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EXPEDIENT REPAIR OF STRUCTURAL FACILITIES

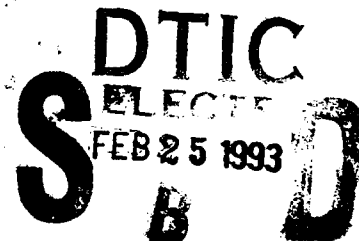
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19. ABSTRACT (Continue on reverse if necessary and identify by block number) Damaged airbase facilities critical to restoring aircraft operations must be repaired quickly after an attack to provide the needed support. Repair technologies have been developed in earthquake damage research which have potential application to bomb damage repair. This report describes the repair techniques developed for earthquake damage and their potential application to bomb damage repair. Although the damage mechanisms from earthquake loads are quite different from damage mechanisms of blast loads, the damage resulting to structural elements can be quite similar. Typical damages and failure mechanisms are categorized and compared for earthquake and conventional weapon loadings. Typical structures are selected based upon design guidelines. Damages expected to the typical structures from conventional weapon attack are described. Functional damages are defined and methods for accomplishing facility repairs are then recommended depending upon the facility function and the degree of damage. Materials, equipment, and procedures developed for repairing earthquake damage are described along with their potential use in repairing bomb damages.					
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EXECUTIVE SUMMARY

A. OBJECTIVE: The objective of this research was to support improvement of Air Force capabilities to recover aircraft operations quickly after an enemy attack through expedient repair of damaged facilities.

B. BACKGROUND: Current capability in expedient repair of structures is dependent upon the skill and experience of the craftsman, as well as the materials available. Standardized, trainable techniques are not available to the workers, and the materials on hand may not restore structures to their previous level of protection. Therefore, development of better methods and materials is necessary.

C. SCOPE: This program identified critical structure types and structural elements, and defined the typical damaged from loadings expected during an attack. The failure mechanisms were defined, and compared with those resulting from earthquake type loadings. Repair materials, equipment, and procedures used to repair earthquake damaged structures were analyzed for use on bomb damaged structures. The repair systems that promised the greatest potential for use on bomb damaged structures were identified and recommended for more detail study.

D. METHODOLOGY: A two phase approach was selected to pursue this research. This part of the program was a detailed literature review, focusing on how expedient repair from natural disasters could be applied to conventional weapons effects damage. Based on the results of this program, a follow-on effort would pursue the development and standardization of these repair methods.

E. TEST DESCRIPTION: There was no testing performed under this effort.

F. RESULTS: The results of this study show a variety of repair techniques that may be categorized by expertise and materials required. Many of these techniques can be incorporated into the existing engineering force structure.

G. CONCLUSIONS: The results of this program mean a standardized set of repair techniques and materials can be developed for expedient structural repair. This would provide the personnel responsible for Base Recovery After Attack (BRAAT) the ability to train for contingency during peacetime.

H. RECOMMENDATIONS: This program should be pursued further in a second phase. The second phase should develop the exact damage modes, repair techniques and materials, personnel required, and develop standard repair kits for training and actual use. The level of support and protection offered by each repair method should also be documented.

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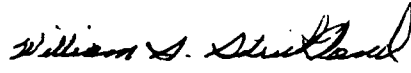
PREFACE

This report was prepared by The University of Texas at Austin, Bureau of Engineering Research, Phil M. Ferguson Structural Engineering Laboratory, 10100 Burnet Road, Austin, Texas 78758-4497, under NSF grant CES-8416147. This work was sponsored by the Air Force Engineering and Services Center, Directorate of Engineering and Services Laboratory (HQ AFESC/RD), Tyndall AFB, FL 32403-6001. Lt William R. Burkett, USN, CEC, and Capt Richard Reid, USAF, served as project officers. This report summarizes the work accomplished between 1 July 1987 and 1 June 1989.

This report has been prepared by the public affairs office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.


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TABLE OF CONTENTS

Section	Title	Page
I	INTRODUCTION	1
	A. OBJECTIVE	1
	B. BACKGROUND	2
	C. APPROACH	2
II	PREDOMINANT STRUCTURAL TYPES AND DESIGN TECHNIQUES	3
	A. INFORMATION UTILIZED	3
	B. CRITICAL STRUCTURES	3
	C. DESIGN TECHNIQUES	5
	1. Framing Systems Allowed	5
	2. Exterior Wall Construction Allowed	6
	3. Roof Types Permitted	6
	4. Concrete Design Methods	7
	5. Masonry Wall Design Methods	7
III	DEFINITION OF DAMAGE - CONVENTIONAL WEAPONS	15
	A. TYPICAL DAMAGE	15
	B. LOADINGS FROM CONVENTIONAL WEAPONS	16
	C. EXAMPLES OF DAMAGE TO STRUCTURES SIMILAR TO THE PREDOMINANT STRUCTURE	16
	1. Reinforced Concrete Frame	22
	2. Masonry Walls	19
	D. COMPARISON OF CONVENTIONAL WEAPON AND EARTHQUAKE DAMAGE	22
	E. STRUCTURAL DAMAGE CATEGORIES	27
	1. Functional Failure Due to Local Damage	30
	a. Minor damage	30
	b. Intermediate damage	30
	c. Major damage	31

TABLE OF CONTENTS

(Continued)

Section	Title	Page
	2. Functional Failures due to Global Damage	31
IV	REPAIR TECHNIQUES	32
	A. INTRODUCTION	32
	B. MATERIALS AND CONSTRUCTION TECHNIQUES	33
	1. General Concepts	33
	2. Resins	33
	3. Concrete	34
	a. Cast-in-Place	34
	b. Shotcrete	36
	c. Resin Concretes	36
	d. Polymer Concretes	37
	4. Mortars and Grouts	37
	5. Wood	38
	6. Structural Steel or Reinforcement	38
	7. Shear Transfer and Anchorage	38
	C. TEMPORARY SUPPORTS, BASIC MEASURES	42
	1. Vertical Support	42
	a. General Considerations	42
	b. Timber Shoring	45
	c. Steel Shoring	46
	d. Special Techniques	54
	2. Lateral Support	54
	a. General Considerations	54
	b. Lateral Support of Walls	56
	c. Frame Bracing	56
	3. Wedging	61
	D. INTERMEDIATE SOLUTIONS FOR REPAIR	61
	1. Concrete	65

TABLE OF CONTENTS

(Continued)

Section	Title	Page
	a. General	65
	b. Injection	65
	c. Replacement	69
	d. Steel Jacketing	70
	(1) <u>Columns</u>	70
	(2) <u>Beams and Slabs</u>	72
	e. Special Techniques.	77
2.	Masonry	77
	a. General	77
	b. Injection	77
	c. Replacement	80
	d. Strengthening	80
	e. Repair and Strengthening of Intersections	83
E.	ADVANCED SOLUTIONS FOR REPAIR	83
1.	Repair and Strengthening of Existing Elements.	83
	a. Increase in Thickness (walls and slabs)	85
	b. Concrete Jacketing	85
	(1) Columns	89
	(2) Beams	89
	(3) Joints	89
	c. Masonry Walls	95
	d. Special Techniques	98
2.	Structure Strengthening by Addition of New Elements.	104
	a. Structural Walls	104
	b. Infill Walls	107
	c. Wing walls	110
	d. Braces, Frames and Trusses	113
	e. Buttresses	117

TABLE CONTENTS
(Concluded)

Section	Title	Page
V	ASSESSMENT OF TECHNIQUES	120
	A. SELECTION OF REPAIR TECHNIQUES	120
	B. CATEGORIZATION OF TECHNIQUES	120
	1. Basic Techniques	122
	2. Intermediate Techniques	122
	3. Advanced Techniques	123
VI	RESEARCH AND DEVELOPMENT NEEDS	124
	A. GENERAL TOPICS	124
	B. RESEARCH AND DEVELOPMENT NEEDS	124
VII	CONCLUSIONS	127
	REFERENCES	128

LIST OF FIGURES

Figure	Title	Page
1	Typical Concrete Frame Details	7
2	Modular Masonry Coursing, Composite and Cavity Walls	8
3	Horizontal Joint Reinforcement For Composite Walls	10
4	Bond Beams in Masonry Walls	13
5	Typical Masonry Wall	14
6	Damage to Reinforced Concrete Walls	17
7	Visual Comparison of the Effects of Bare and Cased Charges	18
8	Bomb Damage to a Reinforced Concrete Frame	20
9	Blast Damage Curves For Concrete Columns	21
10	Response of Walls Supported on Two Opposite Edges to Blast	23
11	Effect of Steel Perimeter Frame on Crack Pattern	24
12	Column Shear Damage Due to Earthquake effects	25
13	Diagonal Shear Cracking in Masonry Walls Due to Earthquake Motions	26
14	Flexural Hinging in a Reinforced Concrete beam	28
15	Types of Welded Connections	39
16	Shear Force Transfer Mechanisms Between New and Old Concrete	40
17	Anchorage Procedures For Steel Elements	40
18	Mechanical Anchorage For Dowels in Tension	42
19	Shoring Configurations For Damaged Vertical Elements	44
20	Use of Multiple Compression Elements	46
21	Proper Use of Spreader Beams and Wedges	47
22	Support of Damage Load Bearing Walls With Openings	48
23	Standard Industrial Shore	48
24	Industrial Type Scaffolding	48
25	Shoring With Structural Steel Elements	50

LIST OF FIGURES
(Continued)

Figure	Title	Page
26	Use of Steel Multiple Interconnected Steel Units	51
27	Support of Damaged Floor Systems With Supplemental Steel Elements	52
28	Use of Steel Angles at Corners of a Damaged Column	53
29	Use of Wound Spiral to Repair Column	55
30	Additional Prestressing For Unloading Purposes	55
31	Lateral Support of External Load Bearing Wall	57
32	Techniques For Providing Lateral Support of External Load Bearing Wall by Attaching it to an Internal Perpendicular Wall	58
33	Lateral Support of External Load Bearing Wall by Continuous Ties to End Walls	59
34	Compressive Braces	60
35	Lateral Support of Structure With External Tension Braces	62
36	Use of Wood Wedges	63
37	Flat or Plane Jacks	64
38	Crack Injection	67
39	Replacement of Material in a Damaged Column	68
40	Steel Jacketing For Columns	71
41	Steel Jacketing of Column With Steel Case and Expansive Concrete or Grout	73
42	Strengthening of Beam With Steel Straps Attached With Epoxy Resins	74
43	Strengthening by Means of Glued Thin Steel Sheets	74
44	Steel Jacketing of Beams With External Post- Tensioned Steel Rods	75
45	Detail For the Intersection of Two Perpendicular Jacketed Beams	76
46	Strengthening of Column Capital	76
47	Tensioned and Tightened Collars For Confinement of Planar Frame Joint Region	78
48	Steel Jacketing of Corner Joint	79
49	Repair of Crack by Stitching	79

LIST OF FIGURES
(Continued)

Figure	Title	Page
50	Reinforcing Bar Orientation Used to Effect the Repair	79
51	Replacement of Material Along Crack in Masonry Wall	81
52	Strengthening Masonry Walls With Steel Elements	83
53	Repair of Wall Separations	84
54	Strengthening of Concrete Structural Walls	86
55	Strengthening of Structural Wall	87
56	Slab Repair Procedures	88
57	Column Jacketing	90
58	Jacket on One Side of Column	91
59	Interior Face Jacketing of Concrete Beam	92
60	Local Jacketing of Joint	93
61	Global Jacketing of Joint, Columns and Beams	94
62	Jacketing Two Sides of Masonry Wall	96
63	Details of Jacket on Two Sides of Masonry Walls For Corners and Intersections	97
64	Strengthening of Wall Intersections With Post-Tensioned Tie Rods	99
65	Strengthening of Wall Intersections With Perimeter Ties	100
66	Strengthening of Masonry Structure With External Belts of Reinforced Mortar	101
67	Strengthening With External Prestressing	102
68	Strengthening of Precast Concrete Structure Joints	104
69	Typical Load-Displacement Relationships For Different Strengthening Techniques	105
70	Addition of Shear Walls	106
71	Addition of Internal Structural Walls to Existing Structure	108
72	Addition of Infill Walls to Existing Structure	109
73	Infill Wall Connection to Existing Column	111
74	Addition of Infill Walls to Existing structure	113
75	Addition of New Concrete Frame to Existing Structure	114

LIST OF FIGURES
(Concluded)

Figure	Title	Page
76	Diagonal Steel Compressive Brace	114
77	Types of Steel Bracing Systems	115
78	Use of Peripheral Frames in Bracing Schemes	116
79	External Steel Braces	118
80	Use of Buttresses	119
81	Strengthening of Masonry Structures With New Walls	119

LIST OF TABLES

Table	Title	Page
1.	CONSTRUCTION CATEGORIES - CRITICAL FACILITIES	4
2.	RECOMMENDED CONTROL JOINT SPACING AND LOCATION	9
3.	WALL TIE CAPACITY OF HORIZONTAL JOINT REINFORCING	11
4.	BOND BEAM EQUIVALENCE	12
5.	PROPOSED DAMAGE CATEGORIES	29
6.	SUMMARY OF REPAIR TECHNIQUES -CONSTRUCTION NEEDS	122

SECTION I

INTRODUCTION

A. OBJECTIVE

The objective of this research was to support improvement of Air Force capabilities to recover aircraft operations quickly after an enemy attack through expedient repair of damaged facilities. The goals of the research were:

- Identify and define typical damage to critical structures or structural elements caused by impact and blast loads.
- Identify failure mechanisms for each type of damage caused by impact and blast loads.
- Provide preliminary recommendations of repair procedures for impact and blast load damage using the considerable data which have been accumulated in structural engineering studies for repair of buildings damaged in earthquakes.

B. BACKGROUND

The Air Force mission requires the ability to launch combat-ready aircraft after an enemy attack and sustain sortie generation during the conflict. Today's modern aircraft are complex weapon systems which require a variety of support functions including command and control, fueling, weapon loading, avionics maintenance, and others. Loss or interruption of any support operations can severely reduce the ability to perform the intended mission.

To reduce or nullify the effects of an enemy attack on an installation, the Air Force uses protective construction measures to protect critical assets. These passive measures include dispersion and duplication of structures and activities, strengthening (hardening) of structures, camouflage or "tonedown" painting, and physical protection against chemical, biological and radiological agents. Protective construction includes buildings or facilities that minimize effects of enemy weapons on the operation of weapon systems, and permit weapon systems to return to operation quickly after damage from attack. Protective systems include the following categories:

- Dispersion - Reduce the probability of overall damage by separating facilities or elements of a weapon system from other probable targets of enemy attack.
- Alternative Facilities - Provide for substitute or alternative operation from a second facility which has been designed and equipped for such substitute or alternative use in addition to its primary function.

- **Decrease in Recuperation Time** - Decrease the time required to recuperate from attack and thereby reduce the impact on operational effectiveness. Interchangeability of equipment and provision for rapid replacement and reconstruction of damaged elements may be a satisfactory alternative to structural protection.

Protective construction can be expensive, depending on the level of threat and desired level of protection. The Air Force has developed specific policies and procedures for planning and designing protective facilities. Planning policies require careful consideration of a range of actions and alternatives for cost effectiveness. The importance of the facility to be protected is emphasized. The exposure to attack must be consistent with intelligence information and must be extrapolated to the time period during which the facility is to function effectively. Guidelines state that a "realistic" enemy attack changes with protective measures employed, and is related to total enemy capability, as well as to other targets which could be attacked. Developing general design criteria for all measures of protective construction is difficult, because of the dynamic changes in weapons and the diversity of installations and local construction practices. Furthermore, aircraft operation support functions are often located in facilities not designed to survive conventional weapon attack. These unhardened facilities will suffer significant damage when subjected to enemy attack and will require expedient repair to sustain aircraft sorties.

C. APPROACH

The general approach was to identify and define technical issues pertinent to the expedient repair of bomb-damaged facilities and apply repair techniques developed in earthquake damage research to repair bomb-damaged facilities. Specific steps included:

- Identify critical structure types and structural elements based upon lists of critical facilities provided by HQ AFESC.
- Identify and define typical damage to the critical structures from loadings expected during an attack.
- Define failure mechanisms resulting from damage types expected.
- Compare failure mechanisms resulting from bomb damage with the failure mechanisms expected from earthquake-type loadings and identify similarities and differences.
- Identify repair technologies (materials, equipment, and procedures) for earthquake damage which apply to repair of bomb-damaged facilities.
- Recommend repair materials, equipment and procedures which have greatest potential for expedient repair of bomb-damaged facilities.
- Outline research needs to improve repair technologies for bomb damage repair.

SECTION II

PREDOMINANT STRUCTURAL TYPES AND DESIGN TECHNIQUES

A. INFORMATION UTILIZED

Structural details, precise weapon threats, and elaborate descriptions of facility functions were not available for this study. Therefore, a broad approach was needed to define critical structures and typical damage to those structures from an attack. Lists of facilities the Air Force considers critical to aircraft operations were reviewed. Current Air Force design techniques were examined to define typical structures or structural elements which might require repair after an attack. Available literature was reviewed to identify typical damage to structures with descriptions similar to those on the critical facilities list. The level of damage was related to failure of the facility to function properly. Relationships between structural element type, level of damage, and functional failure will determine the need for repairs and guide the selection of appropriate repair techniques.

B. CRITICAL STRUCTURES

A list of critical facilities with very general descriptions of construction types was provided by HQ AFESC. The list presented the facilities, by priority, for seven airbases. Very few of the facilities seemed to be protective structures. None of the airbases were in the continental U.S. Because the construction descriptions were very brief, the design manual for Air Force construction (Reference 1) was reviewed to aid in understanding the design philosophy behind the facilities and perhaps better estimate their construction makeup.

Critical facilities identified on the list from HQ AFESC are summarized in Table 1. The construction types given in Reference 1 were used to categorize frame, wall and roof systems. The descriptions given on the HQ AFESC list were general, therefore, the construction categories selected were quite arbitrary. The predominant structural system found from the list of critical facilities was a reinforced concrete frame with masonry walls. There was insufficient information to determine the predominant type of roof construction; however, the roof systems listed were of common construction and not designed to offer protection against blast loads. Of the seventy critical structures considered, only three were constructed of reinforced concrete walls a structural element common in most protective structures.

More than half of the critical facilities were reinforced concrete frames with rather vague descriptions of wall construction. From the information provided, the predominant critical structure appeared to be a reinforced concrete frame with non-load-bearing composite masonry walls with brick outer wythe and concrete masonry unit inner wythe. Lightweight roofing material, such as metal decking or wood sheathing, is probable.

TABLE 1. CONSTRUCTION CATEGORIES - CRITICAL FACILITIES

Air Base	Frame					Wall				Roof			
	LB R/C	LB MAS	STL	CON	OTH	R/C	MAS	MTL	CRT	CON	MTL	WD	OTH
1	-	-	-	10	-	7	2	-	-	-	3	4	-
2	-	-	-	10	-	-	-	-	7	-	-	-	-
3	1	5	4	-	-	1	5	1	3	-	1	-	-
4	1	4	-	1	4	1	4	-	-	-	-	-	-
5	-	6	2	2	-	-	6	2	-	-	-	-	-
6	-	-	4	6	-	-	6	4	-	-	-	-	-
7	1	1	6	2	-	1	3	4	-	-	2	2	-
TOTAL	3	16	16	31	4	10	26	11	10	-	6	6	-
LB - Load Bearing R/C - Reinforced Concrete MAS - Masonry STL - Steel CON - Concrete, reinforcement unknown OTH - Other MTL - Metal CRT - Curtain WD - Wood													

The critical structures identified were not designed as protective structures. At the outset of the project, it was anticipated that considerable attention would need to be given to protective structures. However, the majority of repair techniques developed in earthquake research will have excellent potential for repairing critical airbase structures.

C. DESIGN TECHNIQUES

Criteria and standards found in Reference 1 are to be applied "to the extent practicable at Air Force installation in foreign countries." However, suitable local materials, labor, and construction methods are used in foreign countries if they produce economical and fire-safe facilities of adequate serviceability. Thus, construction techniques are expected to conform to criteria in Reference 1, but may vary, depending on the location of the construction. Construction categories are given as permanent, semipermanent, temporary, and protective. Although the list provided by HQ AFESC did not specify construction categories, most of the structures appear to be in the permanent, with only a few in the protective and semipermanent categories. However, it is quite possible to have semipermanent facilities as critical structures since this category of construction is designed for weapons or support systems having a potential high rate of obsolescence. An important means

of providing protective construction is to place physical barriers between the expected weapon and the structure being protected. Some of the structures listed on the critical facilities list have revetments as physical protection barriers. Thus, Air Force criteria and standards allow a variety of possible designs for support facilities. The variety was evident in reviewing the list of critical facilities provided by HQ AFESC. To better understand reasoning behind the designs, criteria from Reference 1 for framing systems, exterior walls, and roofs are summarized.

1. Framing systems allowed include:

- One-, two-, or three-story load-bearing masonry or cast-in-place concrete walls with appropriate pilasters for stability.
- Steel beam, girder, and column system, steel joists, and long span metal deck. Steel framing is not to have exposure to the exterior of buildings. Frameless preengineered steel buildings are permitted.
- Concrete beam, girder, and column systems may have exterior exposure in certain structures (shops, warehouses, etc.).
- Systems with long clear span are permitted, but only when long spans are more economical than short multiple spans.
- New structural steel designs are based on ASTM A 36 steel and the related allowable working stresses are based on the economy of reduced section or simplified construction, unless higher strength steels can be justified.

