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Repair and Strengthening of Reinforced Concrete Buildings for Seismic Resistance

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Repair and Strengthening of Reinforced Concrete Buildings for Seismic Resistance

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This paper summarizes a review of the literature on the repair and strengthening of reinforced concrete buildings in seismic areas, with emphasis on the repair and strengthening of reinforced concrete columns. In particular, experimental and analytical investigations are described which provide information on the strength, ductility, and seismic behaviour of reinforced concrete columns repaired and strengthened by jacketing with or without added longitudinal reinforcement placed through the floor structure.

INTRODUCTION

In the past a large number of reinforced concrete structures have been damaged by severe earthquakes, and some of these structures have been repaired and strengthened. Several examples of the repair and strengthening of reinforced concrete buildings damaged by earthquakes have been reported in earthquake-prone countries such as in the Balkan region (UNIDO [l]), Japan (Endo et al [2], Sugano, [3, 4]), Mexico (Aguilar et al, [5], Jara et al, [6]), and Peru (Kuroiwa and Kogan, [7]).

The need for the strengthening of structures also arises in cases where existing structures must comply with more recent code requirements. This was the case for a number of structures in Japan after the 1978 Miyagiken-oki Earthquake (Sugano, [3,4]), as well as a number of reinforced concrete buildings in Mexico City after the 1985 Mexico Earthquake (Jara et al, [6]). This need for strengthening is also mentioned in the case of some reinforced concrete buildings commonly built in California, USA, about 30 years ago (Badoux and Jirsa [8]).

In New Zealand there are many structures constructed before the 1970's that would have inadequate response during a strong earthquake. Comparison of the design levels for seismic lateral loads between previous codes and the current loading code (NZS 4203 [9]) indicates that buildings designed to the previous codes often do not satisfy the strength and ductility requirements of the current loading code. Typical deficiencies of moment resisting frames are: inadequate shear strength of columns and beam-column joints, and inadequate flexural strength and ductility of columns (Brunsdon and Priestley [10], Park [11]).

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Different techniques for the repair and strengthening of structural elements such as reinforced concrete columns have been suggested in the literature (UNIDO [1]), Hayashi et al [12] and Bett et al [13]). Some of these techniques have been used in earthquake-prone countries. However, because of the lack of guidance to designers, the repair and strengthening of structures in most cases has been based mainly on engineering judgement. The repair and strengthening of structures after the Tokachi-oki Earthquake in Japan, 1968, (Sugano [3]), as well as the retrofitting of structures in Mexico city after the 1985 Earthquake (Jara et al [6]), illustrates this situation. It is clear that experimental and analytical research is urgently required to provide information about the seismic behaviour of structures repaired and strengthened by different techniques.

This paper summarizes a review of the literature on the repair and strengthening of reinforced concrete buildings in seismic areas, with emphasis on the repair and strengthening of reinforced concrete columns.

GENERAL ASPECTS OF THE REPAIR AND STRENGTHENING OF REINFORCED CONCRETE STRUCTURES

DECISION TO REPAIR AND/OR STRENGTHEN A STRUCTURE

The decision to repair and/or strengthen an existing structure depends not only on the field inspection of the damaged structure after an earthquake, or in the seismic capacity evaluation of the existing structure, but also in a cost/benefit analysis of the different alternatives of repair and/or strengthening. In the case of Mexico City after the 1985 Mexico Earthquake, it has been shown that repair and/or strengthening of reinforced concrete buildings is generally more economical than demolition and rebuilding, even in the case of severe structural damage. It was found that some repaired and strengthened reinforced concrete buildings had a final price in the real estate market of about three to four times the overall cost of the retrofitting and finishing (Holtz [14]). However, it must be mentioned that the repair and strengthening costs of foundation, structure and hand labour involved in the Mexico City structures might be different from those costs in other countries.

SEISMIC DESIGN CRITERIA FOR REPAIR AND STRENGTHENING

The seismic design criteria for repair and strengthening of existing structures is not yet well established. For example, after the 1981 earthquake in Greece a 50% increase in the base shear coefficient used for the design of repair and strengthening was required (UNIDO [1]). In Japan this seismic design criteria is determined using an evaluation procedure for existing reinforced concrete buildings which is based on evaluating the seismic capacity using a seismic index I_S which is a product of indexes of strength, ductility and other factors (Aoyama [15, 16]). This index is compared with the so called seismic protection index E_T which is related to the base shear coefficient. This Japanese evaluation procedure is based on experience obtained from the evaluation of structural damage of structures observed after earthquakes in Japan, such as the 1968 Tokachi-oki Earthquake and the 1978 Miyagiken-oki Earthquake (Sugano [3]).

The repair and strengthening of reinforced concrete structures in Mexico City after the 1985 Mexico Earthquake was conducted using the current Mexico City Building Code [17] for new construction. Because the amount and detailing of the reinforcing steel in most existing structures would not comply with the full requirements for ductile structures specified by that current Mexican code, most of the repair and/or strengthening was conducted considering that the structures would not qualify as a fully ductile type.

SELECTION OF REPAIR AND STRENGTHENING METHODS

Usually the strengthening method is aimed at increasing the lateral strength of the structure. In most cases with any of the selected strengthening methods there is also an associated increase in the lateral stiffness of the structure. Caution must be taken to avoid an irregular stiffness distribution in the strengthened structure. In some cases an increase in the overall ductility of the structure can be obtained. However, because of the lack of information to assess the increase in ductility of retrofitted structures, this assessment is generally made using engineering judgment.

One of the most common methods used in Japan to increase the lateral strength of reinforced concrete buildings after the 1968 Tokachi-oki and 1978 Miyagiken-oki Earthquakes was providing additional shear walls (Aoyama [16]). This method was also used in Mexico City, but to less extent, for strengthening structures after the 1985 Mexico Earthquake (Aguilar et al [5]). One disadvantage of this method is that the increase in lateral resistance is concentrated in few places, and new foundations or strengthening of the existing foundations may be required to resist the increased overturning moment there as well as the increased dead load of the structure. This could be inconvenient in cases where the strengthening of foundations is an important item in the overall cost of the strengthening project, or when there is not enough or no information on the original foundation design.

A better alternative is generally the strengthening of columns, which is discussed in detail later in this paper. With this method the increased lateral resistance is uniformly distributed throughout the structure. Another method of strengthening having similar advantages uses steel bracing. Some structures in Japan (Endo et al [2]) and Mexico (Aguilar et al [5]) have been strengthened using this method. Some inconveniences may be experienced with this technique; for example: lack of information on the seismic behaviour of the added bracing and undesirable changes to the original architectural features of the building may be caused mainly by using exterior bracing. Additional inconveniences of this method may be cost and lack of field experience in the technique (Badoux and Jirsa [8]).

EXAMPLES OF REPAIR AND STRENGTHENING TECHNIQUES

REPAIR AND STRENGTHENING OF BUILDINGS IN JAPAN

A number of reinforced concrete buildings in Japan were damaged in the Tokachi-oki Earthquake, 1968. Evaluation of damaged reinforced concrete buildings after this earthquake showed that shear failure in columns was a typical type of failure (Endo et al [2]). Repair and/or strengthening of damaged buildings was extensively undertaken for the first time in Japan following this earthquake. Typical strengthening methods used in Japan are shown in Fig. 1.

