique employed. Hysteresis curves and failure modes of strengthened frames by various techniques [11] were presented in Fig.5. Infilled walls behaved similarly to monolithic wall, though the strengths were slightly less. The frame with tension braces indicated good ductility properties while compression braces and steel panels did not develop their yield strengths because of the failure of columns or connections.

The findings of the studies are given as follows. 1) When adequate connections were provided, infill frames exhibited almost the same strength as monolithic wall with identical dimension. 2) Multiple precast infill wall panels indicated good ductility properties, but significantly less strength was attained. 3) The predominance of bending behavior in three-story infilled frames was observed in contrast to shear dominance in one-story frames. 4) Braced frames indicated moderate increase of strength and adequate ductility. 5) Cast-in-situ wall additions provided almost as much strength as identical monolithic construction while the addition of precast units resulted in less strength but more ductility. 6) The ductility of poor columns was significantly increased by the wrapping techniques.

3.3 Strength and Ductility of Test Frames and Columns

To systematically investigate the effects of strengthening, the existing test data were quantitatively reviewed with respect to the strength and ductility of infill frames and reinforced columns. The review was focused on the increased strength of infill frames and the improved ductility of reinforced

Table 1 Outline of Reviewed Test Data

(a) Test frames

a) number of test frames

total	87
strengthened	60 (69.0 %)
unstrengthened	10 (11.5)
monolithic wall	17 (19.5)

b) strengthening element

cast-in-situ wall	53.3 %
precast panels	10.0
side walls	10.0
braces	8.3
others	18.3

c) connection

dowel (wedge anchor)	71.9 %
dowel (adhesive anchor)	8.8
shear key	8.8
none	3.5
others	7.0

d) scale

< 1/4	13.8 %
1/4 ~ 1/3	78.2
> 1/3	8.0

e) number of stories

1-bay, 1 or 2-story	81.6 %
1 or 2-bay, 3-story	13.8
others	9.6

(b) Test columns and beams

a) number of test columns and beams

total	72
strengthened columns	45 (62.5 %)
strengthened beams	3 (4.2)
unstrengthened	24 (33.3)

b) strengthening elements

steel straps	27.1 %
welded wire fabrics	27.1
side walls	20.8
steel incasement	10.4
others	14.6

c) scale

> 1/2	25.0 %
1/2	59.7
< 1/2	15.3

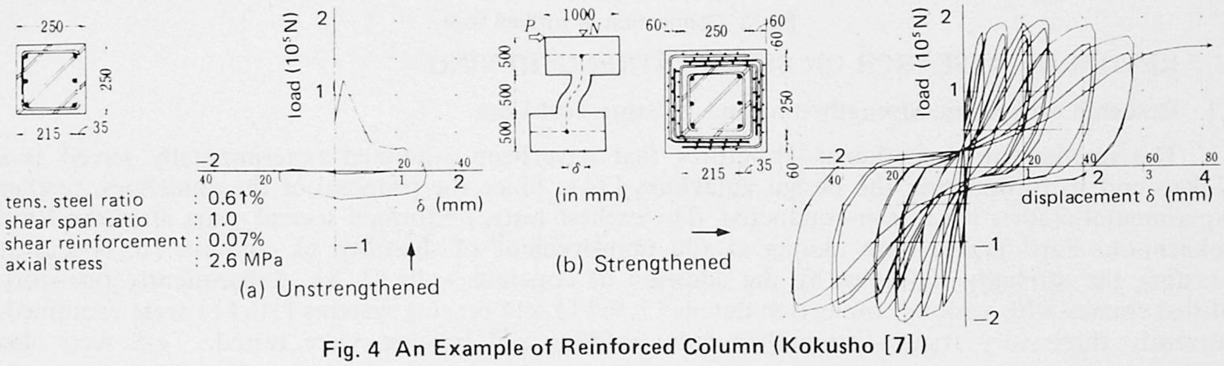

Fig. 4 An Example of Reinforced Column (Kokusho [7])