2. Exterior wall construction (primarily for concrete or steel frames) allowed includes:

- Clay or shale brick or facing material of cavity walls or for walls backed with structural clay or concrete masonry units.
- Cast-in-place concrete for solid walls or walls backed with structural clay or concrete masonry units, structural clay facing tile, glazed ceramic structural units or brick as required.
- Structural clay tile units, for cavity or solid walls.
- Precast concrete panels for solid walls or walls backed with structural clay or concrete masonry units, structural clay facing tile, glazed ceramic structural units or brick as required. Precast concrete sandwich panels with insulation in the panels when cast. Tilt-up concrete walls are permitted.
- Local stone for solid walls, for facing material of cavity walls or for walls backed with structural clay or concrete masonry units, structural clay facing tile, glazed ceramic structural units, or brick as required.

- Hollow concrete masonry units for solid walls. Solid or hollow concrete masonry units for cavity walls. Hollow concrete masonry units reinforced with steel bars and grouted as required.
 - Metal prefabricated and insulated panels in locations where mechanical damage will not occur.
 - Metal siding. Similar guidelines are given for load-bearing walls.
3. Roof types permitted include:
- Cast-in-place concrete slab.
 - Precast concrete slab.
 - Flat slab or plate slab or waffle slab.
 - Lift-type precast concrete roof slab for use in multiple-story buildings (with special approval).
 - Ribbed slab.
 - Metal decking.
 - Open web steel joists or light steel framing with decking.
 - Corrugated metal.
 - Corrugated cement asbestos sheets.

4. Concrete Design Methods

Concrete design for Air Force structures (Reference 2a) is based on methods developed by the American Concrete Institute Committee 318 "Building Code Requirements" (Reference 3). Air Force requirements call for framing to be rigid or to include load-bearing and/or shear walls. Therefore, design details for the critical structural types and elements should follow conventional concrete frame designs. For the purposes of this study, the reinforced concrete frame is expected to be similar to that given in Figure 1. The rigid frame is made of concrete columns and girders having a rectangular cross section.

5. Masonry Wall Design Methods

Typical architectural detail drawings for composite masonry walls were taken from Reference 2b and are shown in Figures 2, 3, and 4.

A typical masonry wall would be a composite wall with a clay or shale brick exterior face and a concrete masonry unit interior face. Because the structural loads are supported by the reinforced concrete frame, the masonry wall is taken as an in-fill wall and is not expected to be reinforced for vertical or flexural loads. However, reinforcement is

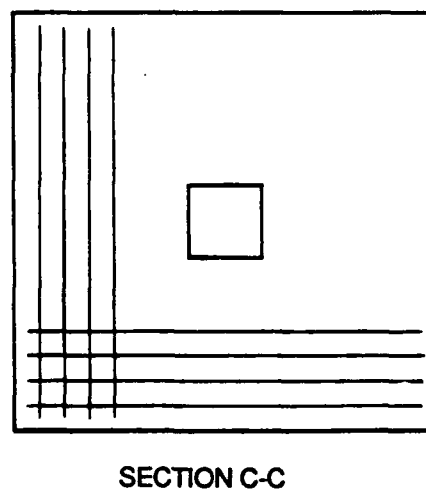
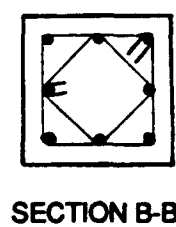
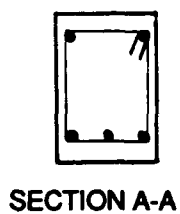
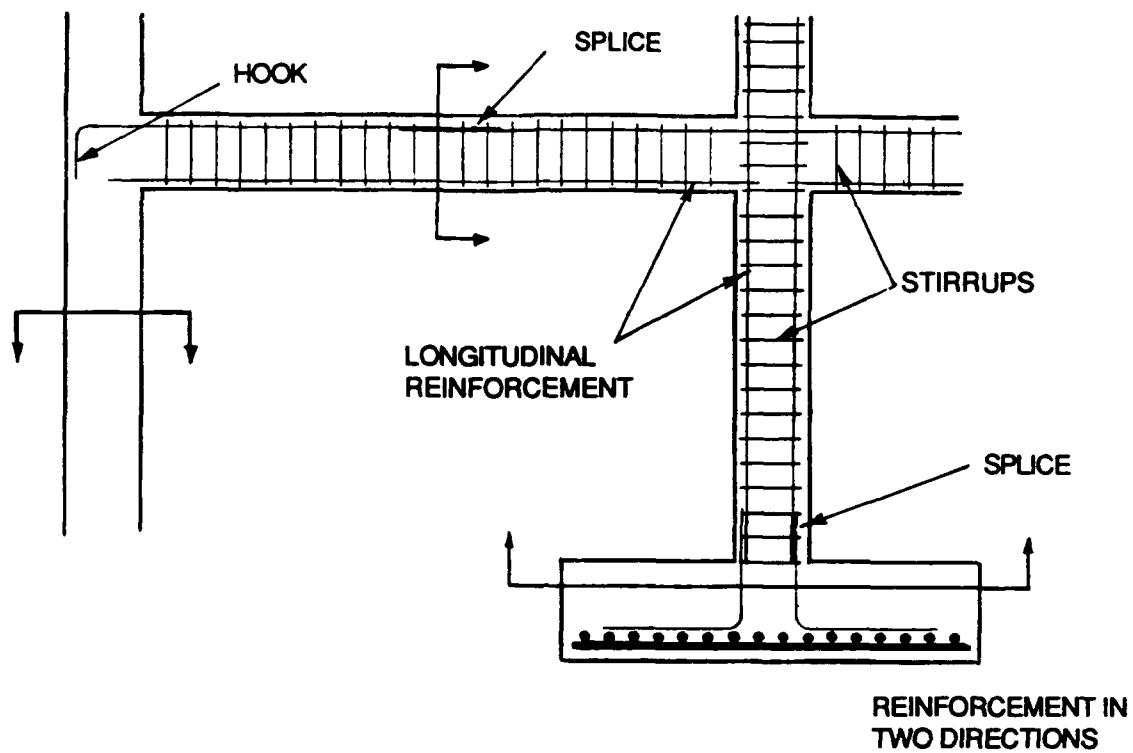


Figure 1. Typical Concrete Frame Details

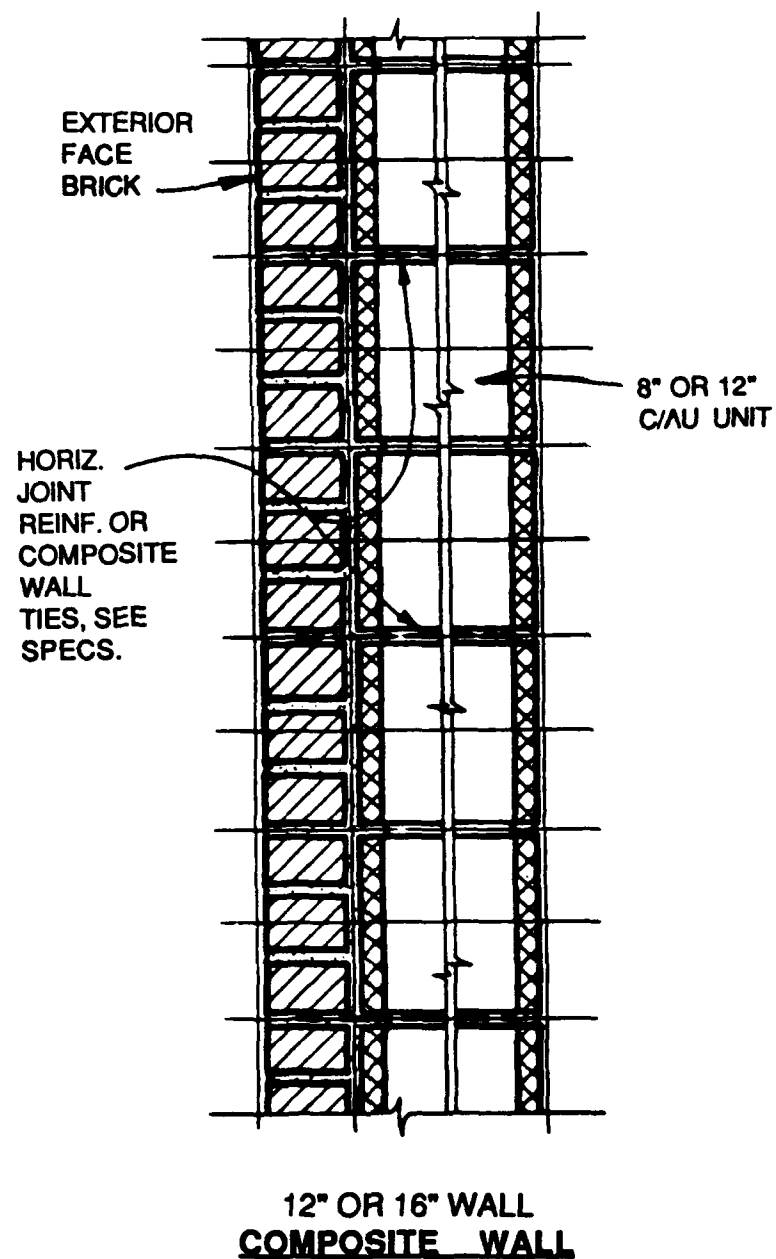


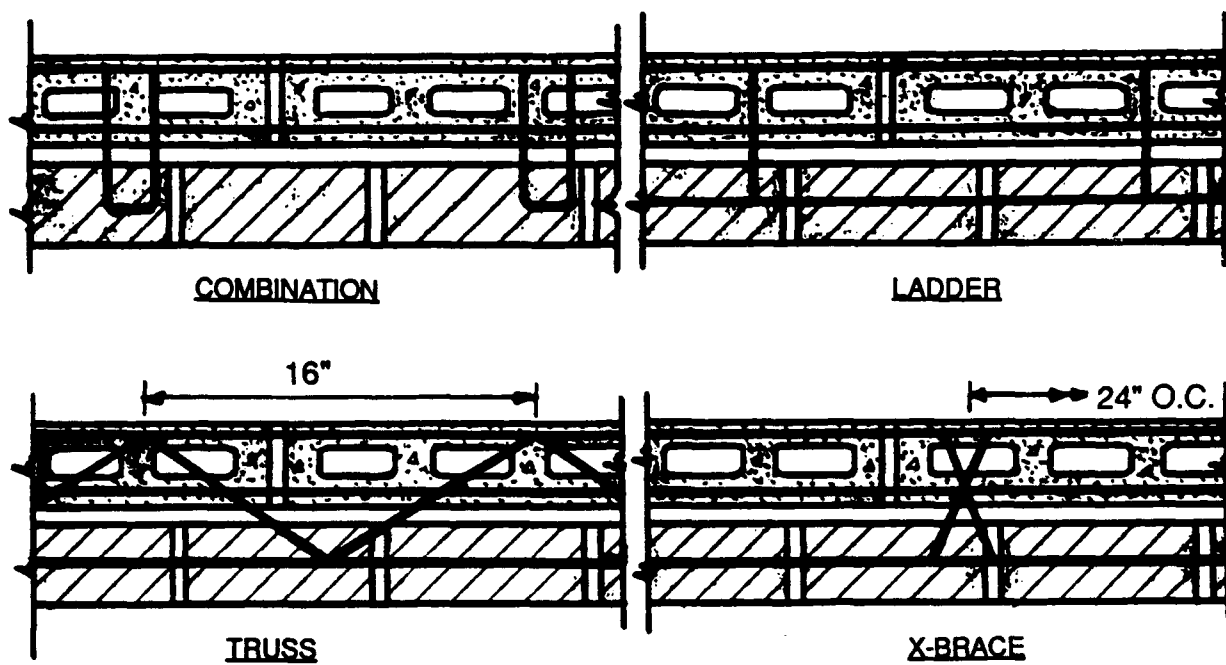
Figure 2. Modular Masonry Coursing, Composite and Cavity Walls (Reference 2b)

expected to be present for joining the two wythes and providing crack control. Crack control in nonload-bearing composite masonry walls is accomplished with control joints and joint reinforcement, and bond beams. The recommended control joint spacing in composite walls is 35 feet for nonreinforced concrete masonry backup. Horizontal joint reinforcement is used to control cracking and allows greater spacing between control joints. Typical steel patterns for horizontal joint reinforcements are shown in Figure 3. Recommended control joint spacings for various vertical spacings of horizontal reinforcement spacings are given in Table 2.

TABLE 2. RECOMMENDED CONTROL JOINT SPACING AND LOCATION
(REFERENCE 2B)

Recommended Control Joint Spacing		
Vertical Spacing of Joint Reinforcement (in.) (2-#9 Wires)	Maximum Spacing of Control Joints (ft.) ⁽¹⁾	
	Exterior Walls	Interior Walls
None	18	22
16	24	30
8	30	38
⁽¹⁾ Based on moisture-controlled type I concrete masonry (ASTM C 90). Type II units, which have no moisture control, shall not be used. Maximum linear shrinkage potential 0.065 percent.		
Recommended control joint locations		
a. At regular intervals as noted in table. b. At changes in wall height or thickness. c. Near wall intersections in "L", "T", and "U"-shaped buildings. d. At points of stress concentration.		

The amount and type of horizontal joint reinforcement is specified by the designer. Wall tie capacities of horizontal joint reinforcing for a 20 pounds-per-square-foot lateral load are given in Table 3. Bond beams can be used in lieu of horizontal joint reinforcement. Recommendations for bond beam equivalences are shown in Table 4.



COMPOSITE WALLS

CLAY OR SHALE BRICK
EXTERIOR WYTHER

Figure 3. Horizontal Joint Reinforcement for Composite Walls (Reference 2b)

TABLE 3. WALL TIE CAPACITY OF HORIZONTAL JOINT REINFORCING
(REFERENCE 2B)

Wall tie capacity of horizontal joint reinforcement 20 psf LATERAL LOAD				
Cross Wire Size	Wall Tie 3/16-inch Crimped	Ladder 3/16-inch Crimped	Truss Type No. 9 Crimped	Cross Braced (X Brace) 3/16-inch Weld at Center
Spacing (vert. and horiz.)(in.)	16 x 32	16 x 16	16 x 16	16 x 24
Area (sq. ft.)	3.56	1.78	1.78	2.67
P @ 20 psf (lb.)	71.2	35.6	35.6	53.4
88% P (lb.) ⁽¹⁾	62.7	31.2	31.2	47.0
Ultimate load from test data (psf) ⁽¹⁾	96	85	106	140
Factor of Safety	1.53	2.72	3.44	3.00
⁽¹⁾ The maximum transfer of lateral loading to the inner wythe is 88% as noted in chapter 6. Therefore, for a 20 psf wind load, a rectangular tie will transfer 20 psf x 3.56 sq. ft. x 88% = 62.7 lb. The maximum loads were obtained from Table 1 in Reference 53.				

A cross-sectional view of a bond beam in a composite wall is shown in Figure 4. Special "U"-shaped blocks are used to construct bond beams as continuous horizontal courses of concrete block, filled with concrete and containing continuous horizontal reinforcement between control joints. Conventional methods are used to design the composite masonry walls and guidelines for determining section properties and allowable stresses are given in Reference 2b.

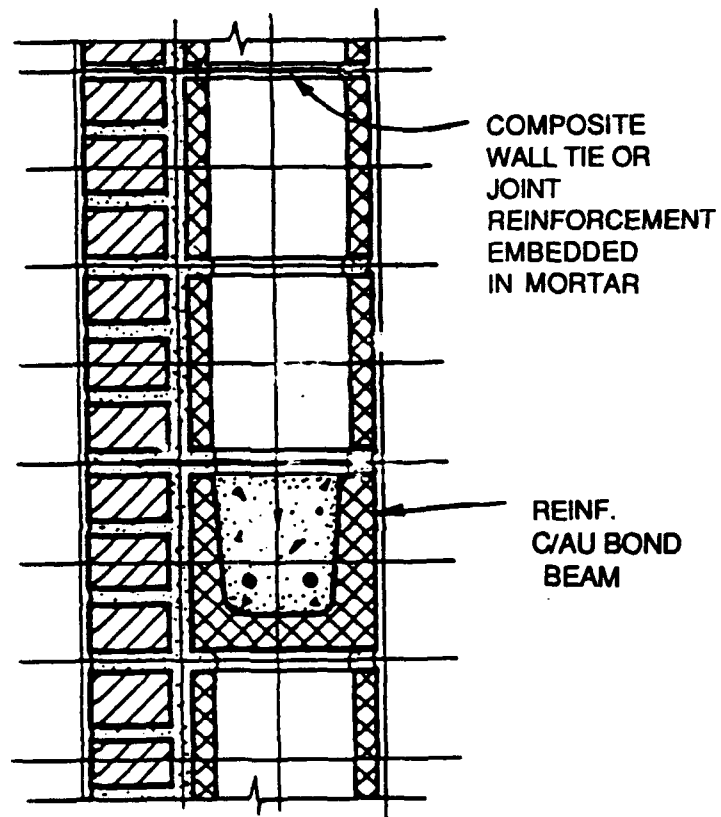
For this study, the typical or predominant structural system is considered to include a composite masonry wall similar to that shown in Figure 5. Specific details and materials used in constructing the wall depends on local materials and construction practices.

TABLE 4. BOND BEAM EQUIVALENCE
(Reference 2b)

Bond Beam Equivalence			
Equivalent Jt. Reinf. Spacing		Bond Beam Reinforcing and Vertical Spacing	
	2-#4	2-#5	2-#6
16"	5'-4"	8'-0"	8'-0"
8"	2'-8"	4'-8"	6'-8"

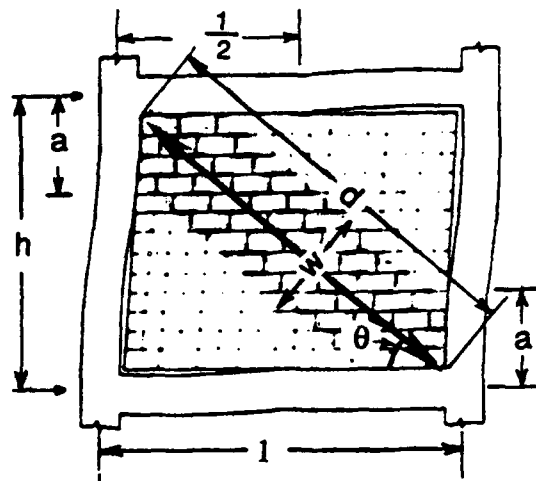
Cold drawn joint reinforcement wires have a minimum yield strength of 65,000 psi and a working stress of 30,000 psi. ASTM A 615 Grade 40 reinforcing steel has a minimum yield point of 40,000 psi and a working stress of 20,000 psi. Because of high bond characteristics, joint reinforcement prevents visible cracks until it yields. The area of a #9 wire is 0.0173 in. and is 30,000/20,000 more effective than the A 615 steel. The use of bond beams introduces a significant strip of wet concrete in the wall and some wetting of the masonry below the bond beam. For these reasons, the effectiveness calculated below was reduced approximately one-third. On this basis, bond beams with two #4 bars should be spaced at 32 inches to replace joint reinforcement in every course. Spacing should not exceed 8 ft. 0 in. Therefore, the ratio of effectiveness is calculated as follows:

For 2-#4 $4.40/2 \times 0.0173 \times 40/65 = 6.2$ times $2/3 = 4$ bed joints 2-#5 $5.62/0.035 \times 40/65 = 10.9$ times $2/3 = 7$ bed joints 2-#6 $6.88/0.035 \times 40/65 = 15.5$ times $2/3 = 10$ bed joints

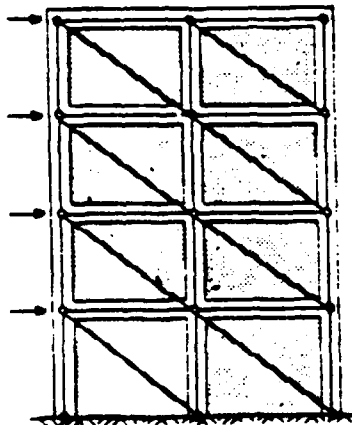


BRICK-FACED
COMPOSITE

Figure 4. Bond Beams in Masonry Walls (Reference 2b)



a) LINE OF ACTION, COMPRESSION STRUT,
IN A WALL PANEL



b) LINES OF COMPRESSIVE ACTION IN A
MULTIPLE PANEL WALL

Figure 5. Typical Masonry Wall

SECTION III

DEFINITION OF DAMAGE - CONVENTIONAL WEAPONS

A. TYPICAL DAMAGE

Typical damage which may be encountered can be described in two broad categories: 1) local damage; and 2) global damage. Local damage will occur to elements within the structural system and will probably be the result of projectile impact or nearby detonations of high-explosive charges too small to destroy the entire structure. Global damage can occur from high-explosive charges large enough to create extensive damage and loading from the blast. The extent of damage will decrease with distance of the charge from the structure. Global damage can also occur when loss of elements from local damage causes progressive collapse of the structure or part of the structure due to inadequate support. One aim of the program was to identify and define typical damage which can be expected for predominant structural types.

Damage level identification is important to:

- Determine the required extent of structural element repair. Repairs can be made at various levels including minor repairs to maintain function and protect occupants from the environment, intermediate repairs to restore protection for future events, and major repairs to stabilize the structure and to prevent progressive collapse of the structural system.
- Develop appropriate repair techniques which are expedient and provide the required strength or stabilization.
- Develop and provide appropriate training for repair crews.
- Stockpile suitable materials and maintain equipment used in the repair process.
- Assess the residual strength and protection level of repaired facilities.