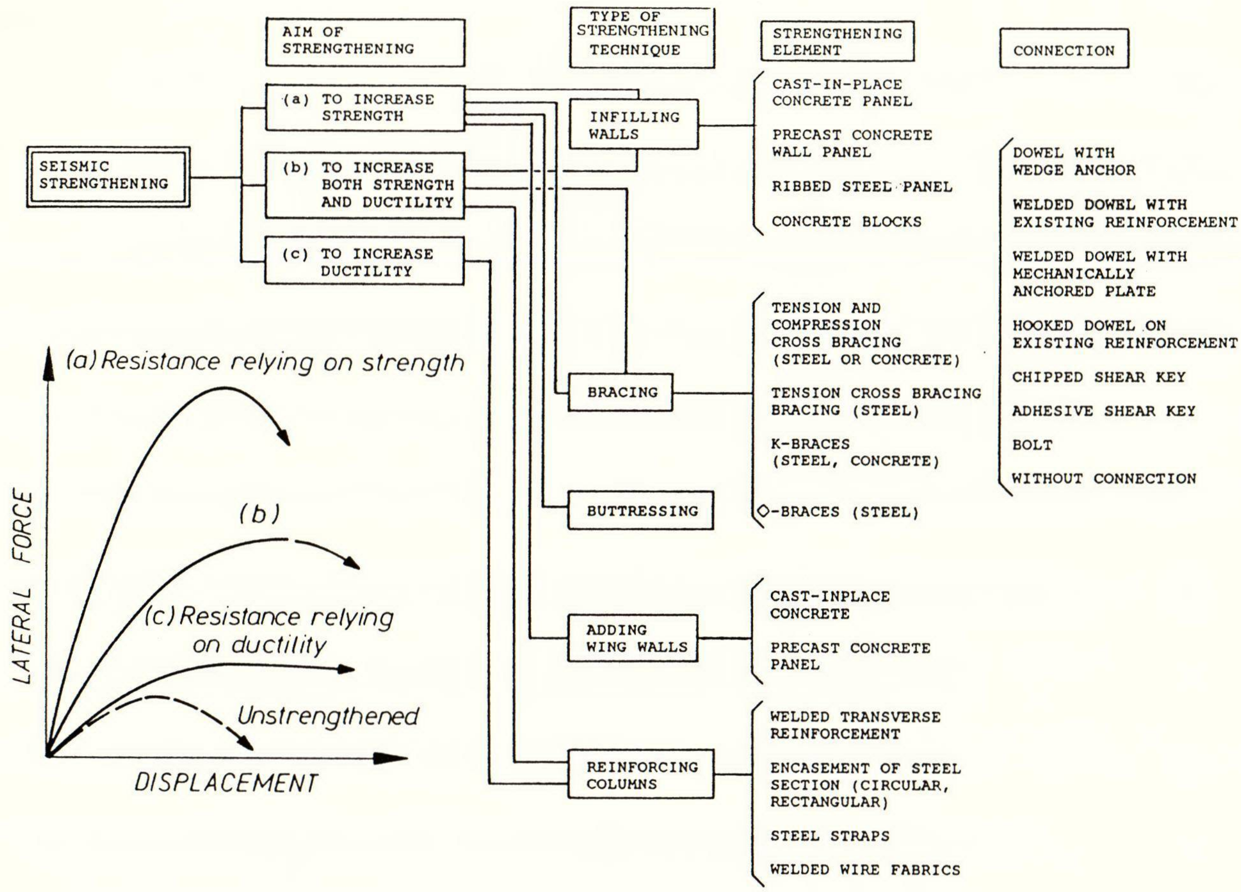


Figure 1 Typical Strengthening Methods Used in Japan [3]

The Japan Concrete Institute collected data on repair and/or strengthening of 157 existing reinforced concrete buildings in Japan constructed between 1933 and 1975. The evaluation of this data shows that most of the strengthening has been done to undamaged buildings, and in only 18% of the cases was earthquake damage the reason for strengthening. This data also shows that 68% of the buildings were either three or four storeys high. Fig. 2 illustrates the different methods used for the repair and strengthening for the 157 buildings reported (Endo et al [2]). Commonly more than one method was used for a building, and the most common methods of strengthening were to add shear walls (85% of cases) which were cast into existing frames. Column jacketing was used in 35% of cases. Adding steel bracing was adopted only in 2% of the cases, mainly because of the difficulty of connecting the braces to the existing concrete frame (Endo et al [2]).

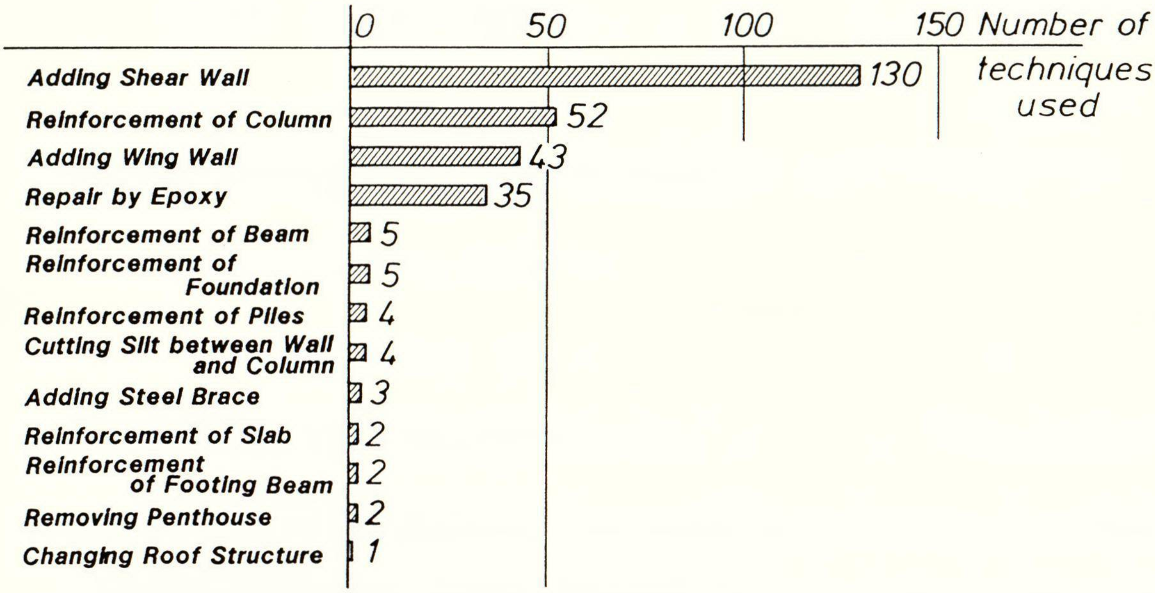


Figure 2 Repair and Strengthening Techniques Used for 157 Buildings in Japan [2]

Experimental studies of strengthening methods using infilled reinforced concrete walls inside existing frames have been conducted extensively in Japan. Sugano and Fujimura [18], Hayashi et al [12], and Aoyama et al [19] report results of experimental studies on various types of infilling techniques for single bay, one storey, one-third scale reinforced concrete frames. Additional studies have been conducted by Higashi et al [20] on specimens representing three storey frames.

Typical lateral load-displacement curves representing results of some of these studies are shown in Fig. 3 (Sugano [3]). As can be seen the various strengthening techniques significantly increased the lateral strength and stiffness of the unstrengthened frame. However, in using these techniques in most cases the experimental results showed reduction in the ductility capacity of the strengthened frame. It is also mentioned that to achieve a strength for a frame with an infilled wall of more that 60% of that a monolithic wall, it is necessary to provide connectors all around the existing frame, and some special recommendations for designing the connectors must be followed (Sugano and Fujimura [18]).