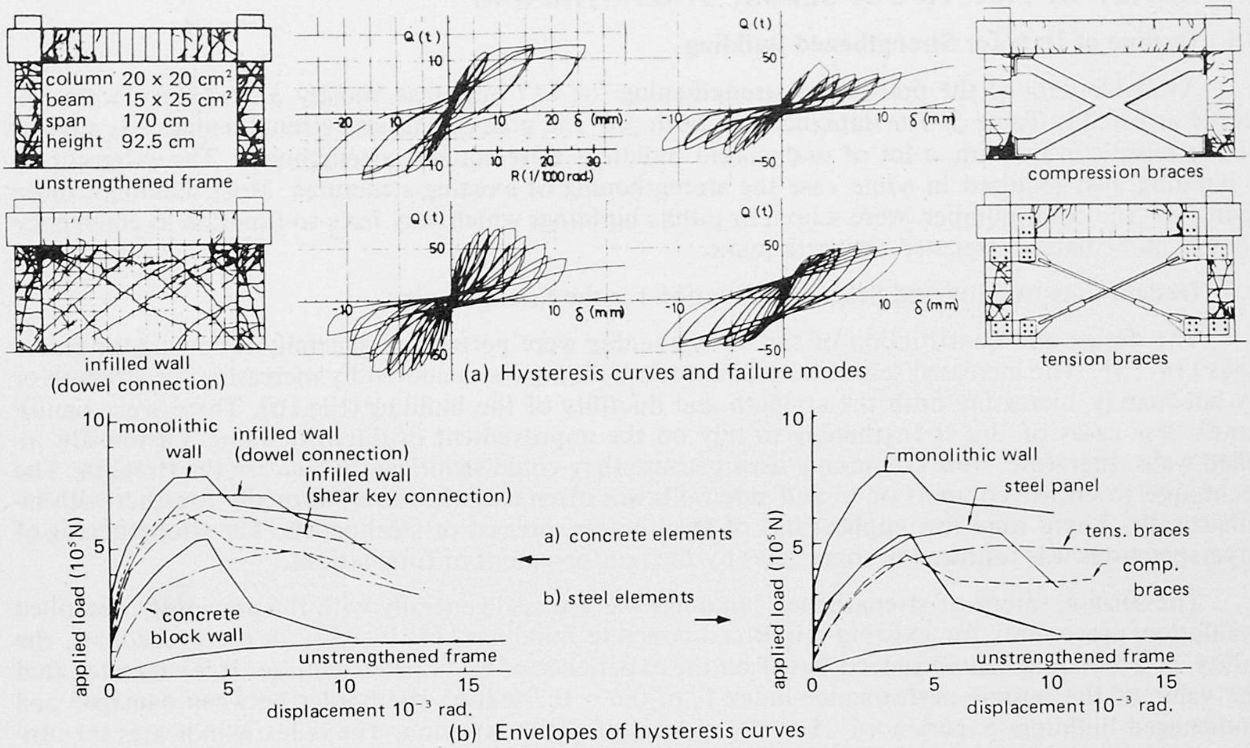

Fig. 5 An Example of Strengthened Frames (Sugano and Fujimura [11])

columns, respectiely. The selected frames for the review were those strengthened by infilling concrete wall and they included several frames of three-story or precast panels. Narrow slits were provided along columns in some of the infilled walls. The selected test columns were those reinforced with each one of the wrapping techniques in Fig.2(b). Figures 6 to 11 show comparisons of the obtained ultimate strength of infill frames with the strength of walls of monolithic construction or unstrengthened frames, and with the calculated strength by available procedures. The observed displacement ability of reinforced columns is presented in Fig.12 to 14.

The observed ultimate strength of cast-in-situ infill frames was in a wide range of 1.5 to 7.0 MPa in terms of the nominal shear stress of wall, and it clearly increased with the strength of connections (Figs.6 and 10). Their strength was 60 to 100% the strength of monolithic wall with identical boundary elements, and 2 to 5 times that of unstrengthened frames, respectively (Fig.7 and 8). These frames experienced similar displacement at the ultimate strength, 0.003 to 0.010 radian in terms of the slope of deflection, to that of monolithic walls (Fig.6). Another group of frames, those of three-story, with narrow gaps along columns and with multiple precast panels, indicated different feature because of the predominance of bending behavior. They obtained considerably less strength, however, significantly larger displacement ability than those of the above group.