Typical damage will be defined by:

- Describing the types of loadings which can be expected from conventional weapons;
- Presenting examples of bomb damage to protective structures;
- Presenting examples of bomb-damaged structures, found in available open literature, similar in construction to the predominant structural systems found for critical Air Force facilities.

B. LOADINGS FROM CONVENTIONAL WEAPONS

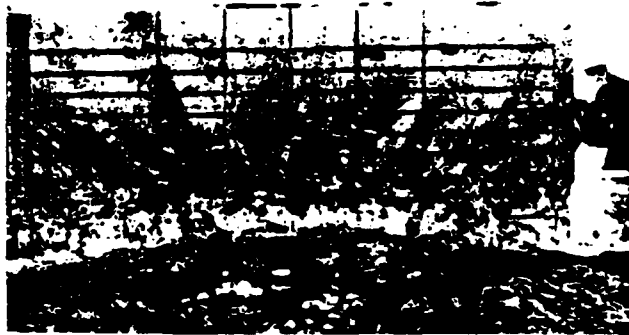
Blast damage to facilities can result from bombs detonating near to or in contact with structural elements. Detonations near a facility propagate a blast through air or soil, depending upon the location of structure (aboveground or buried) and the position of the detonation. Reference 4 provides prediction methods for determining loads on structures from explosion and fragment loadings. Other reports and papers discuss loadings from buried explosions (References 5 and 6). Generally, detonations in air load the structure with both overpressure from the rapid release of chemical energy and the impact of numerous solid fragments. Detonations at long distances impose uniform blast loads on the structure and fragment velocities decreased with air drag. The entire structure may be involved in the response depending on the duration of the loading. Detonations very near or in contact with the structure impose intense loadings (thousands or tens of thousands of psi) over a limited region of the surface of the structure. Pressure intensities decrease rapidly with distance.

Fragments add to the impulsive loading on the structure and can penetrate the structural element or deteriorate member strength by causing spalling of the concrete surface. Reference 7 contains excellent examples of damage to a concrete wall subjected to blast and fragment loading. Figure 6 (from Reference 7) shows blast and impact damage to the exterior face of the wall and spall damage on the wall interior. Spalling results from tensile stresses produced by the reflection of the stress wave traveling through the wall section.

The effect of weapon casing fragments for detonations close to the structure can be seen in Figure 7 (Reference 8). Although the two charges were of similar weight and distance, the bare charge produced only minor cracking while the cased charge completely destroyed the concrete wall.

C. EXAMPLES OF DAMAGE TO STRUCTURES SIMILAR TO THE PREDOMINANT STRUCTURE

A search of the open literature yielded few references on conventional weapon damage to structures similar to the selected critical structure. Incident summary reports from World War II were found which described actual bomb damage to reinforced concrete frame and masonry wall structures. Some information was found on blast and other dynamic lateral loads on masonry walls. There are probably two main reasons for the paucity of applicable information: (1) weapon effects data are not usually found in the open literature; and (2) most of the current research is performed in relation to protective, or hardened structures. It is important to note again that many critical facilities may not be designed as protective structures.



(a) DAMAGE TO AN EXTERIOR WALL FROM BLAST AND
FRAGMENT LOADING

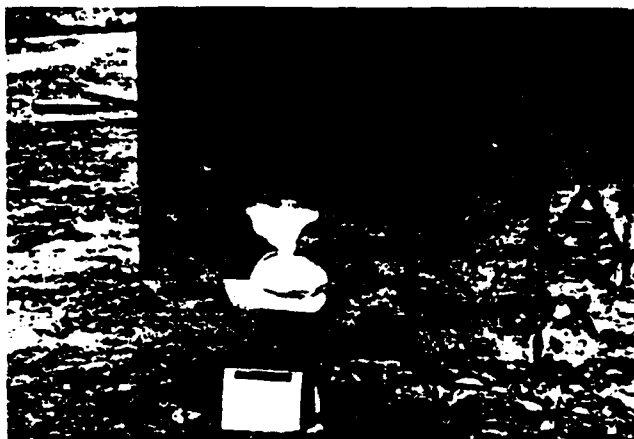


(b) SPALLING DAMAGE TO AN INTERIOR WALL SURFACE

Figure 6. Damage to Reinforced Concrete Walls (Reference 7)

BEFORE TEST

Bare Charge: 10 kg TNT
Distance $r = 0.5$ m
Wall Thickness $t = 0.3$ m

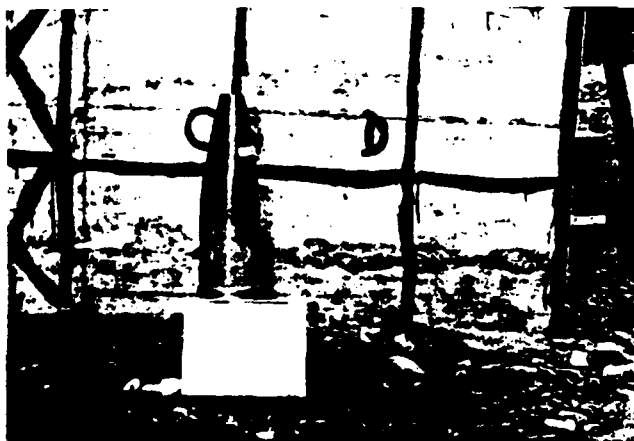


AFTER TEST

Back of exposed wall shows minor cracks



Cased Charge: 15.5 cm (6.85 kg TNT)
Distance $r = 0.5$ m
Wall Thickness $t = 0.3$ m



Exposed wall completely destroyed



Figure 7. Visual Comparison of the Effects of Bare and Cased Charges (Reference 8)

1. Reinforced Concrete Frame

The damage to a multistory, reinforced concrete frame apartment building struck by a 500-kg German bomb is shown in Figure 8 (Reference 9). Although the bomb detonated inside the structure, damage to the walls and columns illustrate the kinds of damage which can be expected from bombs detonating near a reinforced concrete frame structure with masonry walls. The description was taken from an incident summary report of damage surveys in London during World War II. The 500-kg general purpose bomb was determined to contain approximately 550 pounds of explosive and detonated less than 10 feet inside the exterior wall of the building between the seventh and eighth floors. Several reinforced concrete columns completely disintegrated. Other columns were broken up, bowed, or badly damaged. Walls were blown out for several floors and bays in each direction. The authors commented that some of the excessive column damage was probably due to bonding of partitions to columns. Such connections transmitted forces from partitions to columns. Some damage from bomb fragments was found on other buildings near the apartment building attacked. Peak overpressures of several thousand PFI on the structural elements from 550 pounds of explosives 10 feet away can be expected. Masonry walls cannot survive such extreme loads and are completely destroyed.

Data from the war damage reports were compiled and used to prepare blast damage curves for concrete columns as shown in Figure 9. Three categories of column damage are identified: (1) blown out or severed; (2) damaged beyond repair; and (3) not damaged critically. The broad band shown in Figure 9 represents a range of reasonable variations between damaged beyond repair and not damaged critically. All three categories of damage are in Figure 8. The two columns in the right foreground of Figure 8 (View B) are obviously no longer carrying load and would require major repairs or replacement to restore their original strength. The column shown in the left foreground of Figure 8 (View B) is badly deformed, but could regain some of its original load-carrying capabilities with expedient repair techniques. Other columns in the background of Figure 8 appear to be undamaged.

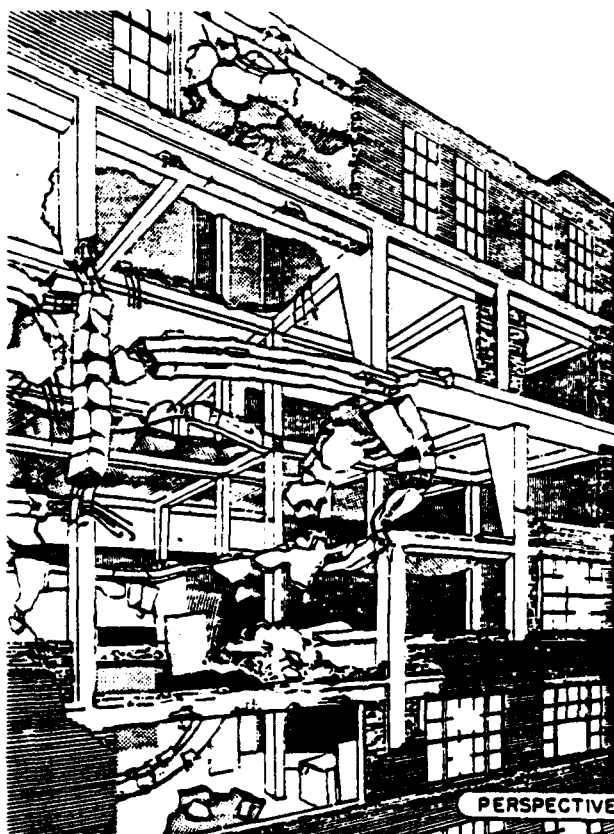
Columns which require repair after attack generally fall within the range between Categories 2 and 3. An example given in Reference 9 shows that a square column with a depth one-tenth of the height can be expected to be blown out or severed by a 1000-pound bomb (approximately 538 pounds of explosive) at a distance of 6 feet. The same bomb will damage the column beyond repair at distances up to about 16 to 22 feet. However, some variation of column damage is expected within the 16- to 22- foot range and could require expedient repair techniques to restore operation of the facility. Guidelines will be needed for determining the extent of damage to columns to decide whether repairs are needed or will be effective.

INCIDENT SUMMARY

MULTISTORY, REINFORCED CONCRETE FRAME
APARTMENT BUILDING STRUCK BY A 1100 POUND G.P. BOMB

C 4100
MS-RCF
INCIDENT ONE

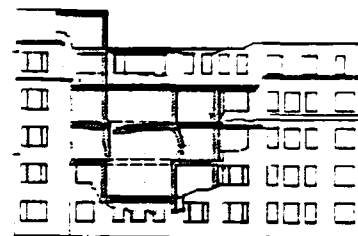
(GERMAN 500 Kg S.C. chg. wt 50 %)



PERSPECTIVE VIEW A

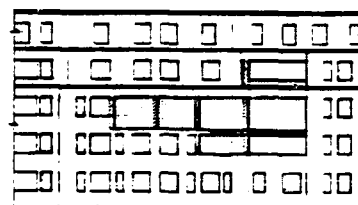
ELEVATION A

roof
ninth
eighth
seventh
sixth
fifth



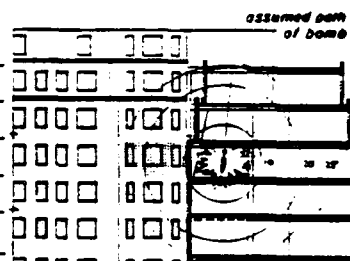
ELEVATION B

roof
ninth
eighth
seventh
sixth
fifth

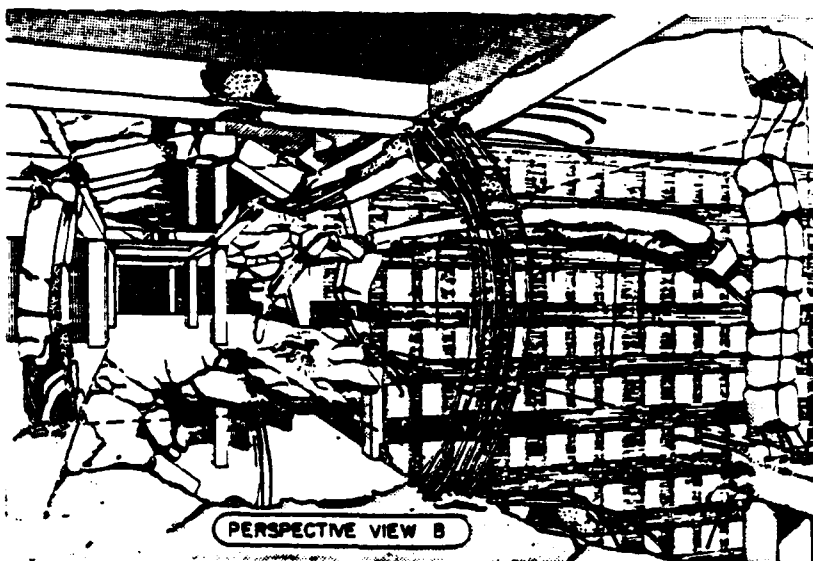


SECTION AA

roof
ninth
eighth
seventh
sixth
fifth



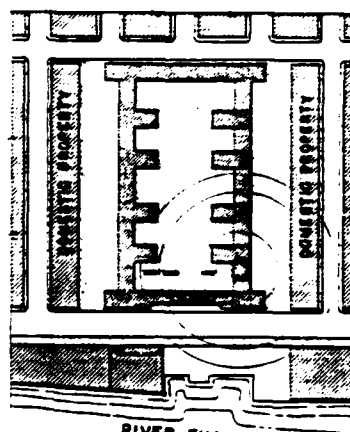
assumed path
of bomb



PERSPECTIVE VIEW B

SITE PLAN

SCALE 1" = 100'



RIVER THAMES

Figure 8. Bomb Damage to a Reinforced Concrete Frame (Reference 9)

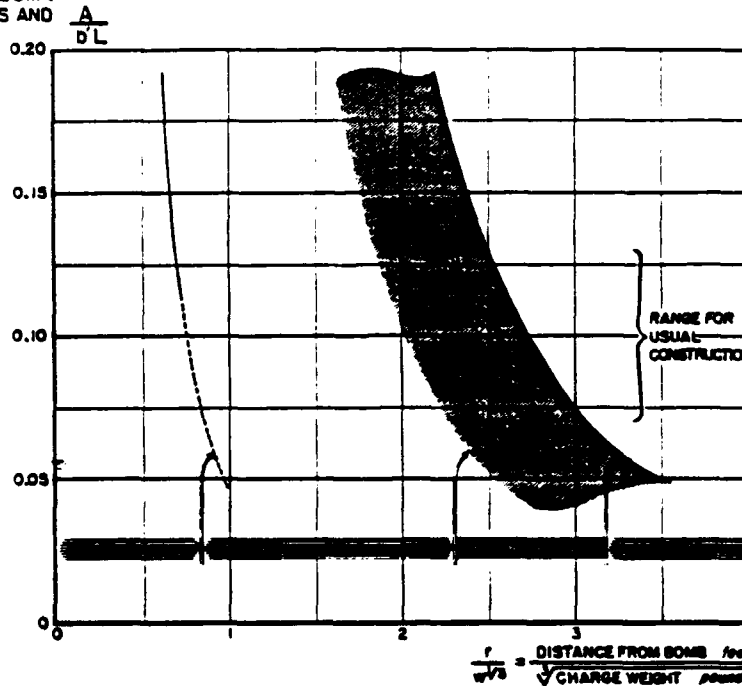
WEAPON DATA



BLAST DAMAGE TO CONCRETE COLUMNS

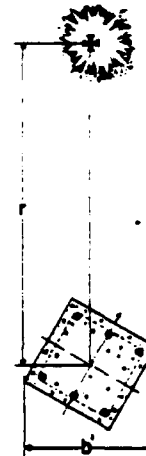
DATA PREPARED FROM INFORMATION GIVEN IN BRITISH RE 4 DAMAGE REPORTS AND DATA COMPILATIONS

INDEX OF COLUMN
SLENDERNESS AND
ASPECT



DEFINITIONS

A - area of cross-section, *sq. inches*
L - clear height of column, *inches*
b - horizontal dimension of column exposed to blast, *inches*
r - distance from center of column to center of explosion, *feet*
w - charge weight of explosive, *pounds*



The curves define approximately the limiting distances from various bombs at which concrete columns will be damaged by blast in different ways - blown out or severed, damaged beyond repair, or not damaged critically. The width of the band is computed on the assumption of reasonable variations in the shape of a cross-section designed to carry a given load. The column index, plotted vertically, is the ratio of the cross-sectional area of the column to the area exposed to the blast. This area is the product of the length of the column and its projected width on a line perpendicular to the line joining the column to the bomb. The index is thus approximately equal to the ratio of the depth of the column to its length, i.e. large values of the index correspond to stubby columns and small values to slender columns.

The columns are assumed to have no partitions or walls attached, and to be exposed to blast on all sides. If there are partitions attached to the columns the radius of damage is likely to be greater, since part of the force on the attached elements is transmitted to the columns. Further, in such cases the blast wave cannot so readily make its way around the column to back it up from behind. On the other hand, where the column is supported by a wall or partition approximately in line with the blast wave, the radius of damage should be considerably smaller.

The chart does not contemplate the destruction of the columns in the lowest story of a building by undermining of the footings. Such an action may cause destruction at a value of $r/\sqrt{W}^{1/3}$ of about 3. Neither does the chart consider the action of blast in a relatively confined space, which may cause tensile failure of the column by so-called "uplift" at a greater distance than shown by the chart.

For charge weights less than about 200 pounds, the radius of damage appears to be less than that given by the chart.

EXAMPLE: Given a building of average R/C frame construction having square columns with depth 1/10 the height. Then for blast perpendicular to the face of the column, the column index will be 0.10. It may be expected that such a column will be blown out or severed by a 1000-lb G.P. AN-M44 bomb at distances up to about 6 feet; the same bomb will damage the column beyond repair at distances up to about 16 to 22 feet.

Figure 9. Blast Damage Curves for Concrete Columns (Reference 9)

2. Masonry Walls

The blast resistance of a variety of masonry wall panels was studied experimentally and is reported in Reference 10. Although the blast loads were designed to simulate nuclear weapon loadings at large distances, the response modes of the masonry wall panels were of the same type as can be expected from conventional weapon overpressures for large distances or large incidence angles. A variety of wall configurations and mounting techniques were tested. Tests included load-bearing, curtain, infill, and solid walls. Some configurations included walls with doors and windows. The majority of the tests were performed on walls supported on two edges and four edges. Typical response modes are illustrated in Figures 10 and 11.

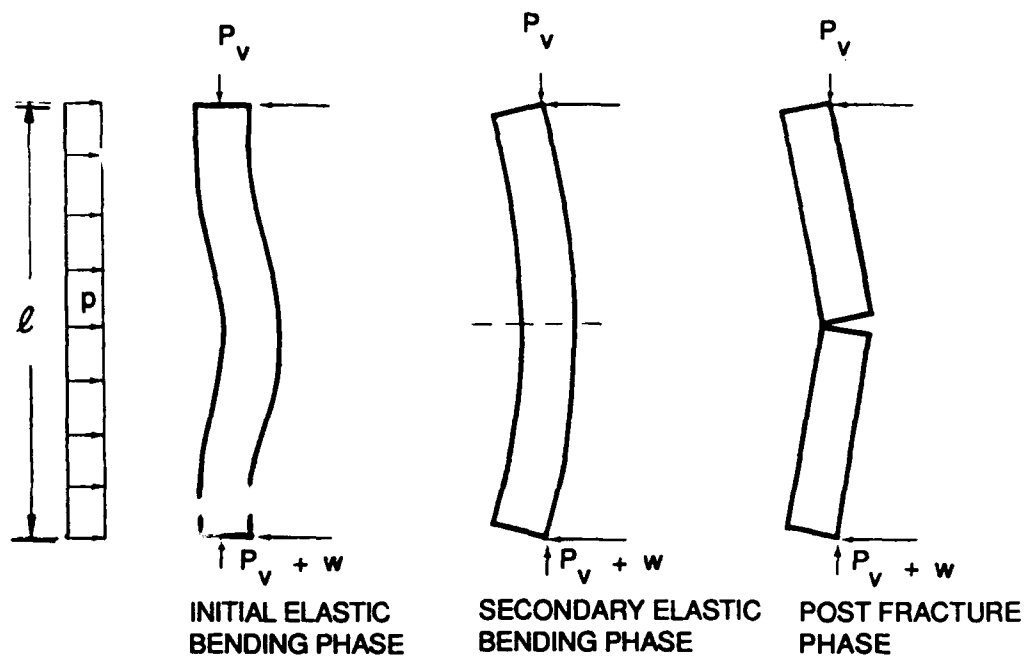
Actual response and failure loads are affected by the rigidity of the supports and the presence of openings such as windows or doors. The least resistance to blast loads is provided by wall elements acting as simply supported beams with no restriction to lateral motion at two edges. Walls supported on four edges offer more blast resistance because arching action (resistances of wall flexure from in-plane forces) can occur.