Typical methods considered in Japan for strengthening reinforced concrete columns using steel encasement either with complete covering or with steel straps and angles, are shown in Figs. 4a and 4b. Welded wire fabric, as illustrated in Fig. 4c, has also been used in Japan. However, because there are difficulties in passing the steel encasement or wire fabric through the floor structure when using these techniques, the column flexural strength is not significantly improved. Fig. 5 shows sections of short columns tested in Japan (Hayashi et al [12]) using welded wire fabric for column strengthening. The shear span to column depth ratio ranged between 2.0 for

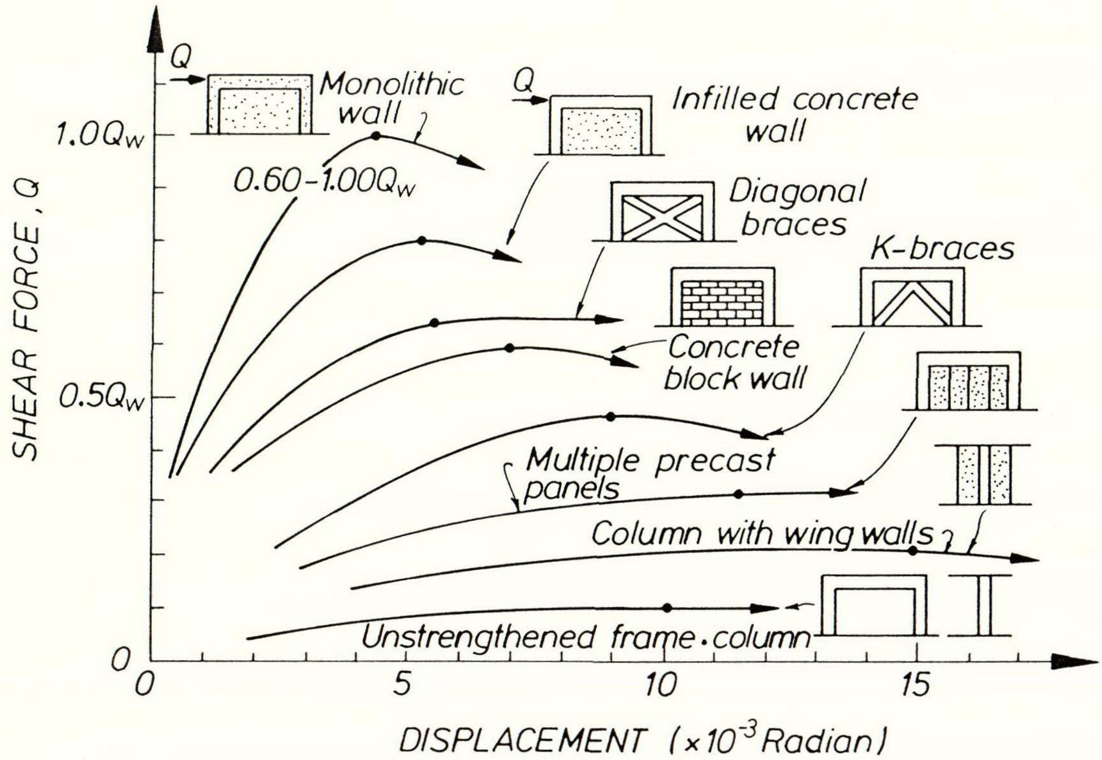


Figure 3 Typical Load-Displacement Relationships for Different Strengthening Techniques [3]

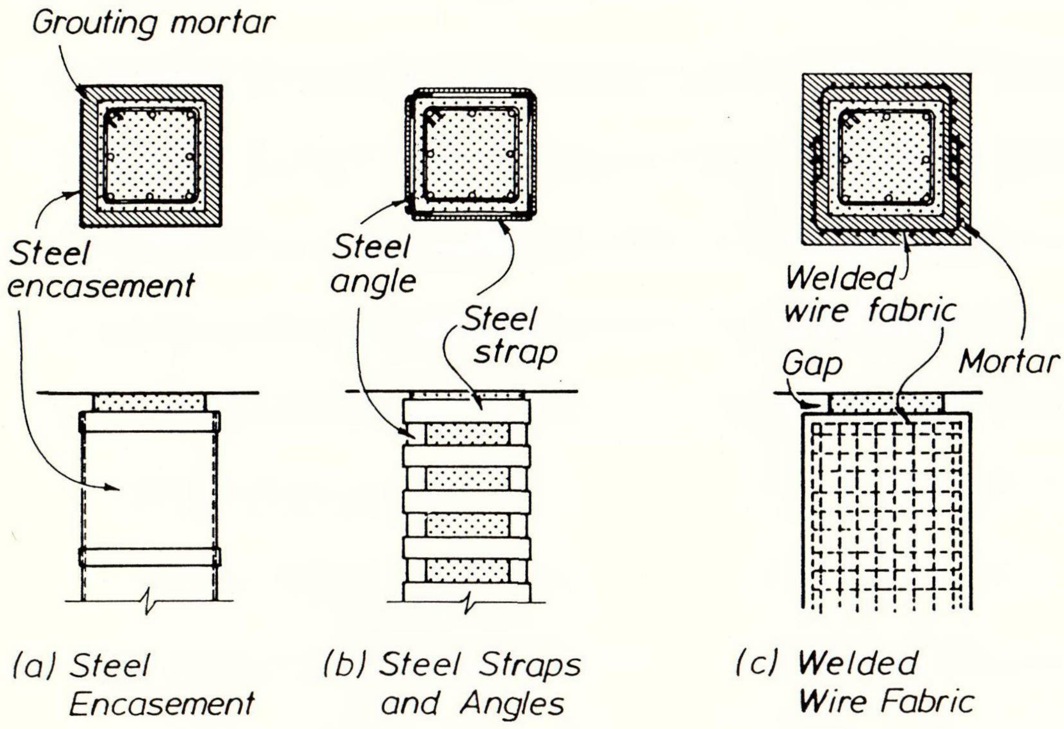


Figure 4 Techniques for Strengthening of Columns [3]