Figures 9 and 11 presented the calculated shear strength as molithic wall [18] or that by the design guidelines [14]. The design strength of an infilled wall assembly in Fig.11 was given as the smaller of either; (1) the total shear strength of the wall panel and both columns, or (2) the total shear strength of one column and the connection along beam and the punching shear strength of the other column. The observed strength of cast-in-situ infill frame was 60 through 115% the calculated strength as monolithic wall. This indicated again that these walls could have as much strength as that of monolithic wall when adequate connections were provided. The above design procedure provided considerable margin of the strength for cast-in-situ infill frames (Fig. 11).

The significant improvement of ductility of columns was achieved by any one of the wrapping techniques (Fig.12 to 14). Displacement capacity larger than 0.02 rad. or displacement ductility larger than 3.5 could be attained. The increased displacement capacity was 1.5 through 7 or more times the capacity of unstrengthened columns. Moderate improvement of strength, resulting from the increased concrete section, was also attained by wire fabric wrapping and steel incasement. The design equation for the ductility factor [16,18] in Fig.14 provided considerable safe-side estimation.

4. REVIEW OF PRACTICE OF SEISMIC STRENGTHENING

4.1 Outline of Data for Strengthened Buildings

Available data of the practice of strengthening for 157 buildings, mostly 3 or 4-story, were collected as listed in Table 2. The data included both pre- and post-earthquake strengthenings. As a result of the seismic evaluation, a lot of undamaged buildings were actually strengthened. The extension of a building also required in some case the strengthening of existing structures. Most buildings, more than 70% the total number, were school or public buildings which may have to function as emergency centers immediately after a severe earthquake.

4.2 Design, Construction and Seismic Evaluation for the Strengthening

The design and construction of the strengthening were performed generally following the guidelines [14,15]. The increased seismic resistance of a building was achieved by increasing the strength or by adequately increasing both the strength and ductility of the building (Fig.16). There were significantly less cases of the strengthening to rely on the improvement of ductility alone. Cast-in-situ infilled walls, therefore, were commonly used because they could significantly increase the strength. The technique to encase columns or to add side walls was often used, however, normally together with infilled walls. There were few applications of steel braces, precast or steel panels. The strengthening of superstructures was followed in some cases by the reinforcement of foundations.

The seismic safety of strengthened buildings was assessed generally with the previously described evaluation procedures for existing reinforced concrete buildings [15, 16, 18]. In the procedures, the safety of a building can be judged based on the experience of earthquake damage. It is suggested that the value of the seismic performance index I_S of $0.6 \sim 0.7$ will be the border between damaged and undamaged buildings experienced $25 \sim 30\%$ g level of ground motion. The index I_S indicates the ultimate horizontal strength of the building in terms of the shear coefficient, or equivalent strength when