D. COMPARISON OF CONVENTIONAL WEAPON AND EARTHQUAKE DAMAGE

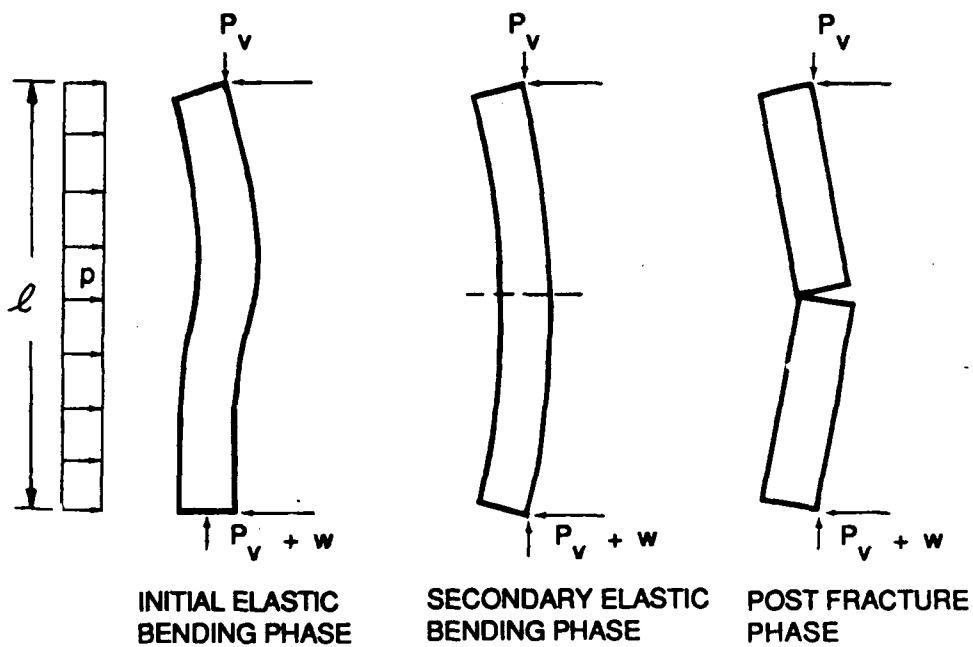
Failure mechanisms under earthquake loads are quite different from those due to blast loads. However, the visible damage to structural elements can be similar. Earthquake damage is due to low frequency ground motions. The ground motions can be from any direction with respect to the structure and structural elements fail when their inertial loadings exceed material strengths. For structural columns, inertial masses of the structure can be considered as lumped at the ends of the columns which means the primary mode of response will be relative movement of the individual floors resulting in a general sidesway deformation of the structure. Damage to concrete frames often is seen as diagonal shear cracks along the height of the columns similar to the damage shown in Figure 12.

Excessive differential displacements between the top and bottom of the columns can lead to eccentric axial loadings that produce frame stability problems. The cyclic nature of earthquake loadings can cause several cycles of structural response leading to rapid deterioration of the damaged elements.

Masonry walls have little tolerance to lateral cyclic loads of large deformation and may collapse in early cycles of loading. In-plane loadings of masonry walls result in diagonal shear cracks across the face of the wall, as shown in Figure 13. Roofs are designed for out-of-plane loadings and are not as subject to earthquake damage as vertical walls which are usually designed primarily for axial loading or act nonstructural element. Damage to the roof will depend on the amount of damage to supporting members under large lateral deformations.



(a) FIXED-FIXED WALLS



(b) FIXED-pin WALLS

Figure 10. Response of Walls Supported on Two Opposite Edges to blast (Reference 10)

STEEL PERIMETER MEMBERS

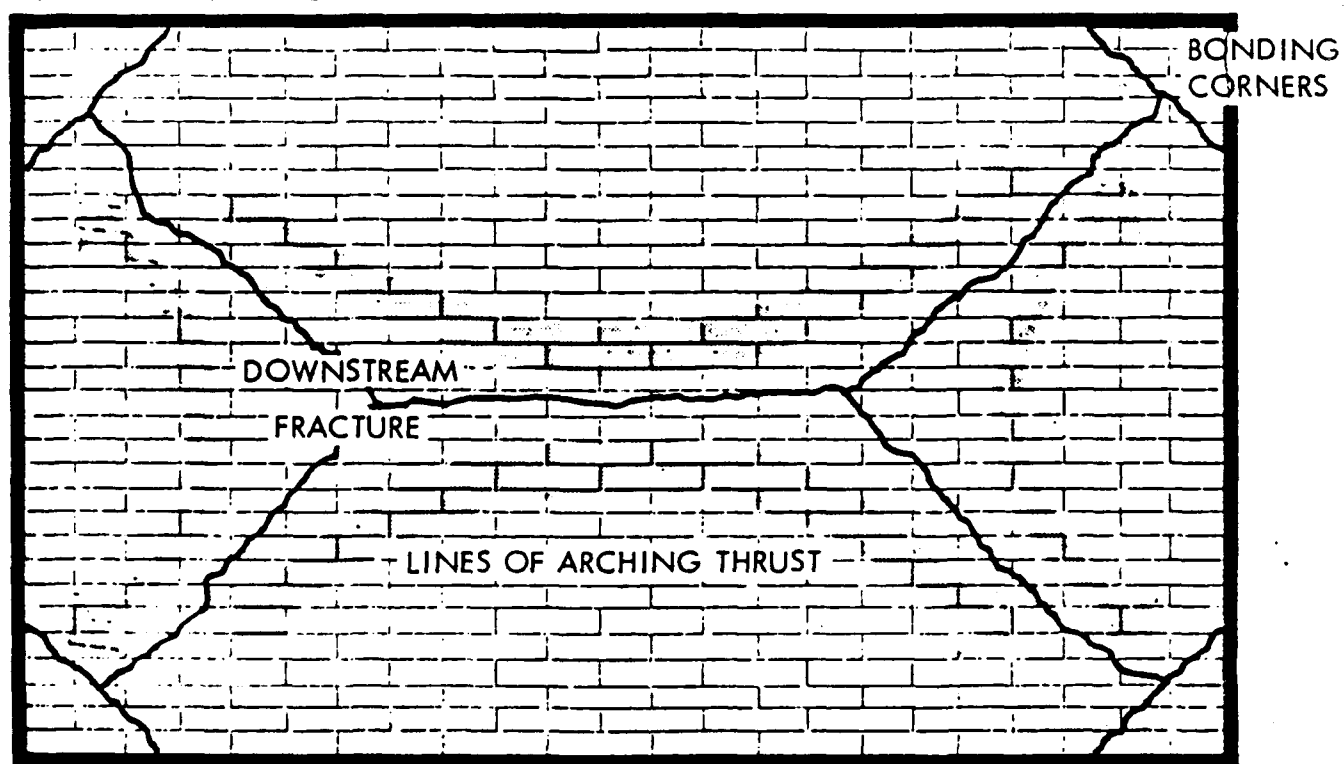


Figure 11. Effect of Steel Perimeter Frame on Crack Pattern (Reference 10)

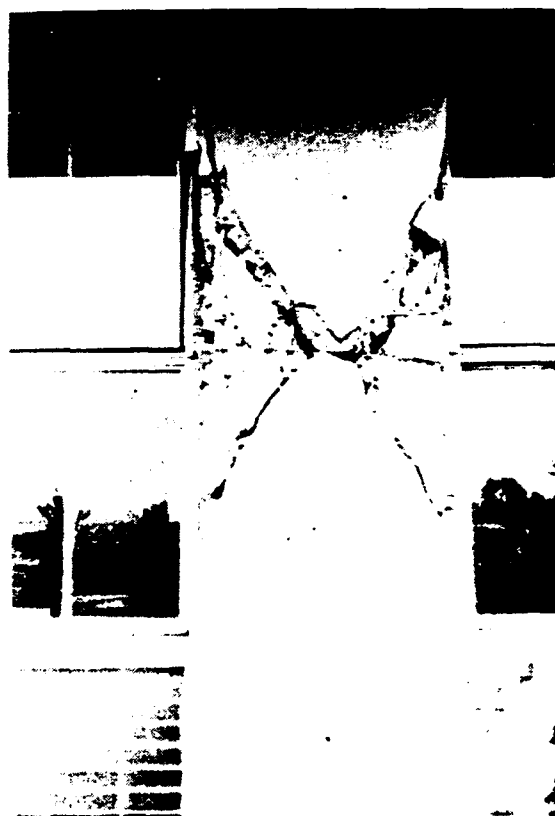


Figure 12. Column Shear Damage From Earthquake Effects

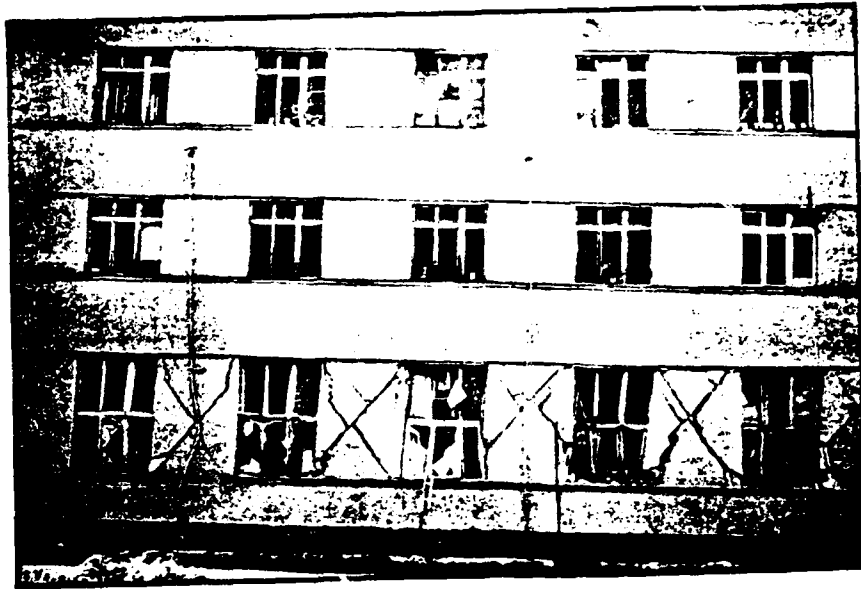


Figure 13. Diagonal Shear Cracking in Masonry Walls From Earthquake Motions

Blast damage occurs due to the excessive overpressure from the explosion or the forces from the fragments impacting the structure. Areas of the structure subjected to the distributed overpressure or fragment loadings will transmit the loads to supporting elements of the structure. Once the loaded element fails, the dynamic forces cannot be transmitted fully to supporting elements. Damage will be restricted to the failed element. If the element continues to transmit forces to other parts of the structure, the degree of damage will depend on the strengths of other structural elements and the direction and distance from the blast. Columns or beams may be damaged along their entire length or may suffer localized damage from high intensity loads over a small area. Fragments or missiles impacting the reinforced concrete frame members can cause spalling of the concrete and loss of material. If the extent of the material loss is significant, the strength and ductility of the member can be affected. If the frame member responds in a shear mode, i.e., the flexural capacity is greater than the shear capacity under blast loading, the damage will be similar to that shown in Figure 12. Similar damage can be seen in beams near the supports. If the column or beam responds in flexure, i.e. the shear capacity is greater than the flexural capacity under blast loading, the damage of the support will be similar to the damage shown in Figure 14

Damage to masonry walls during blast loading is primarily from overpressures normal to the wall, but lateral distortions of the frame in the plane of the walls can cause diagonal shear cracking similar to earthquake damage. As shown in Figs. 10 and 11, masonry walls damaged from lateral blast loads can remain in place with crack patterns determined by the nature of the loads and boundary conditions.

Slab systems transfer load to supporting elements in much the same way described for walls. However, slab elements generally are not involved in a major way in an earthquake, and damage is usually relatively light even under large deformations. However, somewhat greater slab damage would be expected from the effects of a detonation within the structure.

E. STRUCTURAL DAMAGE CATEGORIES

Structural damage from conventional weapon loading can be categorized by structural element type, extent of damage, and degree of damage. Categorizing structural damage helps to determine the possible functional failures of the structural system and identify proper repair measures. Possible functional failures for various combinations of structural elements (for the selected critical structure) and degree of damage are shown in Table 5. Degrees of damage have been given for local and global considerations. The following definitions are suggested:

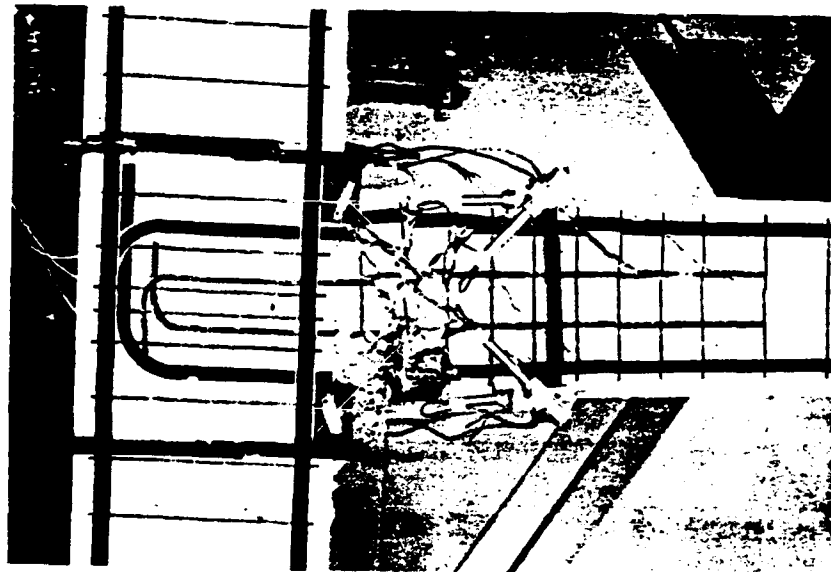


Figure 14. Flexural Hinging in a Reinforced Concrete Beam

TABLE 5. PROPOSED DAMAGE CATEGORIES

Structural Element	Local*			Global*		
	Minor	Intermediate	Major	Minor	Intermediate	Major
Frame (Reinforced Concrete)						
Column	0	2	3	0	3	3
Beam - Shear	1	2	3	1	3	3
- Flexure	0	1	2	0	2	3
Slabs	0	1	2	0	1	2
Wall (Nonloadbearing Masonry)						
One-Way Support	1	3	3	1	3	3
Two-Way Support	0	2	3	0	3	3
Roof (Conventional)	0	2	3	0	2	3

* 0 - No loss of structural function

1 - Reduced level of safety for occupants (falling debris); no loss of structural function

2 - Loss of strength but occupancy possible with temporary repairs or shoring

3 - Loss of stability of structure or portion thereof; structure not usable without major repair

- **Local Damage** - loss of a structural element or part of an element which probably results from concentrated loading on the element and missile impact or nearby explosions. Examples of local damage include holes in the masonry wall or loss of concrete over a small portion of a reinforced concrete member.
- **Global Damage** - Structural damage over a large area may involve several structural members. Loading over a large area of the structure is evident.

Progressive collapse due to loss of one or more supporting members may also occur.

Degrees of damage are defined as:

- **Minor** - Slight cracking with no observable permanent deformations of the structural element. Not considered to be a problem for reinforced concrete members, but can lead to undesirable weaknesses in masonry walls.
- **Intermediate** - Significant cracking with observable permanent deformations of the structural element. The load carrying capacity and stiffness of the structural element may be reduced and any subsequent overloading may cause widespread damage or collapse.
- **Major** - Extensive cracking or loss of material with gross permanent local or overall deformations. The strength and stiffness of the element or structure are reduced to dangerously low levels and failure under dead loads is possible due to general instability of the system.

1. Functional Failure Due to Local Damage

a. Minor Damage

Masonry walls with one-way support are the only structural elements whose safety is degraded by minor damage. Because the walls have little resistance to lateral loads and no redundancy of support, they may collapse once their generally low material tensile strength has been exceeded. Masonry walls with support at all edges are more likely to develop arching (in-plane compressive forces) and are less likely to collapse. The reinforced elements provide ductility against collapse.

b. Intermediate Damage

Columns with observable permanent deformations may be subject to eccentric loadings for which they have not been designed. Beams are usually designed with enough ductility to support large flexural deformations. However, if well-deformed diagonal shear cracks are evident, the load-carrying capacity of the floor system may be suspect. Masonry walls have virtually no ductility and are subject to strength and stability loss under large deformations. Slabs with supports on opposite edges only are less redundant than those with supports on all edges. The performance of roof systems is highly variable. Conventional roofing systems should not be expected to provide resistance to loadings after significant deformations have been observed.

c. Major Damage

When significant material loss has occurred, structural elements may become unstable and collapse. Columns and walls under compressive dead loading cannot continue to sustain load if material loss is extensive. Beams and slabs designed to reach flexural failure can sustain extremely large deformations without significant loss of strength. Beams exhibiting major shear distress, such as wide cracks and concentrated shear deformations, are likely to be relatively unstable and could fail under small additional load or deformation.

2. Functional Failures due to Global Damage

Minor Damage - The cumulative effect of minor damages over several structural elements is not expected to result in significant functional losses except for the case when large areas of masonry walls are cracked and could collapse.

Intermediate Damage - Permanent deformations to several columns or over large wall areas could result in eccentric loadings which could lead to collapse of large portions of the structure. Flexural failures of several beams or large areas of the roof or of floor slabs could result in

reducing the strength of the structure to subsequent attack, but probably would not lead to imminent collapse of the structure.

Major Damage - Extensive damage to any of the element types over a large area interrupts the system integrity and can lead to instability of the entire system. Progressive collapse should be considered when large portions of the structure have suffered major damage.

SECTION IV

REPAIR TECHNIQUES

A. INTRODUCTION

An overview of the different possibilities for repair of a damaged facility will be presented. Repair techniques must be carefully selected to restore the structure to its intended function. Three main aspects should be considered in any repair project: quality, cost, and time. These variables are closely interrelated, the faster the operational level of a structure is restored, higher costs and lower quality can be expected. Time strongly influences the selection of any repair process. Repair is defined as the procedure(s) carried out to restore sufficient load-carrying capacity and stability of a structure or element so that safety of the occupants is assured and operations within can continue. Normally the restoration of the original level of resistance of any element can be achieved; however, the same is not true for the element stiffness. Very fine cracks in the concrete or masonry are impossible to repair completely. If the element is repaired to recover its stiffness, it generally will be strengthened as well. In emergency situations, the repair of nonstructural elements such as partitions and ceilings consists of restoring their function as fast as possible by any means.

In the following sections, materials and construction techniques will be discussed as they apply to all types of repair procedures. The description of repair procedures is divided into three categories: (1) Basic techniques which involve temporary measures to stabilize the damaged structure, but in many cases may become permanent repair solutions; (2) Intermediate techniques which involve restoration of the damage elements; and (3) Advanced techniques which require considerable time and effort, and may involve development of added parallel load-carrying elements or systems. Any of the three levels of repair could be used to return a damaged structure to service. The level of damage (Table 5) and the time and personnel available to return the structure to service will dictate the sophistication of the repair technique selected. The aspect of time and personnel considerations will be discussed in Section V.

The summary of repair techniques was based on an extensive review of the literature in natural disaster mitigation, particularly earthquake engineering. However, this relatively new and growing area of design and construction is in a state of flux. New work is constantly being reported and it is virtually impossible to include or mention all studies related to repair. The report is concentrated on those reports and techniques which best appear to meet the criteria of quality, cost, and time.

B. MATERIALS AND CONSTRUCTION TECHNIQUES

1. General Concepts

In the repair and/or strengthening of any structural element, a monolithic behavior between the old and new material must be accomplished for satisfactory behavior of the elements and the structure. In general, any repair material should meet the following guidelines (References 11, 12, 13):

- Be durable and protect reinforcement.
- Be dimensionally stable. Low shrinkage repair materials must be provided to avoid loss of contact between the old and new materials.
- Achieve adequate bond between materials, including bond between steel and concrete. Bond is essential to satisfactory performance.
- Be able to develop resistance at early ages, whenever the need to restore the damage element capacity as soon as possible exists.

To achieve satisfactory behavior of the repaired element, the compressive strength of the new material should be higher than that of the original material. The use of materials of diverse strength must be carefully studied to avoid bond failure and crushing of the contact surface. It is advisable that the repair material properties match relatively well the existing materials uniform structural properties of the repaired element. The elastic moduli and time or temperature effects on the materials must be compatible to avoid problems under high stresses, sustained loads, or temperature changes (References 12, 13, 14).

In the case of repair by the addition of new elements, a proper connection must be provided to adequately transfer forces between new and existing elements without further damage to the structure. The new elements must be anchored and/or attached to provide for development of design capacity.

2. Resins

Resins are used to repair cracks and to anchor or attach new (steel or concrete) elements to concrete and masonry members. Low viscosity resins are used for small width crack injection while higher viscosity resins can be used to fill larger cracks or voids (Reference 15).

Resins are two component systems, resin (epoxy, polyester, acrylic, polyurethane, etc.) and hardener. Both components can be liquid or solid. Once they are mixed, a reaction takes place and hardening of the material can be accomplished within minutes. Normally final resistance is reached after a few hours or days. A large range of properties can be obtained due to the availability of resins with different chemical structure and mixing ratios. Resin compounds are highly sensitive

to the type of filler or aggregate added. In general, the properties, application, preparation, and curing are specified by the manufacture (References 12, 14, and 15).

Attention must be given to the need for a careful selection of the type of resin based on a thorough investigation of the properties of the resin and compatibility with the existing material. Most epoxy components deteriorate with time (shelf life). Field quality control is highly advisable. Resins cannot be used in all environments. The hardening process is suspended at temperatures below about 10°C. Certain epoxies may not cure properly in the presence of moisture. In warm weather, the liberated heat produced by the reaction of both components may increase shrinkage and provoke the loss of bond with the old material (References 14 and 15). Few data are available on the effect of long-term aging on the mechanical properties of epoxy compounds.

The most pertinent properties of epoxy resins include (References 12, 14):

- Excellent bond to concrete, masonry and steel
- High early strength and hardness
- Resistance to acids, alkalies and solvents
- Small expansion coefficients
- Loss of integrity at temperatures above 100°C. Resin must be protected against high temperature variations, especially fire exposure. Test results show that the resistance of epoxy repaired elements is substantially reduced under fire. Strength properties of epoxy compounds deteriorate rapidly at elevated temperatures (Reference 16).
- Limited pot life. Once the resin and the hardener have been mixed, the setting reaction takes place in a short time. The resin must be placed during this period.
- Limited shelf life. The resin changes with storage time and cannot be used if the shelf life specified by the manufacturer has expired.

Detailed descriptions of epoxy resins and their recommended use can be found in manufacturers' specifications. Well-documented information for epoxy use can be found in ACI 503, "Use of Epoxy Compounds With Concrete" (Reference 17).