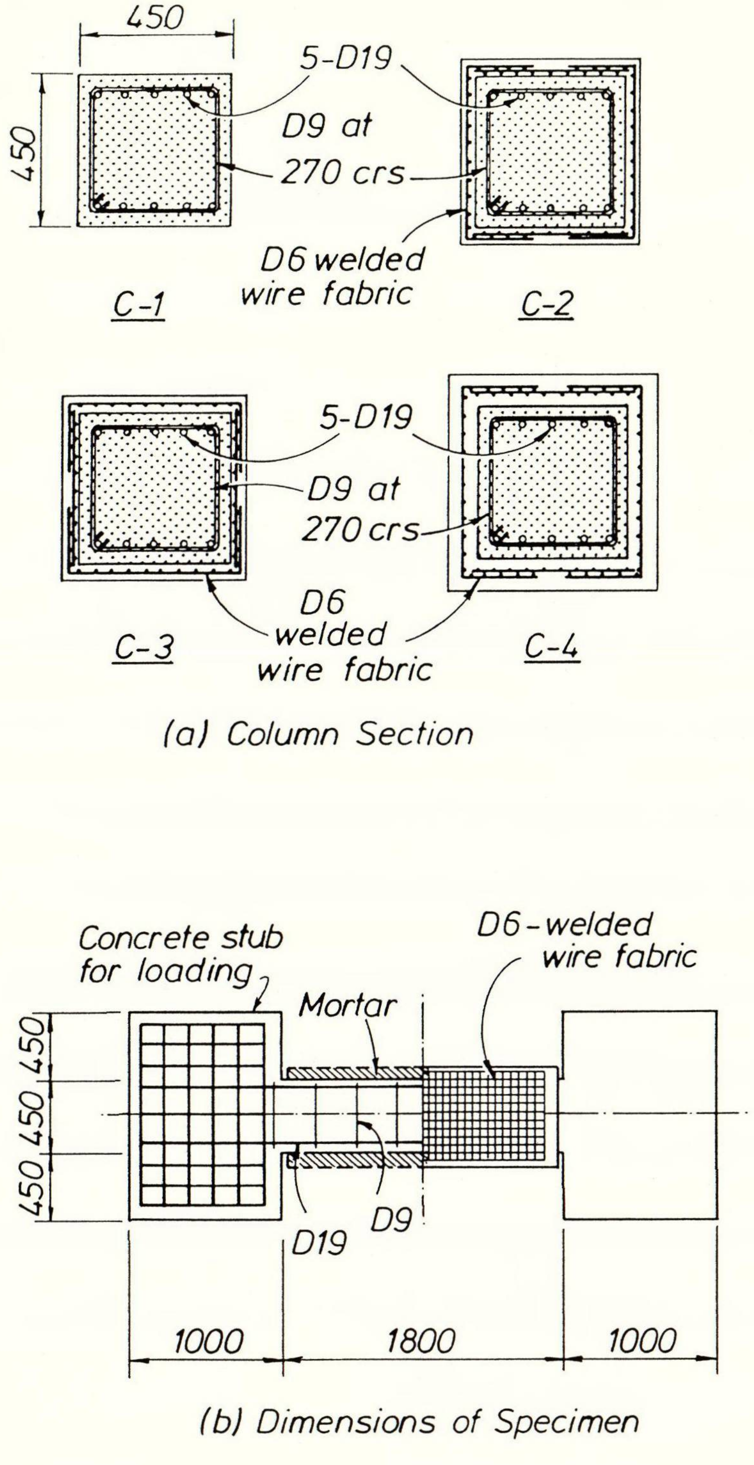


Figure 5 Columns Tested in Japan using Welded wire Fabric [12]

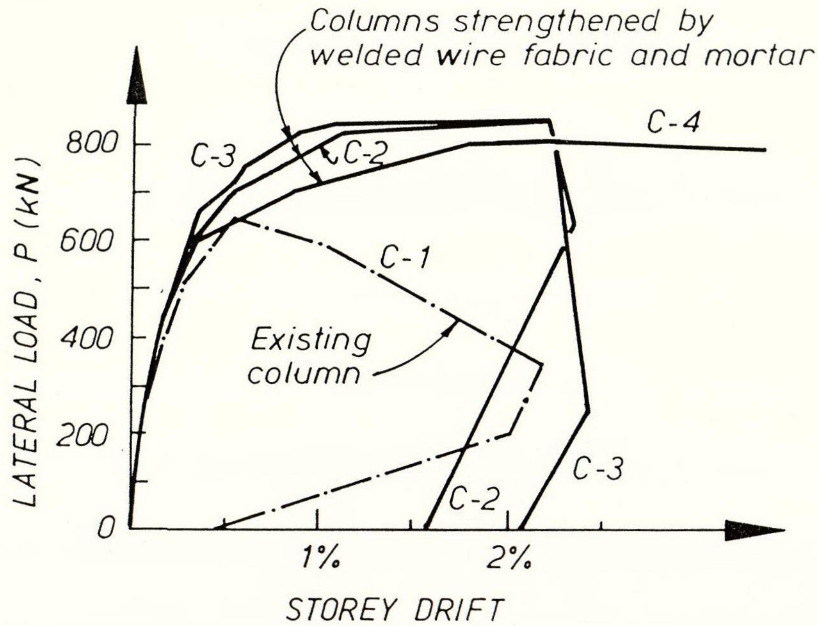


Figure 6 Lateral Load - Storey Drift Envelopes for Specimens Tested in Japan Using Welded wire Fabric [12]

the unstrengthened specimen (C-1) to about 1.4 for the strengthened specimens (C-1, C-2 and C-3). Shear span is defined as the distance between the points of zero moment and maximum moment. Typical lateral load-storey drift envelopes for these specimens are shown in Fig. 6. As can be seen in Fig. 6 the increase in strength was not large (since the strengthening did not pass through the floor), but there was some increase in the ductility capacity. This suggests that framed structures with columns retrofitted using this technique may not have significantly increased flexural strengths but the shear strengths and ductility may be enhanced.

THE BALKAN REGION MANUAL FOR REPAIR AND STRENGTHENING OF BUILDINGS

In 1983 the United Nations Industrial Development Organization (UNIDO) with the participation of several countries in the Balkan Region, and based on experience gained in this region, produced a manual (UNIDO [1]) which gives mainly qualitative guidelines for the repair and strengthening of buildings. Some case studies are also presented in this manual.

An example of local strengthening of reinforced concrete columns by jacketing suggested by this manual is shown in Fig. 7, which illustrates strengthening only between the floors. The jacket consists of added concrete and longitudinal and transverse reinforcement, around the existing column. While this type of strengthening improves the axial and shear strength of the column, both the flexural strength of the column and strength of the beam-column joints remain the same. To improve bond between the old and new concrete the manual also suggests chipping away the concrete cover of the original member and roughening its surface.

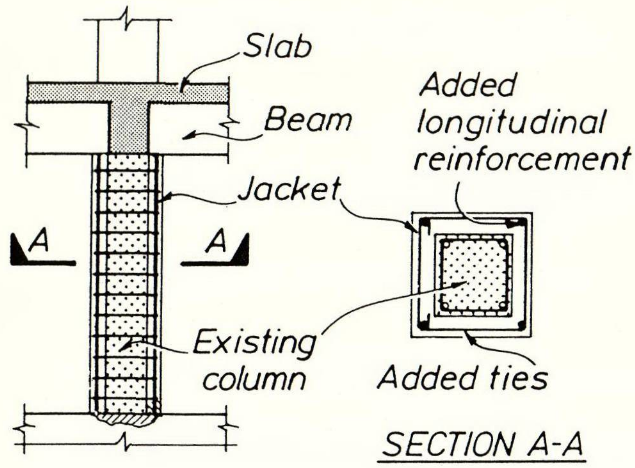


Figure 7 Example of Local Strengthening of Reinforced Concrete Columns [1]

Some experimental research using this type of strengthening has been undertaken at the University of Texas on short columns constructed at two-thirds scale, as shown in Fig. 8 (Bett et al [13]). These columns had a shear span to column depth ratio ranging from 1.5 for the unstrengthened specimens to about 1.0 for the strengthened specimens. Low shear span to depth ratios are typical of short columns and in this type of column shear-dominated behaviour could be expected. The unstrengthened column (specimen 1-1) failed by shear during testing, and after strengthening the specimens showed either a flexural or a combined shear-flexural failure. Fig. 9 shows typical lateral load-storey drift envelopes for these specimens. The results showed that the repaired and strengthened specimen 1-lR and the strengthened specimens 1-2 and 1-3 had improved shear and flexural strengths compared with the of the original specimen 1-1. However, the ductility capacities found in these tests were very poor.

The UNIDO Manual suggests another type of jacketing aimed at improving the column flexural strength. This is achieved by passing the new longitudinal reinforcement through holes drilled in the slab and placing new concrete in the beam-column joint as is illustrated in Fig. l0(a).