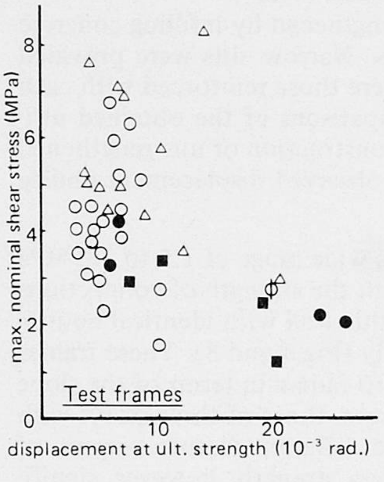

Fig. 6 Ultimate Strength and Displacement

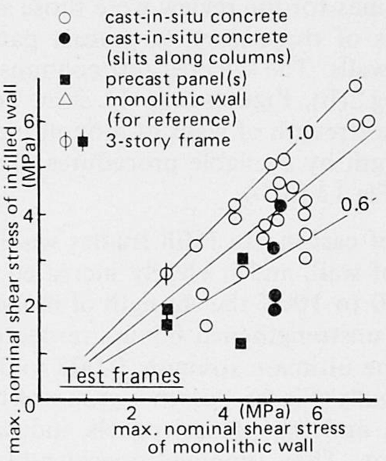

Fig. 7 Strengths of Infilled and Monolithic Walls

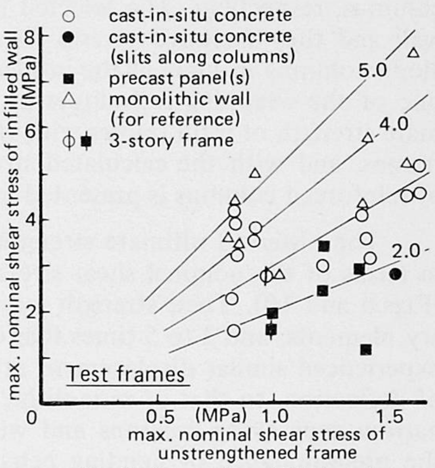

Fig. 8 Strengths of Wall and Unstrengthened Frame

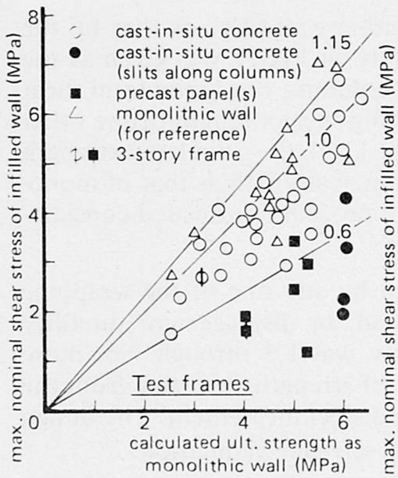

Fig. 9 Observed & Calculated Strengths of Wall

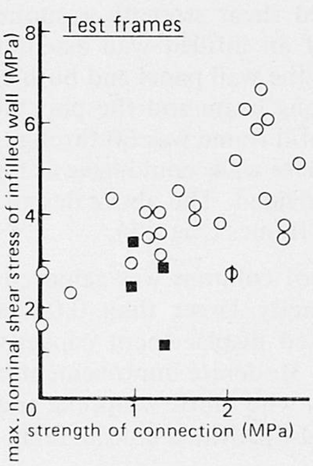

Fig. 10 Strengths of Infilled Wall and Connection

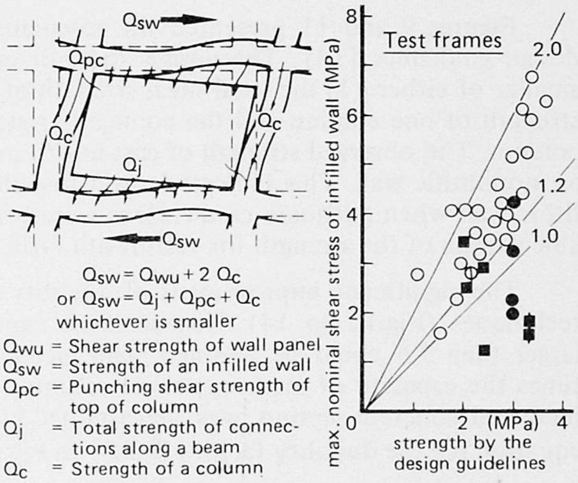

Fig. 11 Observed and Design Strengths of Infilled Wall

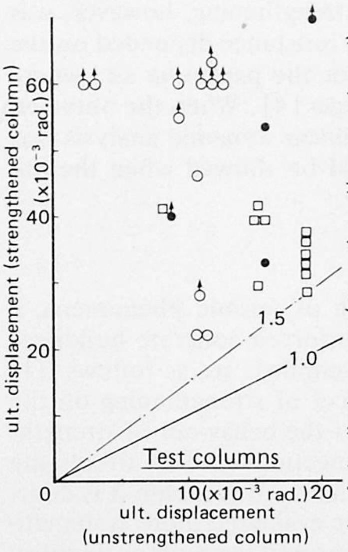

Fig. 12 Increased Displacement Capacity

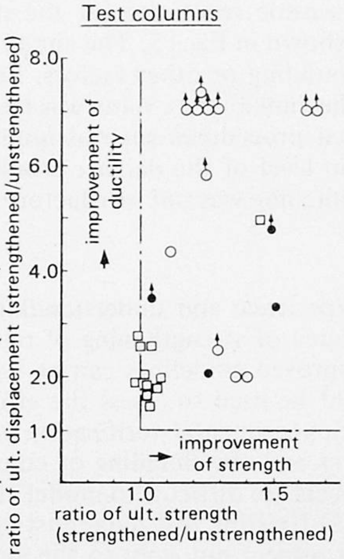

Fig. 13 Effect of Strengthening