3. Concrete

a. Cast-in-Place

When new concrete is used to replace damaged parts, to increase the capacity of an element, or to cast new elements, special care must be taken to obtain monolithic behavior. Cast-in-place concrete has been extensively used in repair projects. In many cases, poor behavior has been observed due to volume changes and shrinkage of concrete which destroy contact between the

old and new materials and prevent proper transfer of stress across the contact surface (References 11, 14).

In some cases, concretes appropriate for normal construction cannot be used because of space limitations. Congestion of reinforcement may make access to the repaired zone difficult. The concrete may have to be placed through holes bored in the existing structure. The workability of the mixture is very important and should be carefully considered to achieve adequate consolidation of the concrete. To reduce the shrinkage, the water content of the concrete must be controlled. The largest size of aggregate that will pass between bars or other openings should be used. Admixtures may improve workability. Superplasticizers can be used to increase workability while maintaining a low water/cement ratio (Reference 13).

Preparation techniques for the concrete surfaces are important to assure adequate contact between new and existing materials. Before placement of new concrete, damaged and deteriorated concrete must be mechanically removed. The old concrete surface should be roughened, cleaned and (in some cases) prepared with epoxy or mortar to improve bond of the new concrete with the existing surface (References 11, 12, and 14). The concrete surface should be saturated with water before placing new concrete. The concrete should be cast in small layers and carefully vibrated to distribute the new material without forming voids and/or rock pockets. Special curing procedures may be used to prevent concrete shrinkage due to rapid drying of the surface (References 11, 12, 14, and 18).

Concrete properties can be enhanced by the addition of glass, plastic or steel fibers to the mix. By adding fibers, shrinkage of the mix is reduced, thereby enhancing bond with the existing material (References 13, 15, 19, 20). The fibers will produce a substantial increase in material ductility and the stiffness, compression, shear and tension strengths are increased. However, there are limited field data currently available. Fiber-reinforced concrete shows great potential for repair work.

Well-documented information for the use of reinforced fiber concrete can be found in ACI 544, "State-of-the-Art Report on Fiber Reinforced Concrete" (Reference 21).

Preplaced aggregate concrete, also known as intrusion or grouted concrete, is a placement technique that can be used in the repair process, especially when the access to the repaired zone is difficult or steel reinforcement is very congested. Clean, well graded, coarse aggregate is placed within the forms before pumping mortar with expansive additives into the casting zone. There is no limitation to the size of the aggregate that can be used. The material placed in this way exhibits high bond strength, and thus, is well-suited for repair and restoration work (References 13, 15).

b. Shotcrete

Shotcrete is often used to repair and strengthen concrete or masonry walls and to jacket (encase) different types of concrete elements. Special equipment, as well as trained personnel (nozzlemen), are required in the shotcrete process. The repair job will only be as good as the technician's workmanship and his knowledge of the material properties.

The term shotcrete stands for the procedures used to place fresh concrete or mortars by pneumatically conducting the materials through a hose until they are conveyed (shot) into place at high velocities. The materials can be "wet-mixed" before pumping or supplied dry ("dry-mixed") to the hose and moistened just before they exit the hose. In dry-mixed shotcrete, the water content of the mixture can be reduced to that required for hydration, thus achieving a free shrinkage material that shows better bond to old material than wet-mix shotcrete. Wet-mix requires high water content and the use of superplasticizer to ensure a plastic mix (References 13 and 15). The procedure can be used to place material in vertical, horizontal, diagonal or overhead positions. One of the most important aspects of shotcrete is the reduced need for formwork and the reduction in construction time. It is sometimes difficult to ensure a proper placement of concrete around reinforcement. The operator's (nozzleperson's) abilities are especially important in avoiding poorly consolidated concrete behind reinforcing bars. Steel fibers can be introduced to the shotcrete mix to improve many of its mechanical properties such as deformation capacity and compressive and tension strengths. Corrosion of the fibers can be avoided by coating the surface of the material with a layer of plain shotcrete or grout (Reference 11).

The contact surface must be prepared before the application of shotcrete. Similar measures to those mentioned in the previous section should be observed. Proper reinforcement and curing are necessary to avoid problems with high shrinkage in some shotcrete applications (Reference 11, 12, 14).

In general, shotcrete provides good bond with concrete, masonry and steel. High strength can be obtained with high compaction energy and low water cement ratios.

Shotcreting practices are well-documented in ACI 506-66, "Recommended Practice for Shotcreting" (Reference 22).

c. Resin Concretes

Resin concretes are obtained by substituting resins (epoxy, polyester, acrylic, polyurethane, etc.) for the cement in the concrete mix. Normally, resin concrete is used to replace and patch small areas of damaged concrete. The aggregates used in the mix strongly influence the properties of the concrete. Before using resin concretes, properties must be established to determine compatibility with the old material. As mentioned before for resins, curing needs for resin concrete are specified by the manufacturer (References 11, 12, and 14).

The properties of resin concretes which may impact on repair applications include excellent bond with a clean, dry, concrete surface. To improve bond, a coat of resin may need to be applied to the contact surface before the placement of the resin concrete. The resin concrete will have high tensile, compression and shear strength and early strength gain. Low resistance against heat and carbonation is a drawback. Proper measures should be implemented to protect the material against these effects. The concrete has a lower modulus of elasticity, compared with portland cement concretes (References 12 and 14).

Well-documented information for use of epoxy compounds can be found in ACI 503, "Use of Epoxy Compounds with Concrete" (Reference 17).

d. Polymer Concretes

Polymer concrete are mixtures obtained by replacing part of the cement by polymers in the concrete mix with the purpose of upgrading or enhancing some concrete properties (References 11 and 14). Bonding between old and repair materials is improved. Concrete resistance to chemical attack is enhanced. The material may have low resistance to heat and carbonation. Proper measures should be implemented to protect the material against these effects. Cost and special requirements generally preclude use of polymer concrete for large volume applications. Therefore, the materials are usually used to patch small areas of damaged concrete (Reference 14).

4. Mortars and Grouts

Conventional grout is a mixture of cement, sand and water used to repair cracks and fill voids in damaged concrete or masonry elements. Grouts can be a fluid mix that can be poured or injected. Forms or sealer must be used to contain the mix until it has set. If the water content is high, large shrinkage and cracking between the old and repair materials can be expected. If the formation of cracks is unacceptable, expansive additives and superplasticizers can be added to diminish the contraction and increase workability with lower water content. Grouts are widely used to anchor metal connectors and dowels to concrete elements (References 12, 14).

Cement milk is a water-cement fluid mixture used to inject cracks up to 0.5 mm width in concrete and masonry elements. It is sometimes applied to the contact surface between old and new concrete to enhance bond. For cracks greater than 0.5 mm width, conventional grouts may be considered (Reference 12).

Epoxy grouts can be used whenever high shear force transfers or positive bondings are required. Epoxy grout generally does not shrink. The combination of epoxy with sand results in a material with a higher modulus of elasticity. Other types of special grouts can be obtained by substituting a part of the cement with polymers in the mix to enhance the material strength, bond and shrinkage properties. Epoxy and polymeric grouts can develop full strength at early ages and can be exposed to service conditions in a matter of hours following their application. One typical

application for epoxy grout is the anchorage of metal connectors or dowels to concrete (References 12, 14, and 15).

When voids are large enough, a material known as "dry pack" can be used. The material is placed and manually packed or tamped into position. Dry pack is a cement-sand mix with just enough water to moisten the mix and provide a cohesive mass that can be compressed into place. Due to its low water content, near optimal for sufficient hydration, a high strength and shrinkage free material should be possible. In reality, the quality of the grout is highly dependent on workmanship. In many operations, the working space may be highly restricted and the resultant dry-packed concrete is neither well consolidated nor of uniform quality (References 13, 14).

5. Wood

Wood is widely used for temporary support functions. It has three basic functions: (1) acting as a compressive element in vertical and lateral support; (2) as a wedge, to adjust and place a compressive element of fixed length; and (3) load distribution, to provide enough area to adequately transmit loads to support elements and to the existing structure, thus avoiding collapse or improving lateral stability.

6. Structural Steel or Reinforcement

Steel can accomplish the same functions as wood in a repair project, but because of its high tensile and compressive strength and its versatility, it serves other purposes. New steel elements can be used to upgrade and restore damaged reinforcement. If old and damaged reinforcement is substituted, the continuity of the old and the new steel must be assured by means of splices, welds or mechanical connectors. If the new bars are welded, preheating and cooling procedures may be needed to avoid altering steel properties and producing a brittle behavior. Different types of welded connections are shown in Figure 15. Welding equipment and trained personnel are needed to produce good quality welds. Steel plates or structural shapes properly attached to damaged elements can restore or strengthen the element and enhance ductility. Transmission of shear forces between new and old materials can be achieved by placing dowels (steel bars or bolts) along the contact surface.

7. Shear Transfer and Anchorage

To provide a monolithic behavior in a repaired structure, complex techniques may be needed when high shear forces must be transferred from one element to the other. Such techniques include dowels across (normal to) the concrete surface and concrete interlock, as shown in Figure 16. Shear keys are formed by removing concrete in the existing surface or by bonding precast concrete shear keys with epoxy adhesives to the surface of the existing element. The shear force between new and old material is transferred through the shear keys and the dowel action of the

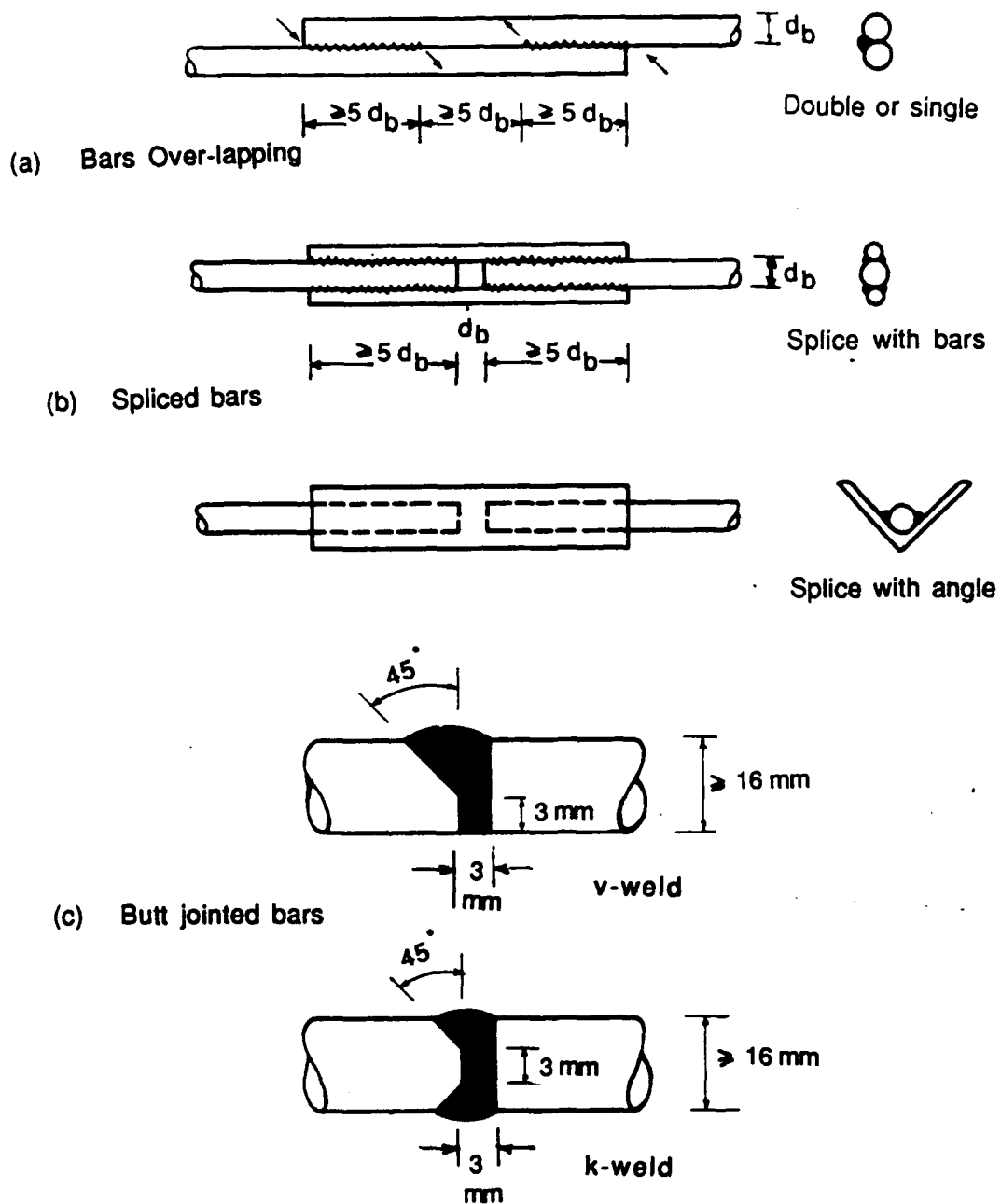
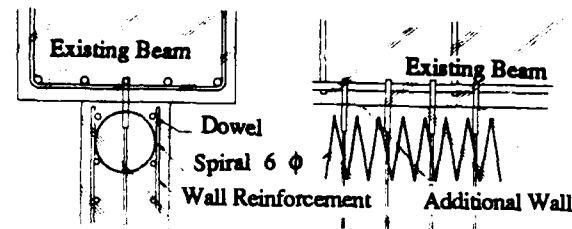
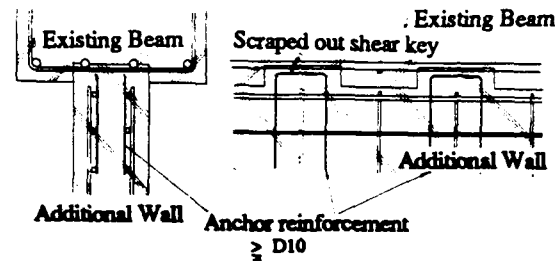


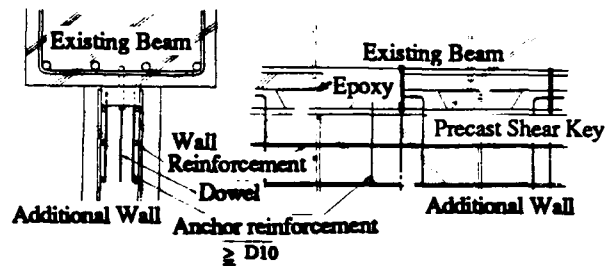
Figure 15. Types of Welded Connections (Reference 11)



(a) Dowel connection method

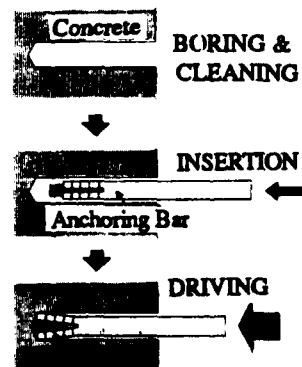


(b) Scraped out shear key connection method

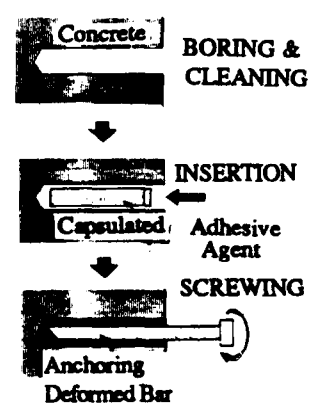


(c) Adhered precast concrete shear key method

Figure 16 . Shear Force Transfer Mechanisms between New and Old Concrete (Reference 42)



(a) Mechanical anchor



(b) Chemical anchor

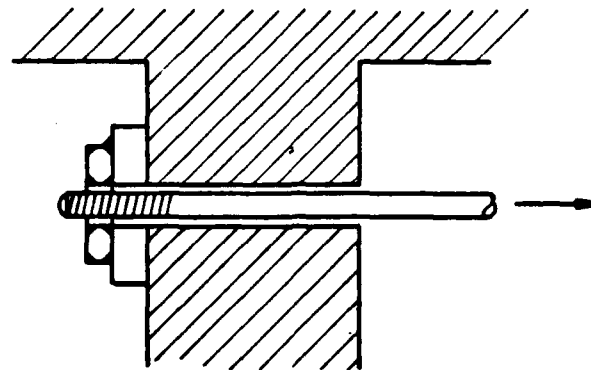
Figure 17. Anchorage Procedures for Steel Elements (Reference 33)

anchored bars. On concrete elements with small width, such as walls, spiral bars may be necessary to confine the steel dowels and prevent a splitting failure. If a perfect bond and no slippage between new and old materials is achieved, the element will behave as a monolithic block and optimum strength and stiffness can be developed.

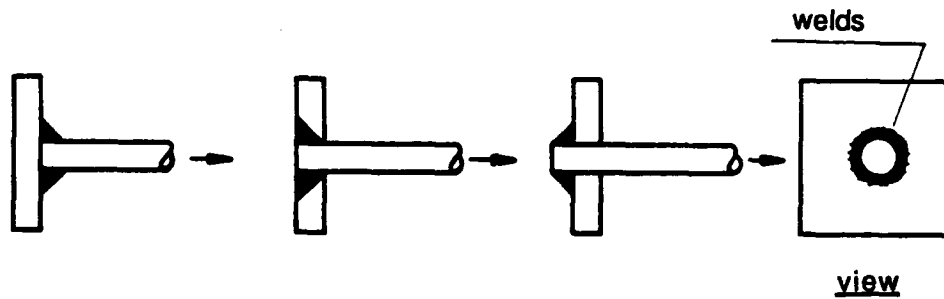
Steel dowels are used extensively to enhance shear transfer between a concrete jack and the original element and/or between new elements, normally infilled within frames, and the existing structure. Normally, the anchorage length within the old and new materials is the same. On infill walls, the development length used for the old concrete is usually less than that for the new concrete. Although some recommendations for the computation of the embedment length for different types of steel dowels can be found in codes or manufacturers' manuals, the determination of this length and the amount of dowels needed for an adequate shear transfer remains more of an intuitive process, based on the experience and judgement of the engineer (References 23, 24, and 25). Dowels are anchored in the old concrete using adhesive (chemical or grout) or mechanical systems.

Steel dowels can be anchored to old concrete, using adhesive materials such as epoxy, epoxy or resin grouts, or nonshrinking cement grouts. After holes have been drilled all along the contact surface, an adhesive or cementitious material is introduced. The hole must be filled so that no air remains trapped. A steel dowel is placed on each hole and rotated as it is introduced inside the hole to accomplish a better distribution of the bonding material around the periphery of the bar. Better results can be accomplished if the holes are cleaned before introduction of the bonding agent. Some studies suggest that cleaning the hole with a brush and vacuum cleaner to attain a dust-free hole increases significantly the pullout resistance of the dowel and the shear transfer capacity as well (References 11, 23, 25). Polyester resins or other chemical grouts can be provided in glass or plastic vials containing the hardener and resin. The vials are placed in the holes and the steel element is inserted and rotated into place, the containers are broken and the materials mixed, thereby starting the hardening reaction of the resin, as shown in Figure 17. Test data show that a larger embedment depth for the dowels and higher amounts of reinforcement crossing the old and new material interface surface enhance the shear capacity of the connection (Reference 26).

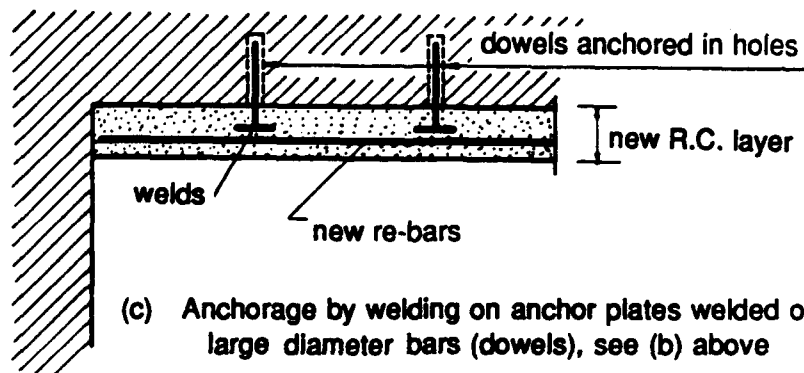
Mechanical anchors consist of an interlocking mechanism between the concrete and a steel anchor. Holes must be drilled on the contact surface and steel elements are introduced. Usually these elements have an expanding type anchor in one end. The anchor is loose sleeve or metal shell that expands around a steel cone or wedge. As the sleeve or shell expands, contact with the internal faces of the hole provides the interlocking mechanism (Figure 17). Some mechanical anchors resist tension while others resist tension and shear. Manufacturers have specific recommendations for installation and strength ratings (Reference 15). Adhesive anchors generally behave better in tension than mechanical anchors (Reference 27). Figure 18 illustrates several techniques to improve tensile capacities of dowels through the use of plates and dowels (Reference 11).



(a) Threaded bar and anchor plate



(b) Bar welded to anchor plate (anchor plate can be fastened on an "old" R.C. element by means of special anchors, expansive or resin ones)



(c) Anchorage by welding on anchor plates welded on short, large diameter bars (dowels), see (b) above

Figure 18. Mechanical Anchorage for Dowels in Tension (Reference 11)

C. BASIC TECHNIQUES INVOLVING TEMPORARY MEASURES

Temporary support is needed when structures and facilities suffer serious damage. Unloading of critical damage elements is required until the capacity to resist its own weight (gravity load) and other possible loads is restored properly. Temporary support may involve emergency measures that need two main requirements: (1) to transfer vertical loads from damaged elements to "provisional" auxiliary elements, and (2) to protect the structure as a whole against lateral instability. Carefully constructed temporary supports provide an interior means of protecting occupants and equipment. In many cases "temporary" protection may serve longer term needs or be incorporated into a more permanent repair scheme.