Lateral load testing of four full-scale interior beam-column subassemblages representing typical USA and Mexican practice in the 1950's has been recently conducted in the University of Texas (Alcocer and Jirsa [21]). Jacketing of columns was performed with bundled and distributed longitudinal reinforcement around columns using similar techniques to that showed in Fig. 10(a). Important increases in strength and stiffness were observed in the jacketed specimens compared with the original unstrengthened specimen, although no significant improvement in the subassemblage ductilities were observed.

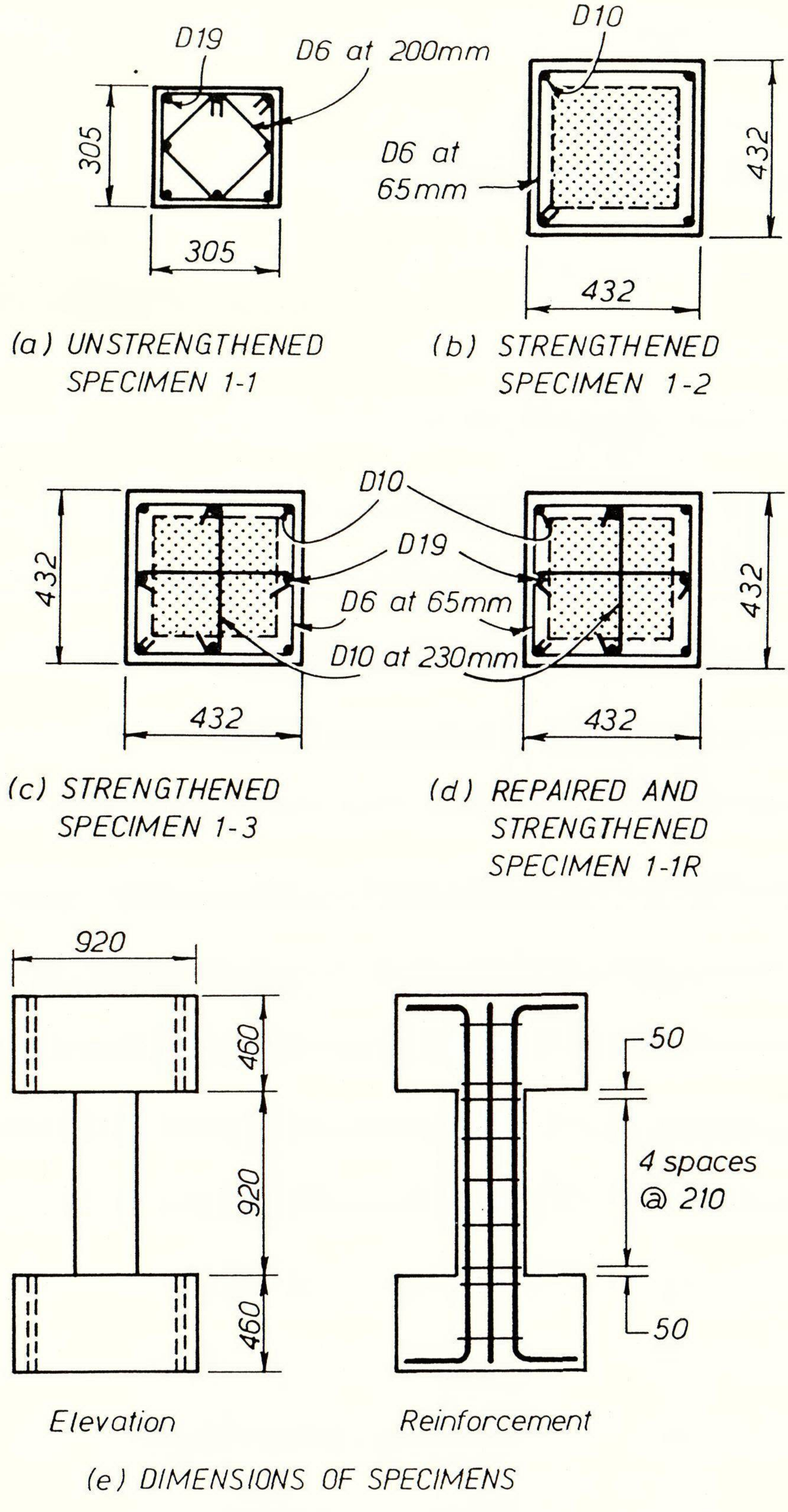


Figure 8 Columns Tested at the University of Texas [13]