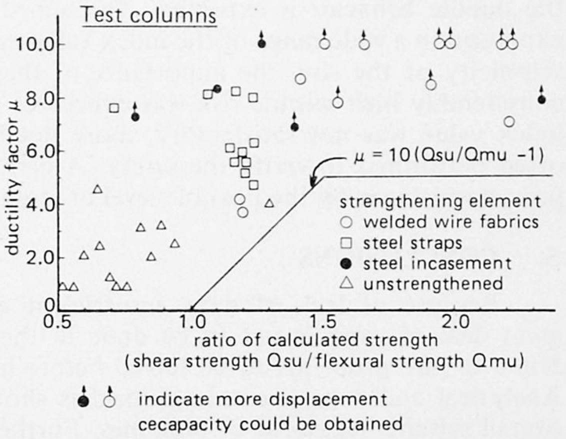

Fig. 14 Improvement of Ductility

Table 2 Outline of Reviewed Data of Strengthened Buildings

a) number of buildings

total	157	
1 ~ 2-story	16	(10.2 %)
3-story	65	(41.4)
4-story	41	(26.1)
5 ~ 10-story	35	(22.3)

b) use of building

school	42.7 %
public office	28.7
private office	7.6
residential bldg	7.6
others	13.8

c) reason for strengthening

pre-earthquake evaluation	66.9 %
post-earthquake evaluation	17.8
others	15.3

d) strengthening element or method (290 cases)

cast-in-situ-concrete walls	130	(44.8 %)
reinforcement of columns	52	(17.9)
addition of side walls	43	(14.8)
reinforcement of foundation	11	(3.8)
reinforcement of beams	5	(1.7)
steel braces	3	(1.0)
others	46	(15.9)