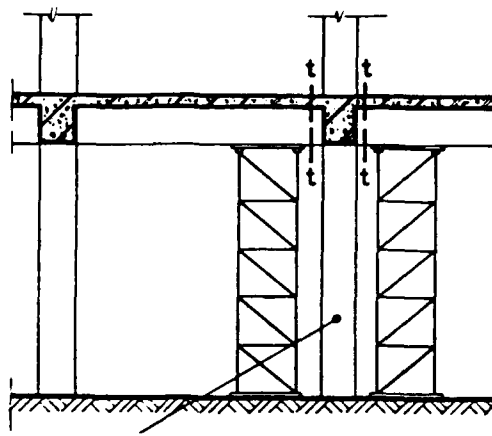
For temporary support of the structure, the load transfer from damaged elements to auxiliary compression elements can only be accomplished by wedging or positioning correctly the new elements. Special care must be focused on supplying adequate bracing to isolated elements to avoid member buckling or sidesway failures. Placing temporary supports is a dangerous process in repairing or stabilizing a structure. When the forces are being transferred from damaged elements to auxiliary supports, special care must be taken to prevent accidents that can involve loss of life or serious injuries.

1. Vertical Support

a. General Considerations

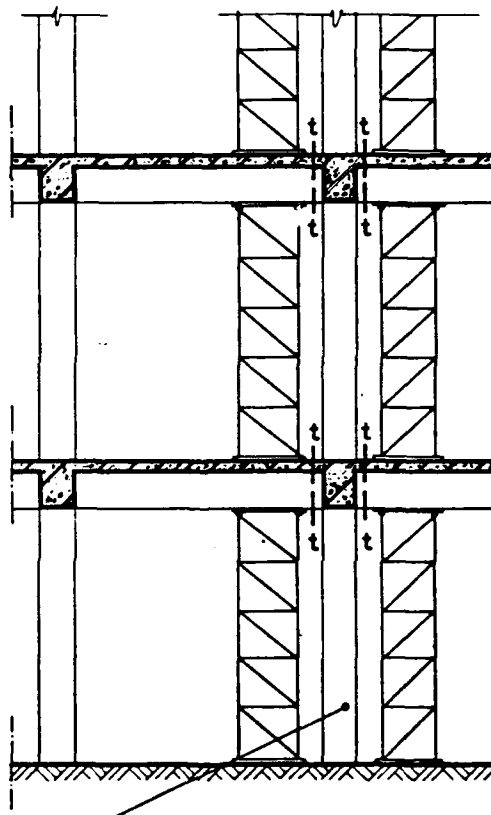
Vertical load capacity must be restored as quickly as possible by installing auxiliary vertical load bearing elements around damaged columns and bearing walls. In some cases it is possible to limit the inclusion of new elements to the damaged story as can be seen from Figure 19. The shear capacity of sections t-t, which includes slab and beams, must be sufficient to carry the floor load plus the shore load (Reference 14). It is difficult to determine the shear capacity (Section t-t) in a damaged structure. Remaining shear capacity cannot be clearly defined. Providing vertical support at every level below and above the damaged element diminishes significantly the shear forces on Sections t-t at both sides of the element. Shoring all floors (Figure 19) is recommended whenever it can be implemented (Reference 14).

When provisional support elements are directly supported by the slab, special care must be taken to avoid punching failure by providing a support surface that can distribute the element load over a bigger area. The support area can consist of wood planks and/or steel plates and must be collinear to avoid shear failures and poor load transfer. The distance from the provisional support elements to the damaged ones must be as short as possible; however, enough space should be provided for the eventual repair or replacement work on the column or load-bearing wall (References 12, 14 and 23).



Column or load bearing wall
to be replaced or repaired

(a) . High shears in floor systems



Column or load bearing wall
to be replaced or repaired

(b) Low shears in floor systems

Figure 19. Shoring Configurations for Damaged Vertical Elements (Reference 14)

b. Timber Shoring

Wood is used extensively to shore damaged elements because of their availability and economy. A variety of elements can be used ranging from tree logs, sawn timbers and utility poles to industrially made elements with different sections: planks, boards, skids and beams. The element's structural properties depend on the type and quality of the wood. Unless such elements are stored and available with load ratings already established, it may be difficult to assess the compressive capacity.

Individual elements can only be used to support light loads; however, in most cases, the section is too small compared to the axial load it must bear. Compound elements can be formed connecting multiple elements by means of wires, nails, bolts, pins, steel straps, etc. The efficiency of isolated elements can be increased by bracing to reduce the effective buckling length, as shown in Figure 20. The interconnecting members should be strong enough to brace and to hold the vertical elements together. Bracing should be done in the direction of the smallest dimension of the element for rectangular sections and may be needed in both for square sections and rectangular sections. To properly distribute loads over a larger area to avoid punching problems, boards, beams or planks can be used at the ends. For heavier loads steel plates may be needed. Vertical elements are more easily adjusted by means of wedges rather than multiple layers of flat plates or timber beams and boards (Figure 21)(Reference 14).

In case of damaged load bearing walls with openings, vertical load can be carried by timber shores (or any other kind of available shore). The use of timber to take vertical load from a damaged masonry pier between two windows is shown in Figure 22. Similar solutions can be adopted for a cracked section of wall above any window or door opening (Reference 14).

c. Steel Shoring

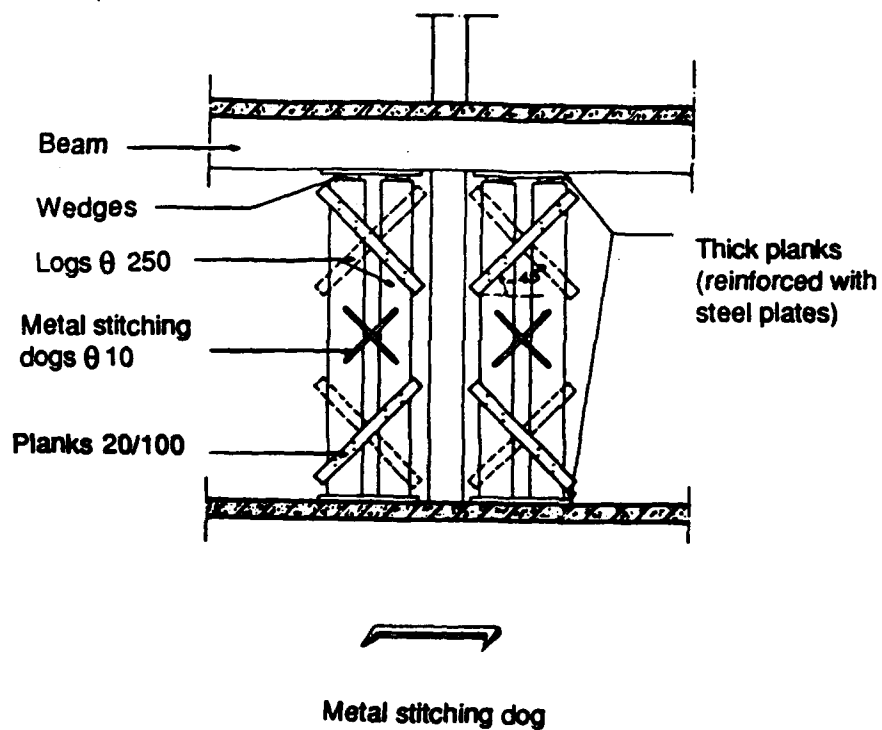
For higher vertical loads, single or compound steel elements can be used. Steel is an efficient material for vertical support but care must be taken to prevent buckling.

A large variety of steel elements with different capacities are used in the construction industry and are appropriate for temporary shoring purposes.

- Standard industrial shoring can be used for light loads (Figure 23). For wedging purposes, the height can be adjusted by an adjusting screw. Support plates are attached to each end to provide load distribution. To further avoid penetration problems, additional boards and beams can be provided at both ends (Reference 14).
- Industrial-type scaffolding can be used in case of light damage to bearing elements with small vertical loads or damaged flexural members, such as floor systems or roofs (Figure 24). The height of the support can sometimes be



(a) Widely spaced and braced timbers (Reference 36)



(b) Closely spaced interconnected timbers (Reference 14)

Figure 20. Use of Multiple Compression Elements

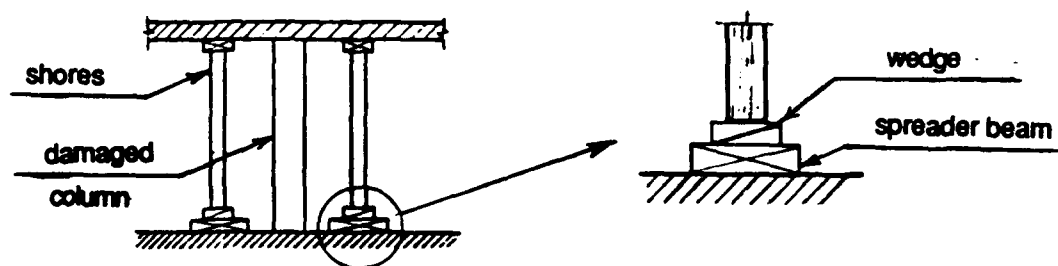
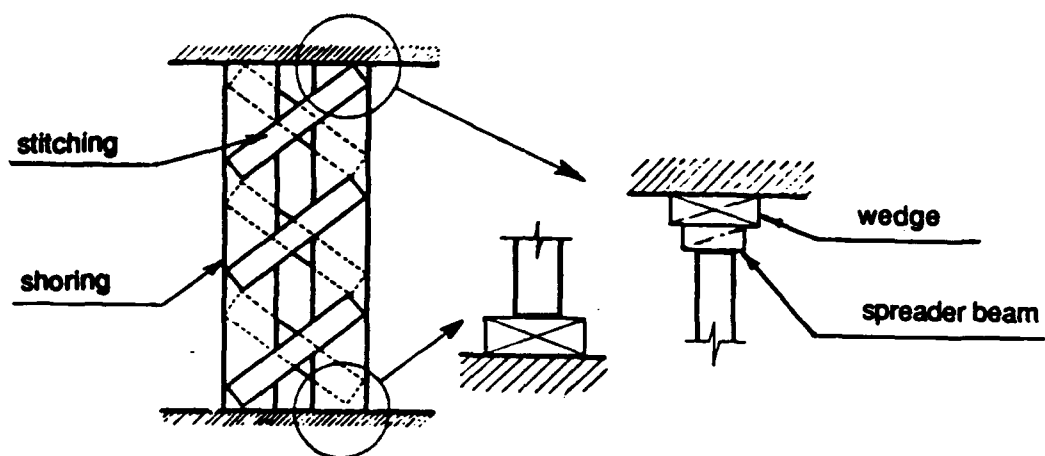


Figure 21. Proper Use of Spreader Beams and Wedges (Reference 12)

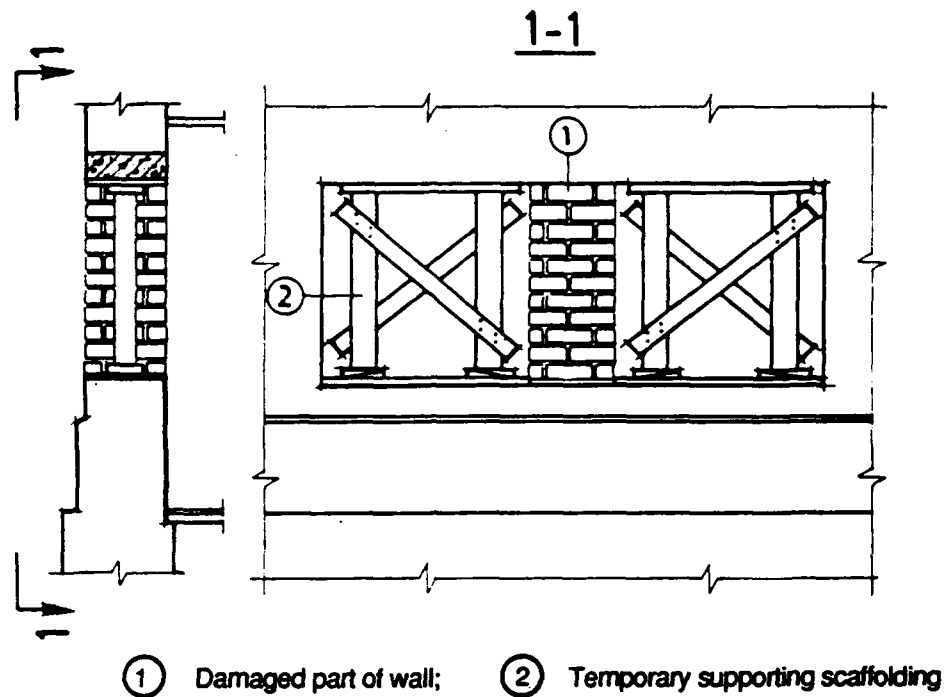


Figure 22. Support of Damage Load Bearing Walls with Openings (Reference 14)



**Figure 23. Standard Industrial Shore
(References 14, 36)**

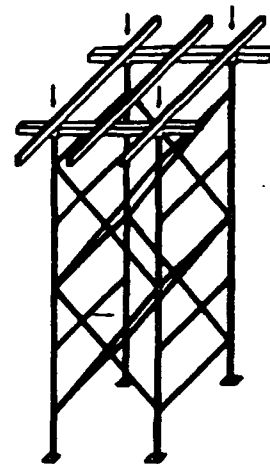


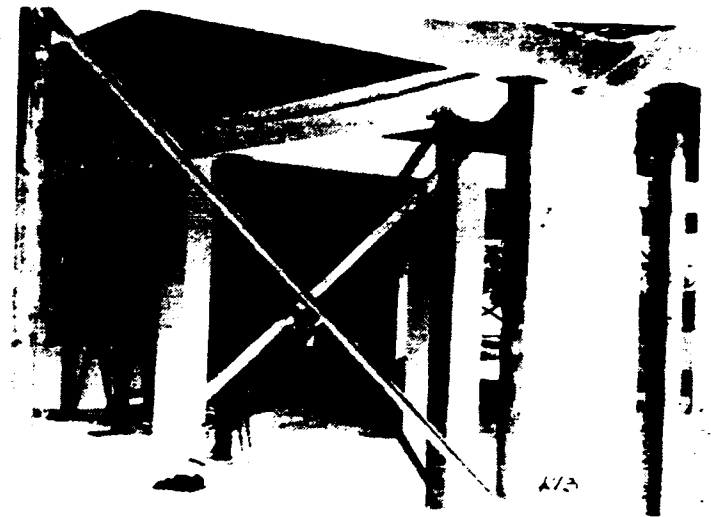
**Figure 24. Industrial Type Scaffolding
(Reference 14)**

regulated by a threaded base plate assembly. To support damaged beams, the props, normally tubular elements, are all distributed through the beam length, supporting the beam by means of auxiliary steel sections with length equal or greater than the beam width as shown in Figure 24 (References 14 and 23).

- Rolled steel shapes, pipes and built-up steel sections can be used to support high vertical loads. The length cannot be adjusted and wood or steel wedges must be used to provide the correct length (Figures 25, 26). Punch and shear failures must be avoided at the support face by means of bearing steel plates on the top and bottom ends to distribute the load carried by the member to a bigger area. Rolled steel shapes are often connected at the top by auxiliary steel sections, while bottom ends rest on I-shaped sections or steel plates (Figure 26). In this way, the system can transfer loads acting on the steel shores to the lower story avoiding punching or sidesway problems. When using isolated steel elements, special care must be focused to prevent them from falling sideways. Figures 25a shows the use of bracing. Figure 26c illustrates a case where the shores were tied to the damaged column by means of wire. This technique is often used to prevent buckling; however, if the column needs to be repaired, the temporary shores must be moved to provide enough space for the repair process (References 23 and 28).
- Supplemental steel members can be used to provide support to a damaged roof or floor system, as shown in Figure 27. If a slab is supported, care should be taken to correctly shim the supplemental beam to the roof system. To provide lateral stability, the supplemental members must be anchored to the existing structure. In case of a damaged beam, temporary supports are needed at both sides so that the new members can transmit loads to the existing foundation. If the damage is located at the beam midspan, the temporary supports can transmit the load directly to the beam ends. When the damage is extended through the entire beam length, new columns must be provided to avoid shear failures as mentioned before. Beam supports can become a permanent repair scheme if the steel elements are adequately protected against corrosion and fire. When necessary, the roof may be deformed upward with mechanical or hydraulic jacks (Reference 29).
- Adding angles to the corners of a damaged column can be used to restore its axial load-carrying capacity. Angles must be connected by steel straps, as shown in Figure 28. A metal plate should be provided at the angles ends to avoid bearing problems at the bottom of the slab. The gaps between the angles and the column surface must be filled with mortar. The technique can easily be transformed to a permanent solution (References 12 and 14).



(a) Steel posts (Reference 14)

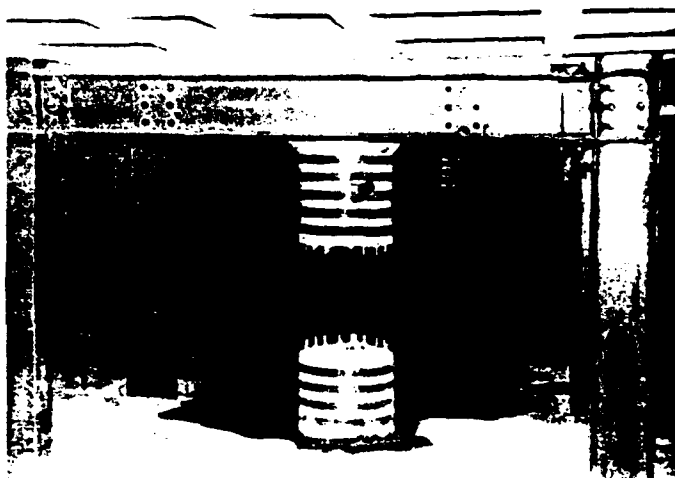


(b) Diagonal braces (Reference 14)

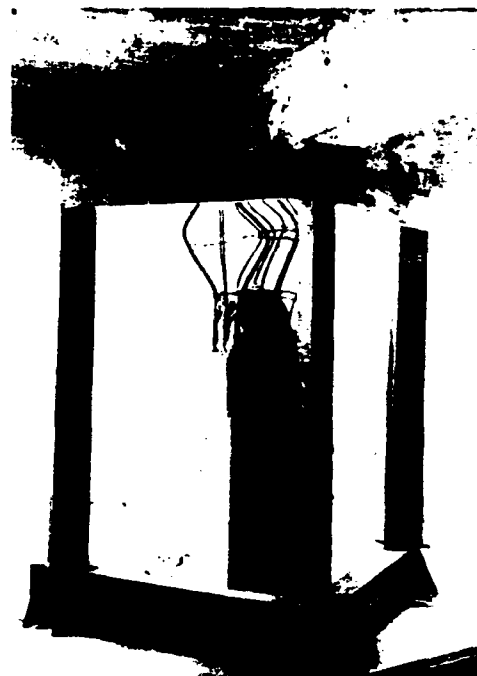


(c) Steel pipes (Reference 23)

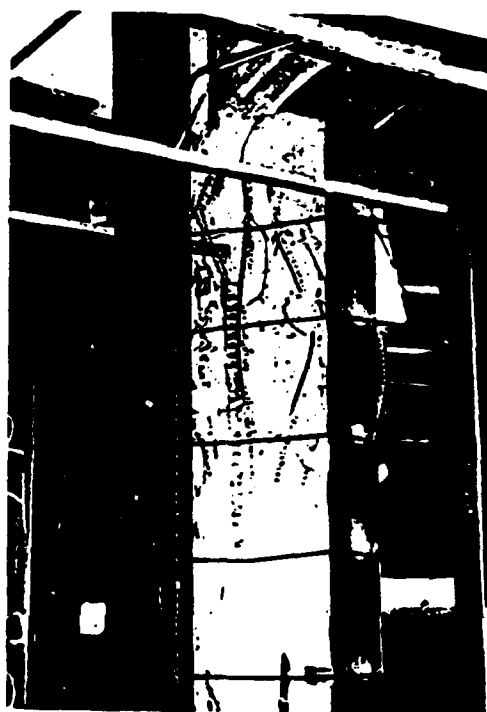
Figure 25. Shoring with Structural Steel Elements



(a) Fabricated frame (Reference 36)



(b) Fabricated frame (Reference 36)



(c) Steel shores tied with wire to damaged column (Reference 28)