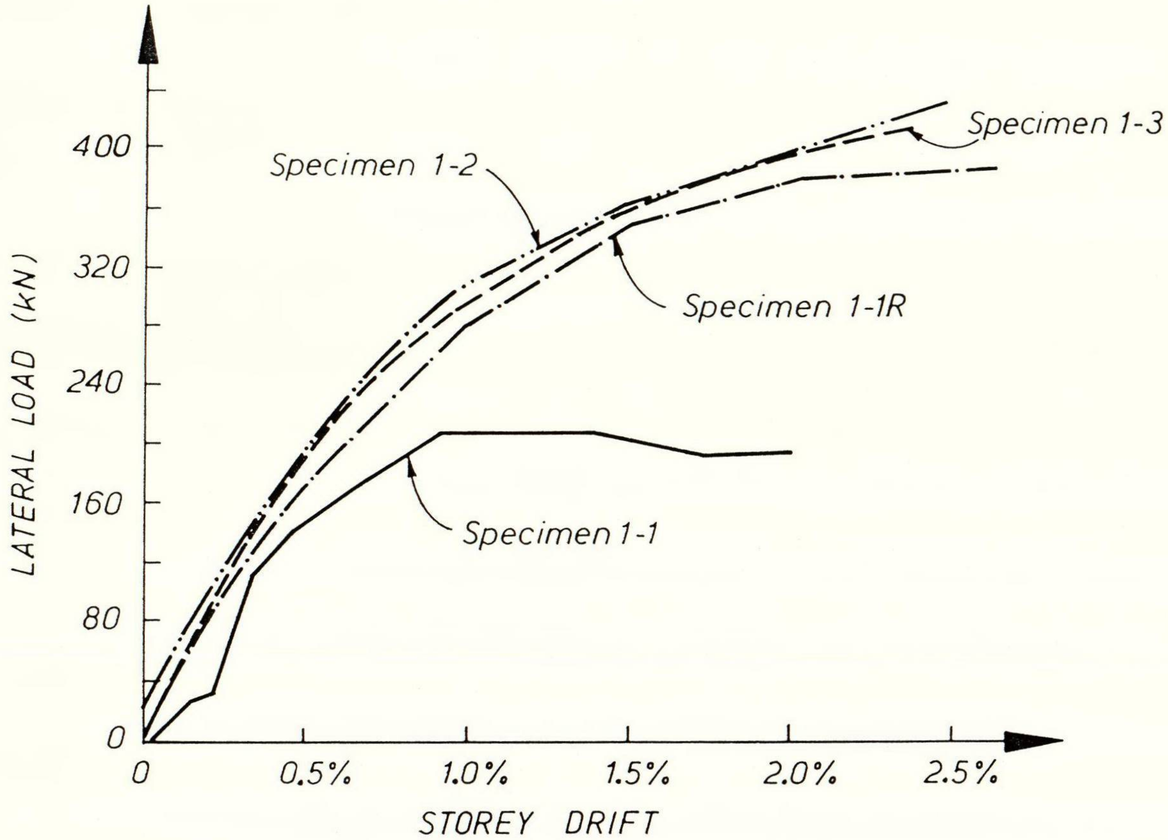
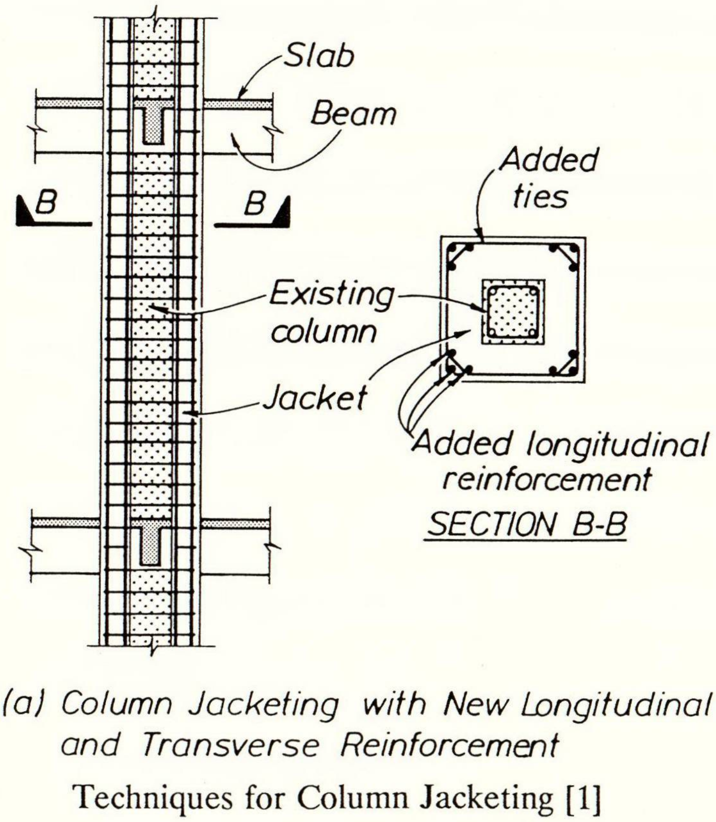
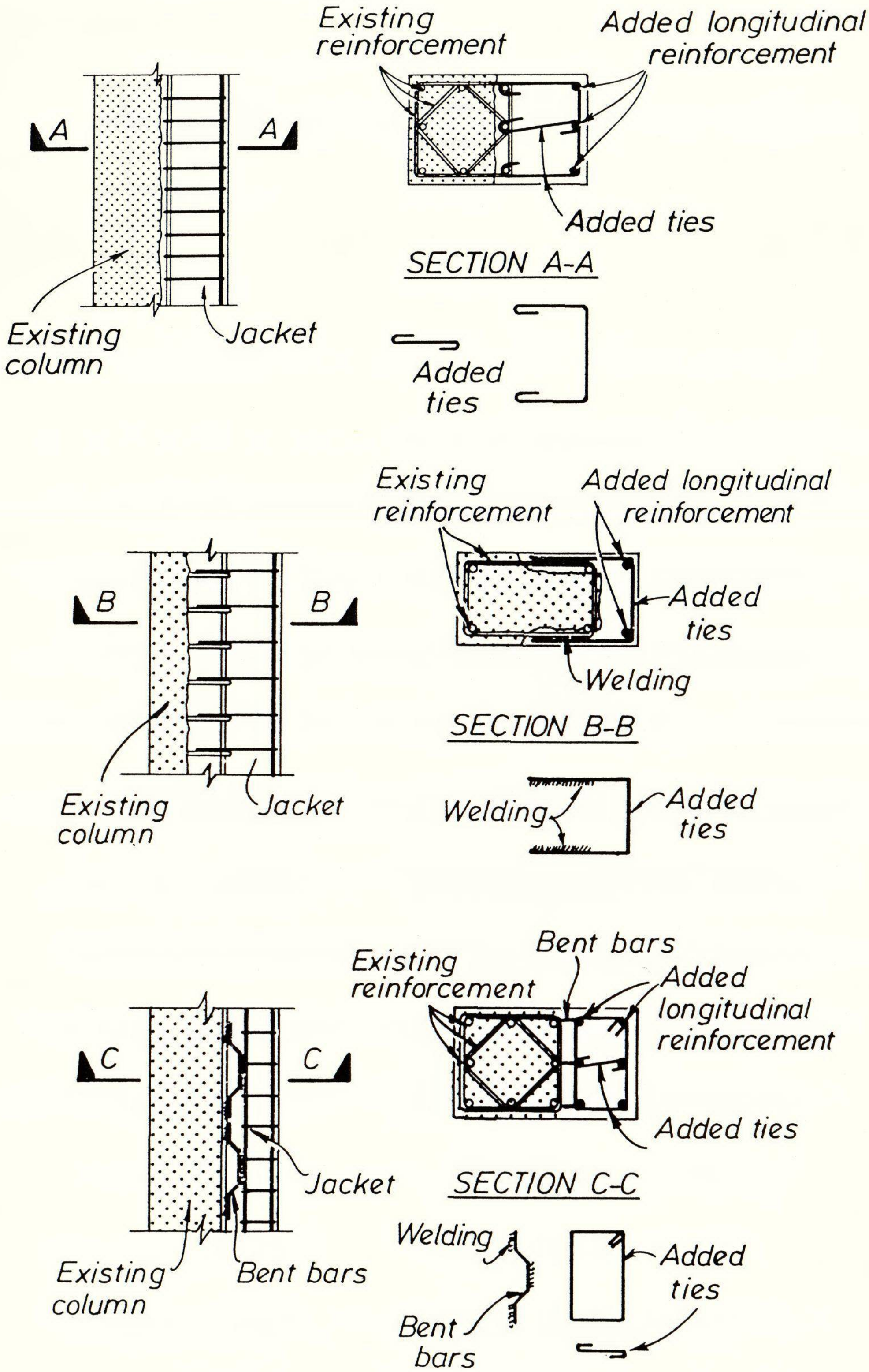


Figure 9 Lateral Load - Storey Drift Envelopes for Column Specimens Tested at the University of Texas [13]



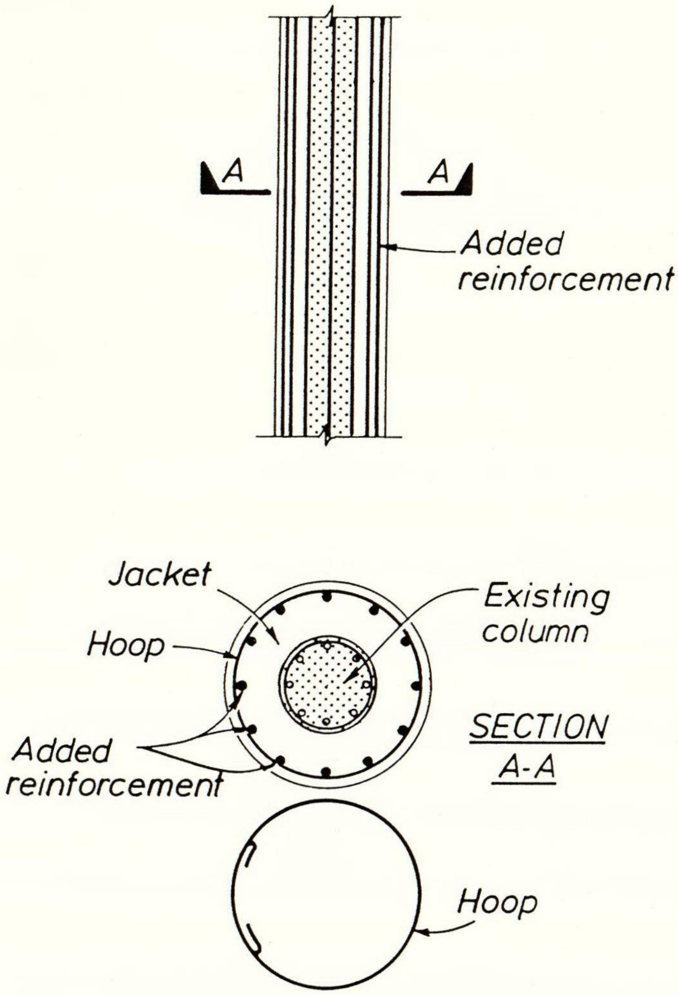
(a) Column Jacketing with New Longitudinal and Transverse Reinforcement