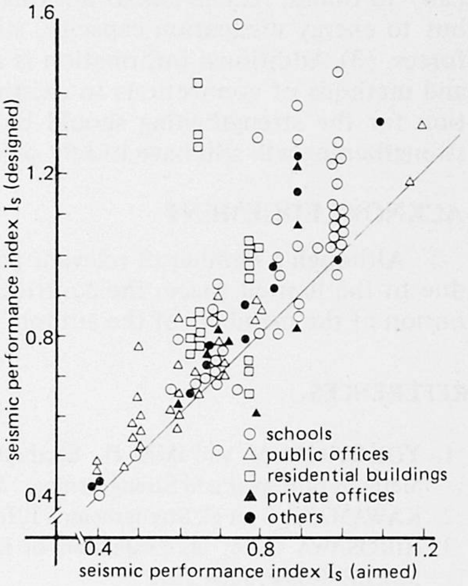

Fig. 15 Seismic Resistance of Strengthened Buildings

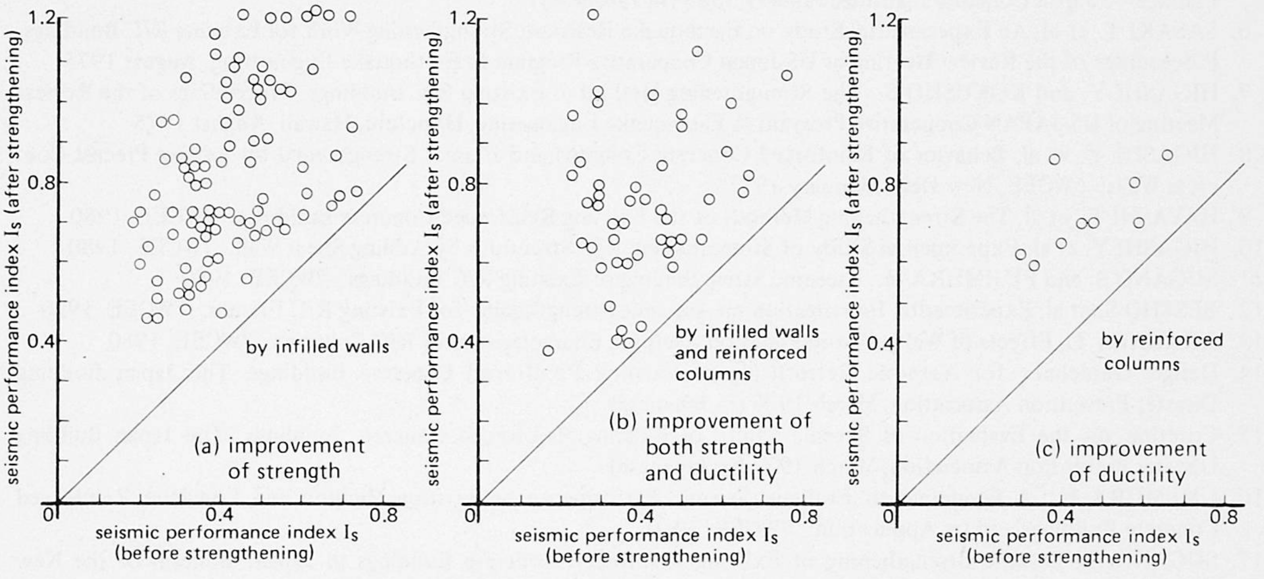

Fig. 16 Improvement of Seismic Resistance of Strengthened Buildings

the ductile behavior is expected. The aimed seismic resistance for the strengthening, however, was expressed in a wide range of the index value as shown in Fig.15. The aimed resistance depended on the seismicity of the site, the importance of the building or other factors. For the particular site where considerably high seismic risk was expected, the aimed index value was larger [4]. When the obtained index value was not satisfactory, more detailed procedures such as nonlinear dynamic analysis was often performed to verify the safety. A certain level of the damage would be allowed when the improved resistance by the possible level of strengthening was not satisfactory.

5. CONCLUSIONS

Because of lack of data, insufficient experience and understanding of seismic phenomena, a great deal of work is yet to be done in the area of strengthening of reinforced concrete buildings. Some of the problems to be solved before improved guidelines can be compiled, are as follows: (1) Analytical and experimental approaches should be used to assess the effect of strengthening on the overall seismic behaviour of buildings. Further experimental verification of the behaviour of strengthened sub-assemblages is required. Workmanship and the detailing of connections greatly affects the response of strengthened structures. These aspects are difficult to model and for this reason it is desirable to test large if not full scale specimens. (2) Existing test data must be evaluated more systematically to obtain relable global information with respect not only to the increased strength or ductility but to energy dissipation capacity, stiffness deterioration and potential strength to resist earthquake forces. (3) Additional information is required with respect to the use of precast and bracing elements and methods of connections to existing structural systems. (4) Available data for design and construction for the strengthening should be compiled for the benefit of potential users. The approach to strengthening will still have to rely on experience so gained and on judgement.

ACKNOWLEDGEMENT

Although a number of relevant papers, particularly those in Japanese, were not listed as references due to the limited space, the contribution of the authors of those papers is acknowledged. The contribution of the members of the authors'committee in the Japan Concrete Institute is also acknowledged.

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