Figure 26. Use of Steel Multiple Interconnected Steel Units

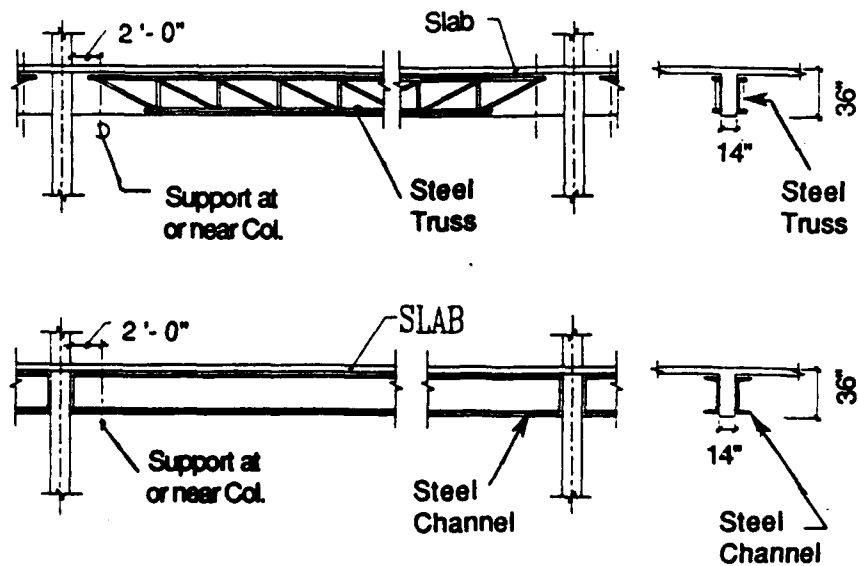
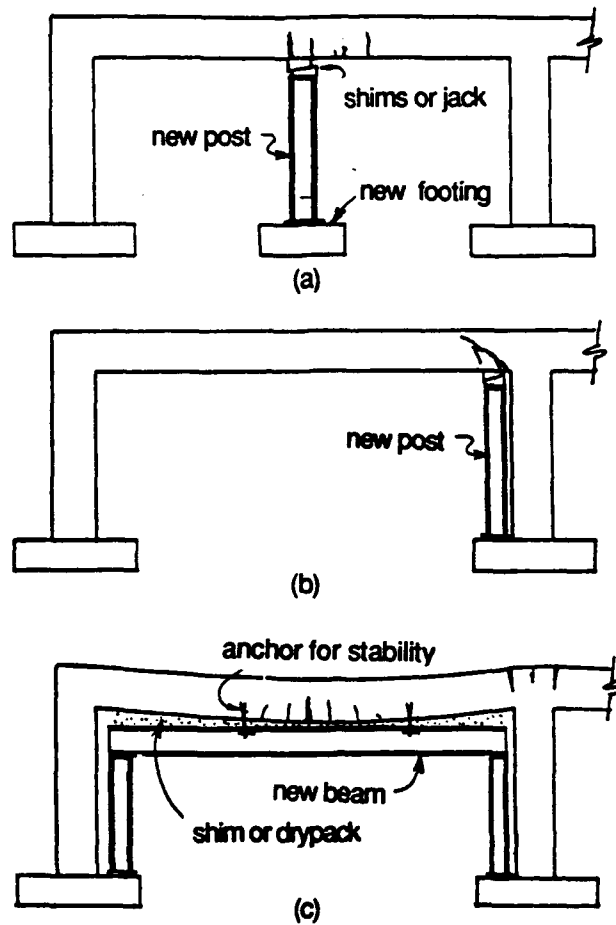


Figure 27. Support of Damaged Floor Systems with Supplemental Steel Elements (Reference 29)

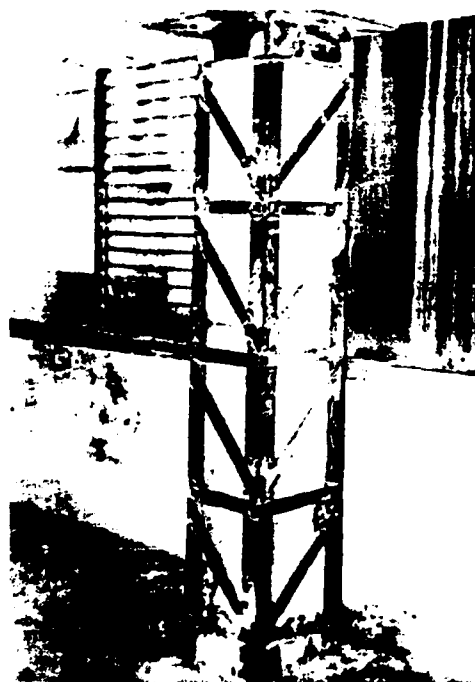
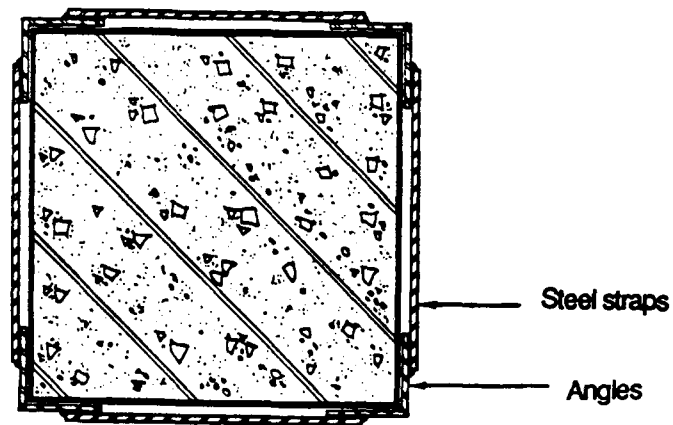


Figure 28. Use of Steel Angles at Corners of a Damaged Column (Reference 14, 36)

d. Special Techniques

Although some of these techniques (Figure 29) are still in a developmental stage, the data available from various tests show that capacity of a damaged column can be restored if confinement is provided by tightly winding a spiral around the column (References 11 and 30). The column is confined for two reasons: (1) to prevent or mitigate further damage in the event of a future overload; and (2) to stabilize the column. Wire rope, steel straps and welded bars have been used for this purpose. In general, flexible materials like wire rope are cheaper and have better workability, but stiffer materials enhance the vertical load-carrying capacity of the column.

High-resistance materials such as carbon fiber have been tested in Japan with favorable results. Carbon fiber can be wound directly into the concrete surface. The main advantages of this material are its lightweight and its resistance against corrosion; however, brittle failures have been observed (Reference 31).

Test data have shown that steel packaging bands secured with pressed clips, and wire spirals greatly increase the ductility of the concrete element and delay shear deterioration (Reference 32). The restoration of the capacity of the column depends on the level of damage. Full capacity can be restored for small levels of damage; however, this percentage diminishes significantly for heavily damaged columns (Reference 30).

External prestress can be used to unload damaged elements, as shown in Figure 30. Suitable and adequate deviators and anchoring devices must be used. Normally unbonded prestress is used, consequently all forces are introduced in the anchorage zones and, thus special attention must be focused on these regions (Reference 11).

2. Lateral Support

a. General Considerations

All structures have some capacity to resist lateral loads, even if not specifically designed for this purpose. If the damage appears to be located only on vertical load-bearing elements, special concern must be given to the possibility of reduced lateral load resistance of the structure as a whole. To prevent the building from collapse in future shocks, the lateral capacity must be restored or enhanced. One of the most difficult aspects in repairing a structure is the restoration of lateral load-carrying capacity. Usually, careful and costly studies need to be done before selecting an appropriate repair scheme. In many cases this will not be possible because of the implicit time limitations.

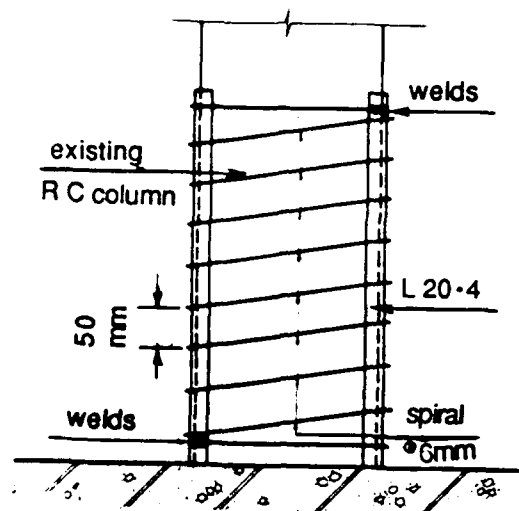
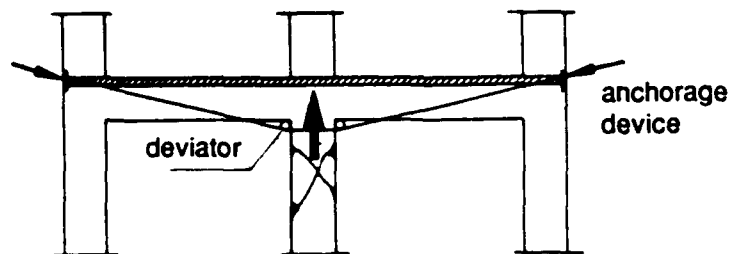
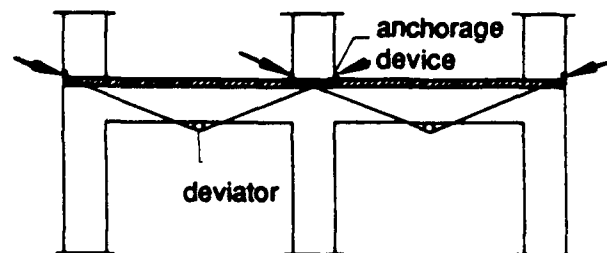


Figure 29. Use of Wound Spiral to Repair Column (Reference 11)



Additional prestressing for unloading of a damaged column



Additional prestressing: Deviators and anchorage devices

Figure 30. Additional Prestressing for Unloading Purposes (Reference 11)

b. Lateral Support of Walls

Wall intersections are vulnerable to damage when two perpendicular walls are not properly tied to each other. The appearance of vertical cracks or the separation of the walls at the intersection indicates the instability of the wall and a possible collapse perpendicular to its own plane. In case of instability of a masonry, stone or concrete load-bearing exterior wall, the wall must be braced to avoid lateral failure and possibly the collapse of stories above. To restore stability, external bracing can be used as shown in Figure 31. Braces can be formed of timber elements, steel rolled sections, profiles or pipes.

The plan distribution of the bracing elements must assure the overall stability of the wall. Braces should be located at the floor level and bear against vertical timber elements to the structure in such a way that vertical shear capacity between the timber and the wall is equal to the vertical component of the strut force. The connection between the strut and the vertical element must be capable of resisting both force components from the brace (References 12 and 14).

The lower end of the brace must have enough support to prevent sliding or soil bearing failure. This is normally accomplished by means of a heavy dead weight. Prop inclination (from the horizontal) should be less than 45 degrees. A 25 degree angle provides better stability. Wedges should be used to adjust and fit the braces (References 12 and 14).

If no external space is available, steel cables or shapes can be used to attach exterior walls to the structure. Exterior steel bearing elements must be used to provide lateral stability and contain the wall in a plane perpendicular to its own plane. As shown in Figures 32 and 33, the wall is attached to the structure with steel tension ties that connect the exterior bearing elements to other structural elements within the structure. Steel tension ties must be anchored properly, cross the wall through holes specifically bored in it for this purpose, and connect to the exterior elements by means of nuts or welds (References 12 and 14). In many cases the tie systems may need to be supplemented by braces.

c. Frame Bracing

Damaged buildings, specially concrete framed structures without infill walls in the first story or structures with heavily damaged walls, must be strengthened laterally by the use of braces.

Compression braces can be formed by diagonal steel or wood elements, stiff enough to avoid buckling and wedged properly at both ends to ensure adequate bearing and transmission of forces through the connection as shown in Figure 34. The beams and columns of the structure must resist shear forces introduced by the brace. The use of timber braces nailed to an internal wood frame to avoid shear failure of the structural elements is illustrated in Figure 34. Diagonal tension bracing using steel cables or rolled steel sections is similar to compression bracing. Special

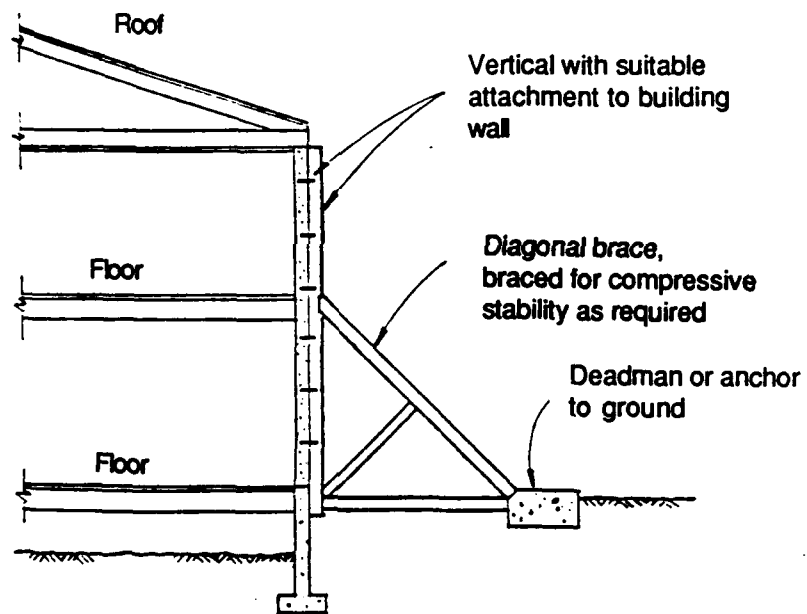
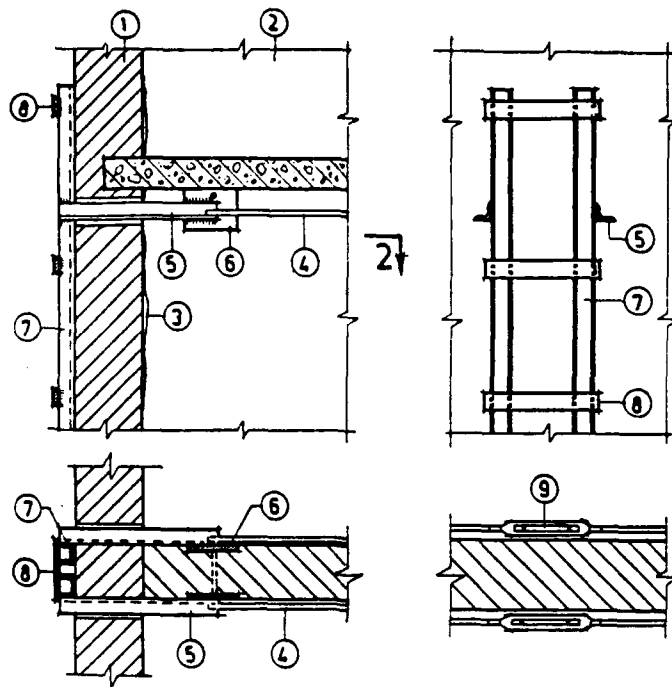
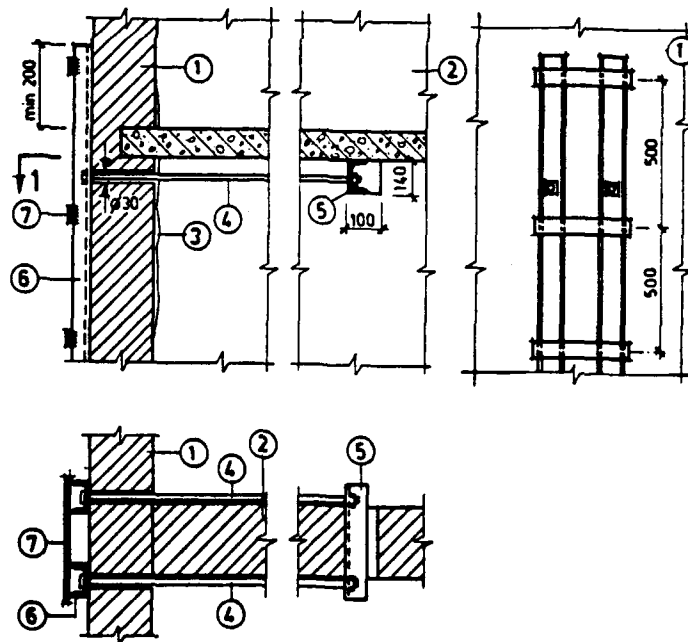


Figure 31. Lateral Support of External Load Bearing Wall (Reference 14)



1 - exterior wall; 2 - interior wall; 3 - crack; 4 - steel tensioner;
 5 - angle 50.50.5mm; 6 - steel plates; 7 - steel profiles;
 8 - steel plates; 9 - tensioner coupler



1 - exterior wall; 2 - interior wall; 3 - crack; 4 - steel tensioner;
 5 - angle 50.50.5mm; 6 - steel plates; 7 - steel profiles

Figure 32. Techniques for Providing Lateral Support of External Load Bearing Wall by Attaching It to an Internal Perpendicular Wall (Reference 14)

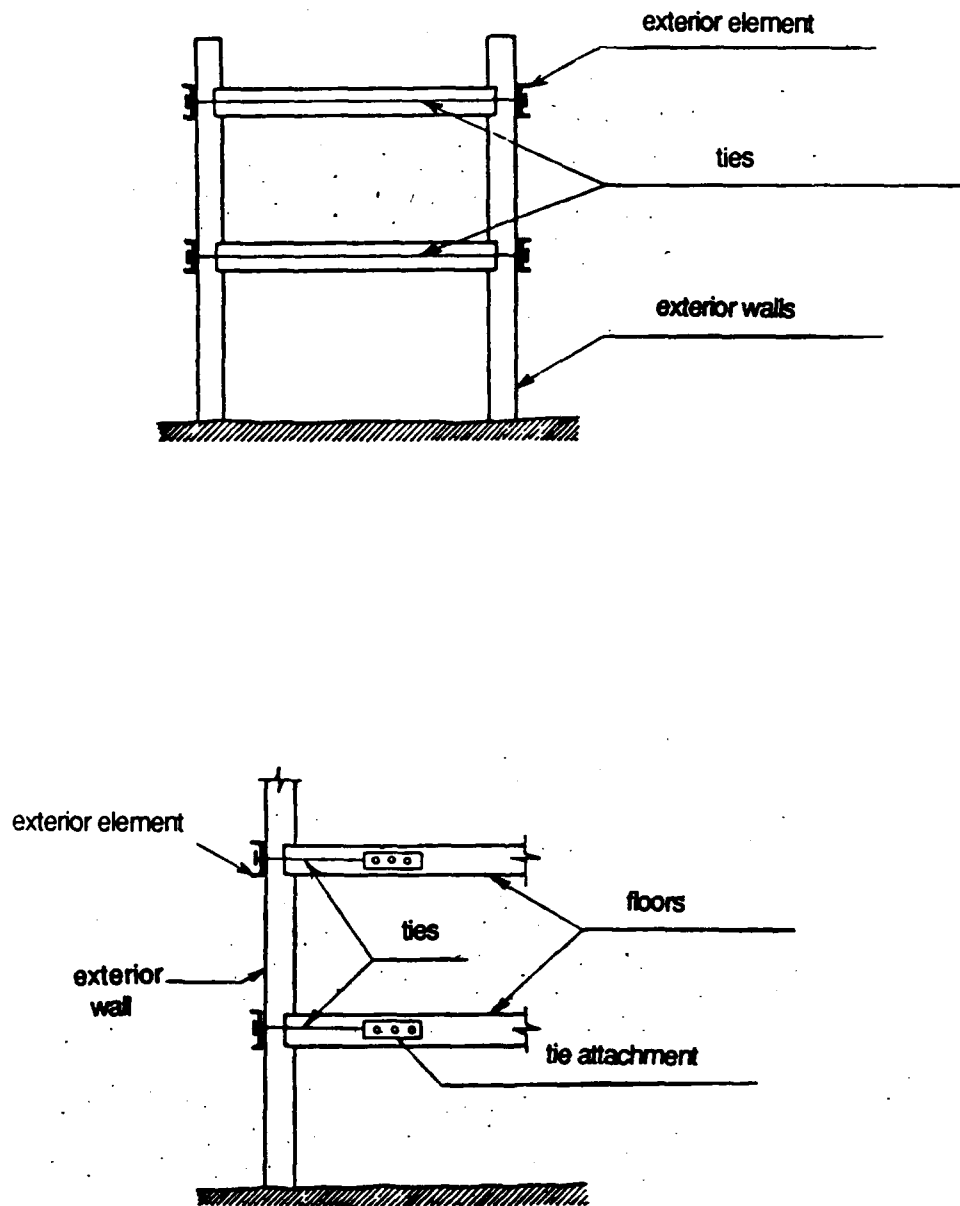
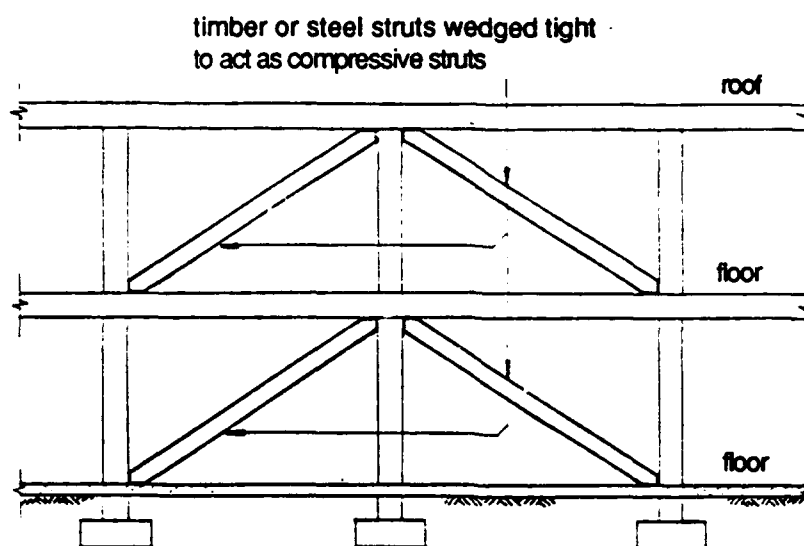
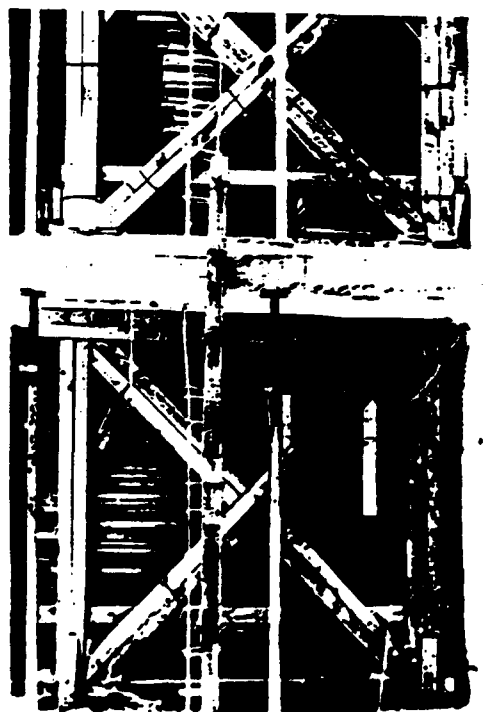


Figure 33. Lateral Support of External Load Bearing Wall by Continuous Ties to End Walls (Reference 12)



(a) Proper wedging (Reference 14)



(b) Timber braces (Reference 23)

Figure 34. Compressive Braces

care must be taken in the anchorage zone to avoid failure (References 12, 14, and 23). In some cases, the structure can be externally supported, as shown in Figure 35. The dead weight must be greater than the vertical component of the force in the cable. The dead weight cable anchor must be located to avoid overturning of the dead weight. (Reference 12). If the structure is leaning slightly, additional braces should be installed to counter the forces due to secondary effects produced by the structures permanent deformation (Reference 14).