Figure 10 Techniques for Column Jacketing [1]



(b) Side Jacketing

Figure 10 (Continued) Techniques for Column Jacketing [1]



(c) Circular Jacketing

Figure 10 (Continued) Techniques for Column Jacketing [1]

The UNIDO Manual also gives some examples of one-sided jacketing of columns, as is shown in Fig. 10(b). In this method special detailing is needed for connecting the additional transverse reinforcement to the existing reinforcement. similar detailing is suggested for cases of two or three-sided jacketing. Additional examples of jacketing of columns, for example circular jacketing, Fig 10(c), are also given in the Manual, as well as examples of jacketing of beams and beam-column connections.

REPAIR AND STRENGTHENING OF BUILDINGS IN MEXICO CITY AFTER THE 1985 EARTHQUAKE

The 1985 Mexico Earthquake caused important structural damage in a large number of reinforced concrete buildings. In an investigation of the consequences of the earthquake, damage was reported for about 2300 buildings (Norena et al [22]). Statistics of typical damage and the repair and strengthening techniques that followed this earthquake are documented in the literature (Aguilar et al [5]).

From a total of about 1200 buildings that have been repaired and strengthened, Aguilar et al [5] selected a sample of 114 reinforced concrete structures. The analysis of this sample data identified several repair and strengthening techniques used in these buildings. Table 1 [5] shows the various types of techniques related to the number of floors of the structures. According to this data, jacketing of columns (identified as Concrete J.C. in Table 1) was the most commonly used repair and strengthening technique for buildings with less than or equal to 12 storeys. Other techniques often used were the jacketing of beams (identified as Concrete J.B. in Table 1) and the adding of shear walls.

TABLE 1

Repair and Strengthening Techniques for a 114 Reinforced Concrete Buildings in Mexico Versus Number of Floors [5]

Repair & Strengthening Techniques	Number of Floors			
	< 5	6 - 8	9 - 12	> 12
Sealing	1	1	0	0
Resins	2	2	3	2
Replacement	7	8	5	6
Hydraulic Jacks	1	1	1	0
Concrete J.C.	11	18	26	5
Steel J.C.	2	7	10	2
Concrete J.B.	4	7	14	2
Steel J.B.	1	0	3	1
Shear Wall	8	12	16	9
Infill Wall	4	9	2	2
Steel Diagonals	0	7	7	2
Concrete Frames	1	3	3	3
Additional Elements	3	3	4	2
Straightening	0	1	2	2
New Piles	2	4	8	3

Some examples of typical solutions adopted for the repair and strengthening of a large number of buildings in Mexico City are described by Jara et al. [6]. The plan and elevation of one of these buildings are shown in Fig. 11. This is a four storey building representing a typical low-rise, moment-resisting reinforced concrete frame designed in Mexico in the late 1950's. The floor was a beam and two-way slab system. The major damage of the building occurred in the columns with buckling of some of the longitudinal bars [6]. The building was repaired and strengthened using the jacketing of columns technique showed in Fig. 10(a), as well as jacketing of beams. This retrofitting technique is a typical example of the type of strengthening of columns adopted in Mexico City after the 1985 earthquake.

Typical examples in Mexico City of the jacketing of reinforced concrete columns by adding new longitudinal and transverse reinforcement are shown in Fig. 12. The details for this technique are similar to those showed in Fig. 10(a).

As can be seen in Table 1, after the 1985 Mexico Earthquake steel bracing systems were also used for the retrofitting of some reinforced concrete buildings of six to twelve storeys. Some experimental and analytical research on the seismic behaviour

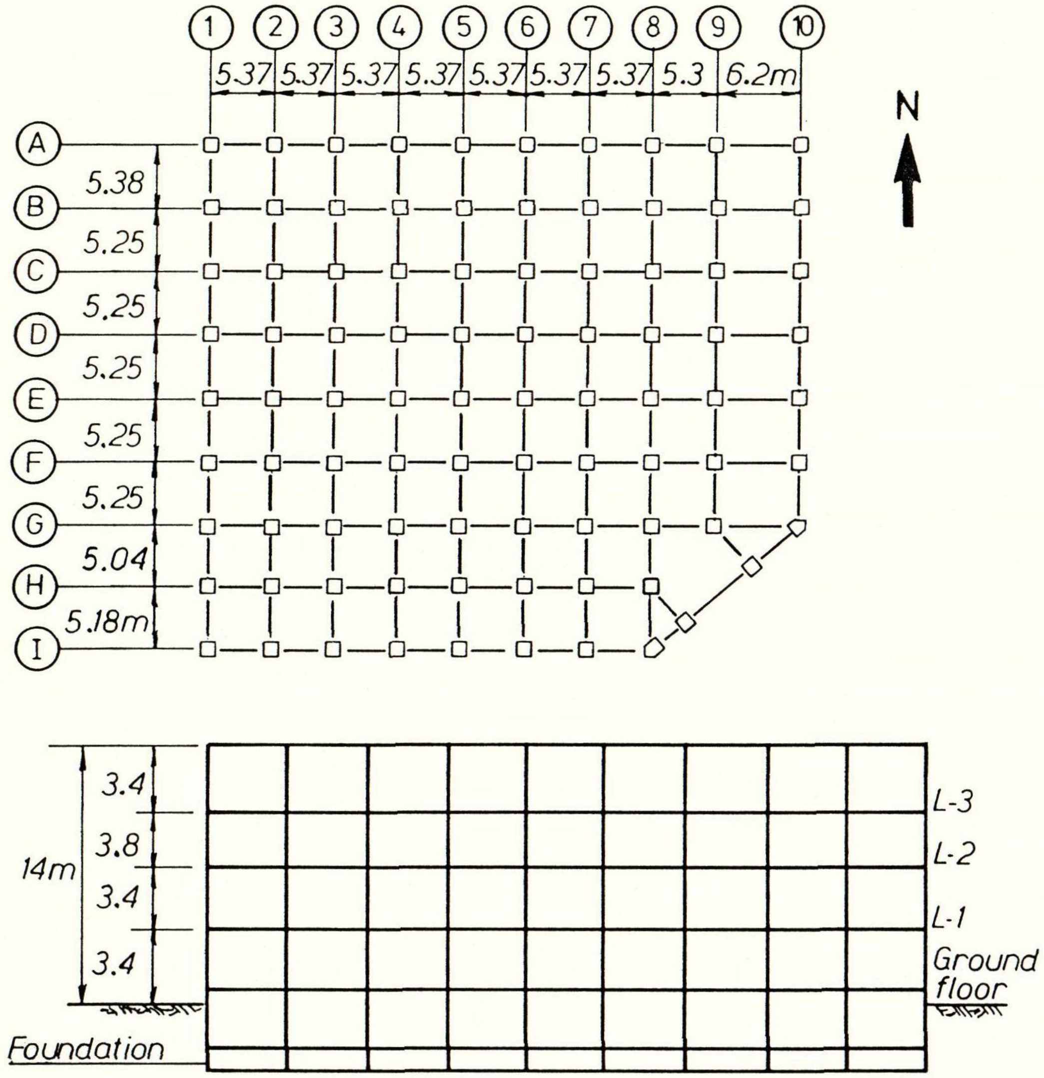


Figure 11 Plan and Elevation of a Building Repaired and Strengthened by Jacketing of Columns

of added bracing systems to existing frames has been conducted in Japan (Sugano and Fujimura [18], Higashi et al [20]), as well as in the USA ([Jones and Jirsa [23], Badoux and Jirsa [8]) and Goel and Lee [24]). An evaluation of the experimental studies shows that, as in the case of added infilled walls to existing reinforced concrete frames, a steel bracing system produces significant increase in strength and stiffness. However, in most cases, this retrofitting technique produces no increase or only small increase in the ductility capacity of the strengthened frame.

It has been suggested in the literature that improving the ductility of frames with short columns and strong beams can be achieved by using a combination of steel bracing and an alteration of the frame. This alteration can be done by reducing the flexural capacity of beams or by increasing the ductility and strength of the columns. The former is achieved by coring the compression zone or cutting some flexural reinforcement, and the latter by using concrete or steel jacketing of columns (Jirsa and Bardoux [25]).

It is of interest that a new technique for strengthening low-rise reinforced concrete structures typical of school buildings has been recently proposed for use in Mexico. This strengthening technique consists of the addition of prestressing cables that are post-tensioned to form a bracing system. One end of the diagonal of this bracing is anchored to the fixed end of the bottom column, and the other end is anchored to top end of the roof column of the structure. Analytical studies have been conducted to evaluate the seismic behaviour of this retrofitting technique (Miranda and Bertero [26]). The results of these studies show that this technique produces significant increases in strength and stiffness of the existing structure. However, it must be mentioned that also these studies show that the level of prestress in the cables can significantly modify the stiffness of the structure. Hence unexpected levels of prestress can produce changes in the dynamic response of the structure not considered in the original retrofitting design. In addition the prestress in the cables can also produce increases in the axial load of some columns, which can lead to significant reduction in the ductility capacity of the columns. Strict and periodic control of the level of stresses in the cables must be achieved by field measurements.

ASPECTS OF STRENGTHENING OF REINFORCED CONCRETE COLUMNS BY PLACING NEW LONGITUDINAL REINFORCEMENT THROUGH THE FLOOR STRUCTURE

Jacketing of columns with new longitudinal reinforcement passing through the slab has several advantages. As was mentioned earlier, a major advantage is that the lateral load capacity of buildings strengthened using column jacketing can be reasonably uniformly distributed throughout the structure of the building, thereby avoiding the concentrations of lateral load resistance which occurs when only a few shear walls are added. Hence, major strengthening of foundations can be avoided. In addition, because there are no major changes in the original geometry of building with this technique, the original function of the building can be maintained. However there are some disadvantages associated with the column jacketing technique. They are: (i) in some cases the presence of beams may require most of the new longitudinal bars in the jacket to be bundled into the corners of the jacket [6], (ii) because of the presence of the existing column it is difficult to provide cross ties for the new longitudinal bars which are not at the corners of the jacket, and (iii) because of the lack of guidelines, this type of jacketing of columns is based mostly on engineering judgement. Experimental and analytical investigations are needed to provide information on the strength, ductility, and seismic performance of reinforced concrete columns repaired and strengthened with new longitudinal reinforcement placed through the floor structure.

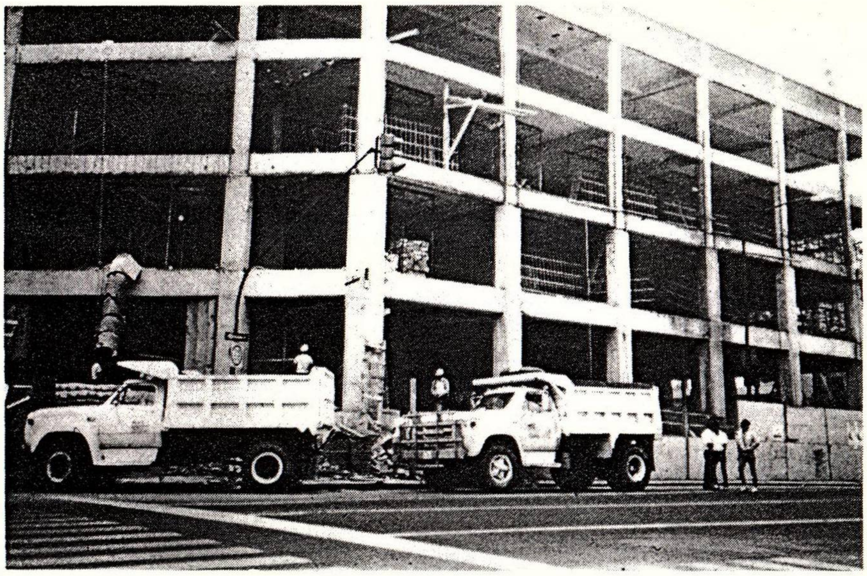


Figure 12 Jacketing of Reinforced Concrete Columns in Mexico City after the 1985 Earthquake

REPAIR AND/OR STRENGTHENING OF REINFORCED CONCRETE BRIDGE COLUMNS

Although this paper is a review of the literature on the repair and/or strengthening of reinforced concrete buildings, it is of interest to mention that similar to existing buildings previously discussed, in earthquake-prone countries there is an significant number of existing reinforced concrete bridge substructures which are substandard according to current codes. Important bridge failures have occurred in California, USA, during the 1971 San Fernando Earthquake, as well as during the 1987 Whittier Earthquake. However, the recent tragic collapse of the Cypress viaduct, among other bridges, during the 1989 Loma Prieta Earthquake illustrates that there is an urgent need of retrofitting bridge substructures designed before the 1970's.

An extensive bridge column retrofit program has been implemented in 1990 in California (Roberts [27]). One technique uses a steel jacket bonded to circular bridge columns using grout. Experimental research on circular columns conducted at the University of California, San Diego, (Chai et al [28]) shows that this retrofit technique leads to a ductile mode of flexural behaviour with good energy dissipation. Typical bond failure observed in unstrengthened specimens was also eliminated by the confinement action provided by the steel jacketing.

CONCLUSIONS

Different methods for the repair and strengthening of reinforced concrete structures proposed in the literature are reviewed in this paper. Results of some experimental research conducted in this area are discussed along with examples of the use of these methods in earthquake-prone countries. The review of the literature indicates that methods for improving the strength and ductility of existing reinforced concrete columns need to be further investigated. The jacketing of existing columns with new concrete containing longitudinal and transverse reinforcement has been commonly used in the past for strengthening columns, as in Mexico City after the 1985 earthquake. However, because of the lack of information for designers, the design and construction of this type of jacketing in most cases has been based on engineering judgement. It is concluded that experimental and analytical investigations are required to provide further information on the strength, ductility, and seismic behaviour of reinforced concrete columns repaired and strengthened by jacketing with added longitudinal reinforcement placed through the floor structure.

ACKNOWLEDGEMENT

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