3. Wedging

In order to properly transfer loads from damaged elements to auxiliary load-carrying elements, compression elements with fixed length must be wedged into place. Three main procedures are normally used: wood or steel wedges, mechanical jacks and ordinary or plane hydraulic jacks (References 14, 23).

Wood wedges are made from dry, hard and node-free wood. The fibers must be oriented, as shown in Figure 36. Once in place, the wedges must be nailed. Loose wedges must be avoided to prevent the sidesway failure of the compression element (Reference 14).

Mechanical jacks are widely used. Enough support area must be provided to avoid shear failures. When the jack base doesn't provide adequate support, a steel plate or wood element can be added between the jack base and the support surface to accomplish better load distribution. Special care must be taken on floors below the one being jacked to avoid shear failures. Similar considerations should be made for hydraulic jacks. Some advantages can be found in use of hydraulic jacks. Simultaneous long distance operation of several jacks reduces hazard to the operator and assures a uniform jacking force on the structural elements (Reference 14).

Plane jacks are an efficient wedging mechanism. Although they normally work with oil or water, cement grout can be injected to accomplish a permanent deformation of the jack. Different types of plane jacks are shown in Figure 37. It is common practice to provide hard wood, grout or lead plates between the damaged element surface and the plane jack to improve support conditions. Once the jacking operation is finished, wood wedges can be installed as a safety measure in case of pressure drop (Figure 37c) (Reference 14).

D. INTERMEDIATE TECHNIQUES FOR REPAIR

Intermediate solutions do not imply just a temporary transfer of loads to auxiliary elements, but require restoration or upgrade of damaged element strength. Intermediate solutions are considered to be such that implementation is possible within a short time immediately following any emergency situation. Although in most cases a trained staff is needed to implement and supervise the repair project, the relative simplicity of implementation makes these techniques applicable to emergency situations. A repair or strengthening scheme is classified as an intermediate solution

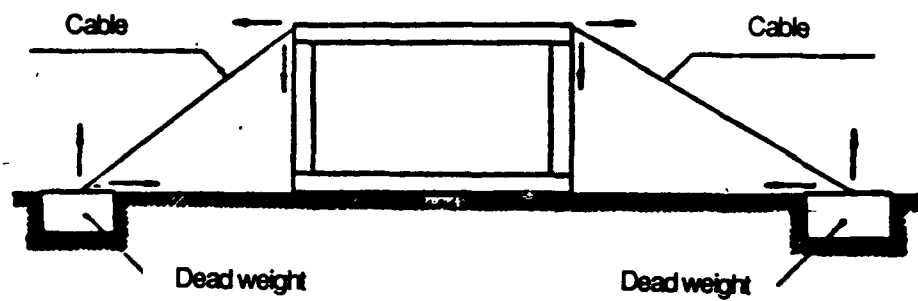
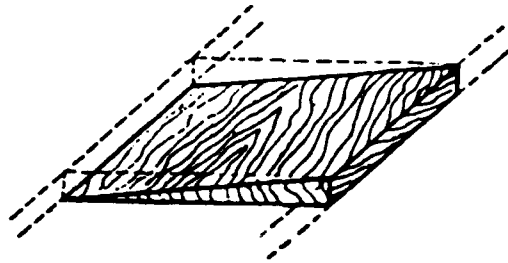
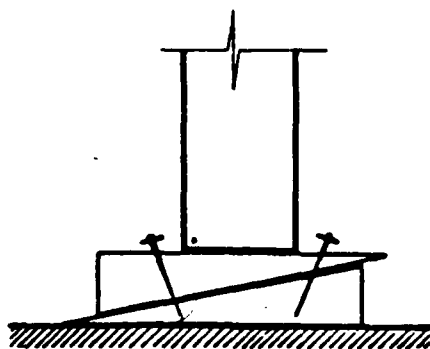


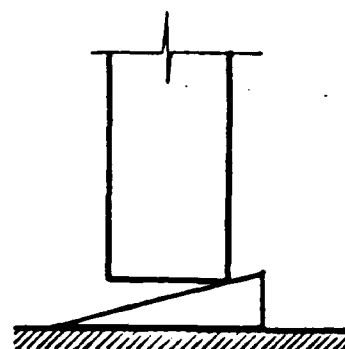
Figure 35 . Lateral Support of Structure with External Tension Braces (Reference 12)



(a) Orientation of fibers on a wood wedge.



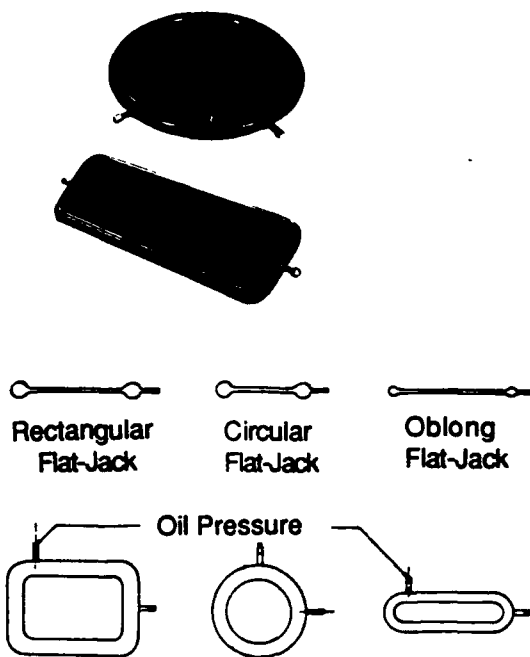
Correct



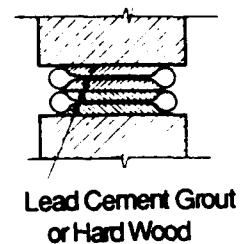
Incorrect

(b) Fastening procedures

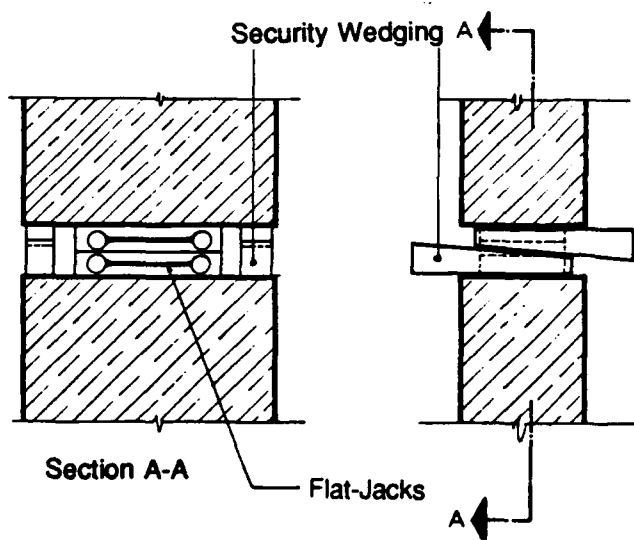
Figure 36 . Use of Wood Wedges (Reference 12)



(a) Types



(b) Use of flat jacks



(c) Safety procedures

Figure 37. Flat or Plane Jacks (Reference 14)

when its implementation does not alter the structure's original load paths. The strength is usually restored to its original levels; however, in some cases, the stiffness cannot be recovered completely. The basic failure mechanisms and overall behavior under lateral loads are not altered.

1. Concrete

a. General

In some cases, damaged concrete must be removed and new material substituted. All damaged concrete that can be easily removed should be eliminated; however, in many cases, a simple reliable way to determine when all damaged material has been removed does not exist. The removal of material until aggregate particles are broken seems to give satisfactory results. In case of doubt regarding the condition of the concrete or reinforcement, removal should be attempted. After the concrete has been removed, a damaged superficial layer that may initiate bond failure should be eliminated by methods such as sandblasting, water pressure jetting, or with wire brush (Reference 11).

A clean, dry and dust-free contact surface must be provided to ensure adequate bond between new and old material. If any source of contamination, such as oil, grease or dirt, is present, the concrete surface must be cleaned by means of impact tools and/or abrasion methods, such as sandblasting or water jetting. In some extreme cases, chemical agents such as detergents or acids can be used. To improve bond conditions, the contact surface must be roughened to create an irregular surface. Sometimes an epoxy resin or mortar coat is applied to the surface to further enhance bond. If new concrete is added, the old concrete surface should be wetted. The new concrete strength should be higher than that of the old concrete for good performance (References 11, 12, 14, 26, 33, and 34). Test data suggest a heavy sandblasting of the existing concrete surface can enhance its shear capacity transfer capability with similar results to those obtained by chipping the surface or providing shear keys. Normal surface treatment procedures result in higher bond strengths (References 11 and 26).

b. Injection

Resin and grout injection are used to repair concrete elements with low levels of damage, no crushed or spalled concrete, no fracture or buckling of steel, and small crack widths. Although the original shear and flexural strengths can be restored with injection, a somewhat lower stiffness results because it is impossible to inject all microcracks. Higher values of stiffness have been observed for repaired elements that have suffered severe damage because a higher percent of crack length can be filled with epoxy. Although not enough data are available yet, data obtained from several tests suggest that a value around 70 percent of the original stiffness can be restored (References 12, 15, 30 and 35).

For crack widths ranging from 0.1 to 0.5 mm, resins without a filler may be used. For wider cracks, a filler must be added to reduce shrinkage, creep and thermal phenomena. For cracks ranging from 1.0 to 1.5 mm, resins can be filled with glass or quartz powder, from 1.5 up to 5.0 mm sand can be used (Reference 14, 15).

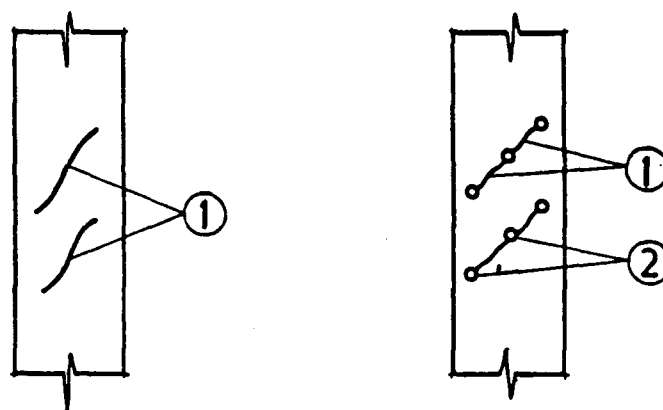
Before injection, cracks should be free of dust. Usually, they are cleaned by air jet. If contaminating substances such as oil, grease or dirt are present, they must be cleaned by flushing water or other solvents into the cracks. If solvents are used, they must be eliminated from the crack with clean water. Before injection, the water may need to be blown away or enough time provided for the crack to dry if good epoxy bond is to be obtained.

The repair material is injected through metallic nipples attached with grout to the old concrete at locations where holes have been bored along the crack path. The ports are spaced at distances of 1 to 1.2 times the thickness of the concrete element to be repaired. After the nipples have been placed, the surface cracks must be sealed to avoid the escape of the injected material (Figure 38). If the cracks extend through the damaged element, the element should be sealed and nipples attached on the cracked surfaces. A variety of techniques and hardware have been developed by epoxy and injection specialists for accomplishing the repair procedure. Injection equipment can be as simple as a hand operated gun to a automated system, with automatic dosification and mixture of ingredients at the point of injection (References 12 and 36).

Before the injection of the repair material, the cracks can be cleaned by means of air pressure applied through the nipples. The continuity of the injection route can be checked by the introduction of clean water. The repair material is pressure injected beginning at the lowest nipple or port until the grout appears at the corresponding port on the opposite side or from the next higher port on the same side. When flow is observed, the port is closed and equipment moved to the next port, advancing upward for a vertical crack, and from one end to the other in case of a horizontal crack. The ports must remain closed until the epoxy sets, after which the nipples are removed and discarded (hardware attached directly to the surface generally is not reusable. A finish material can be applied to the surface.

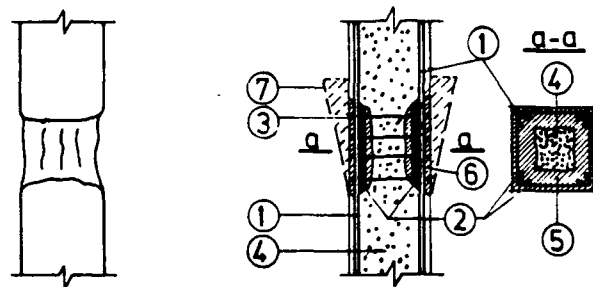
Successful repair requires careful attention to the pressure used for injection, the viscosity of the injected material, and the crack width. The injected material must not create further damage. Smaller cracks require higher injection pressure or closer port spacing. (Reference 12, 14, 15, 37). Vacuum may also be used to inject the repair material. The injection technique procedure is well documented in the report ACI 503R, "Epoxy Injection Procedures" (Reference 38).

Injection techniques can be used to repair any kind of structural element; however, pressure injection cannot restore the integrity of the member (especially bond between concrete and reinforcement) when concrete adjacent to the crack is pulverized to a very fine powder that prevents epoxy from saturating the region (Reference 15). Test results (Reference 39) of a full-scale



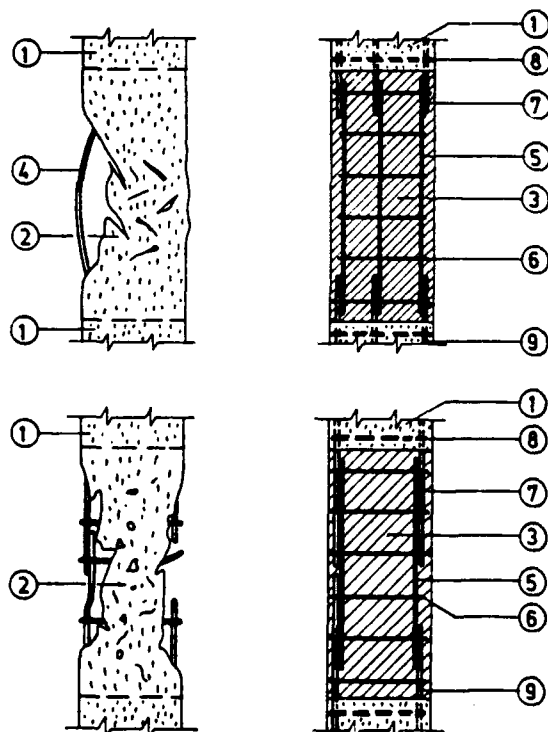
1 - cracks; 2 - injection ports

Figure 38. Crack Injection (Reference 14)



- | | |
|-----------------------------|------------------------|
| 1 - existing reinforcement | 5 - new concrete |
| 2 - added new reinforcement | 6 - welding |
| 3 - added new ties | 7 - temporary castform |
| 4 - existing concrete | |

(a) Replacement of concrete



- 1 - existing non-damaged concrete; 2 - existing damaged concrete;
 3 - new concrete; 4 - buckled reinforcement; 5 - new reinforcement;
 6 - new ties; 7 - welding; 8 - existing ties; 9 - existing reinforcement

(b) Replacement of entire cross section

Figure 38. Replacement of Material in a Damaged Column (Reference 14)

frame indicate that epoxy injection restored the full lateral load-carrying capacity of the frame but lower stiffness was observed for the repaired structure.

c. Replacement

When crack widths larger than 5 mm, concrete crushing, or steel buckling are observed, the damaged elements should be replaced with new material to restore the strength and stiffness of the element. The use of expansive additives in the concrete may be needed to achieve monolithic action between the new and old materials. Carefully designed formwork will facilitate the casting process.

The element must be unloaded. The damaged concrete must be removed and a specially roughened and cleaned surface of contact between the old and new material must be prepared. After cleaning the contact surface, saturation with water or application of a grout or resin adhesive may be considered to improve bond. When buckled steel is present, new longitudinal bars should be substituted for the damaged length of the old bars. The new bars could be attached by means of splices, welds or mechanical connectors such as threaded couplers or bar grips. If welding is used, the weldability of the steel should be taken into account. Preheating and cooling of the bars must be carefully accomplished to avoid changing the mechanical properties. Steel bars that do not need to be replaced should be cleaned before new concrete is cast. This is normally done with wire brushing or other manual procedures. Special care must be focused to avoid a surface on the steel that could result in a lack of bond between the bar and the new concrete. Enough transverse steel must be added to adequately confine the repaired section (References 12 and 14).

Substitution techniques can be successfully applied to columns, beams, joints, slabs and walls. In Figure 39, two different procedures which depend on damage level are shown. Figure 39a shows the repair of a column with crushed concrete and no damage or buckling in the reinforcement. Loose concrete is removed, cracks in the column core within the ties are repaired by means of injection techniques and concrete cast to replace the damaged region. The formwork must allow the passage of new material. New concrete must be placed higher than the final repaired area to allow adequate vibration of the concrete and proper compaction. After stripping the formwork, the excess material should be removed before the concrete reaches a high strength.

The procedure for crushed concrete and buckled reinforcement is shown in Figures 39b. The damaged concrete must be chipped away, damaged steel replaced, enough transverse steel provided, and concrete cast. A similar procedure must be followed for other structural elements such as joints and beams. Sometimes holes must be drilled in the slab to allow the placement of new concrete (References 12, 15, 23, and 36). Damage to wall or floor diaphragms can often be repaired with less cost by adding a layer of new concrete with reinforcement embedded in the new layer rather than replacing the damaged material (Reference 15). Data available from

some tests suggest that the original strength and stiffness of the damaged element can be restored (Reference 11 and 30). Other tests involving the repair of walls, where the damaged concrete was replaced, suggest that the strength and deformation capacities can be recovered completely; however, the stiffness is restored to about the 50 percent of its original value (Reference 40). Test data regarding repaired beams, where the damaged concrete was replaced with steel fiber reinforced concrete, show that the element stiffness and load-carrying capacity can be effectively restored with adequate ductility and enhanced energy absorption (Reference 20). For small amounts of spalled concrete, the damaged concrete can be replaced by epoxy compounds. Some tests indicate that this method works satisfactorily for small volumes of material; for larger volumes the replacement of concrete by epoxy compounds does not restore the damaged element flexural capacity or stiffness (Reference 35).

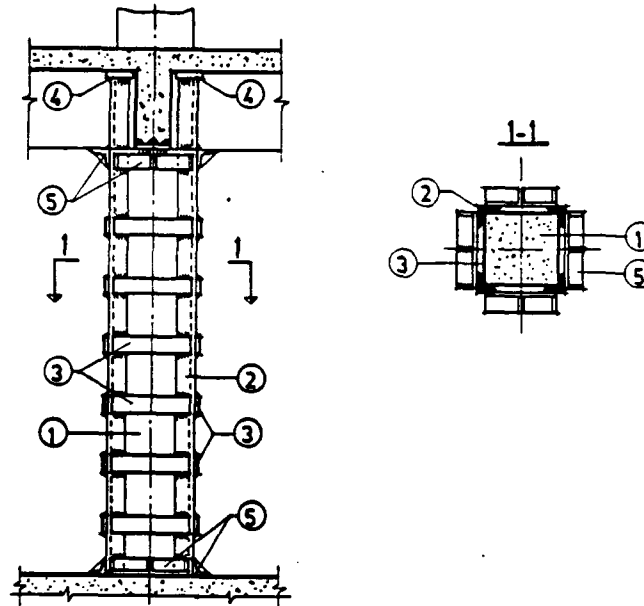
d. Steel Jacketing

Steel jacketing restores, and in many cases, enhances the performance of any element by the addition of steel elements surrounding the original member. When the element is not badly damaged, the steel skeleton can be applied directly without further preparation. If the capacity is significantly reduced, some restoration of the element must be carried out before the jacketing can take place. Special care must be taken to avoid damage to the concrete at the point where high bearing stresses between the steel elements and concrete can develop. After jacketing, the steel must be protected against fire and corrosion, usually by providing a concrete or mortar cover.

In some cases, steel plates are glued to the concrete surface to create a concrete-steel composite section. An epoxy adhesive is used to provide bond between the concrete and steel. The contact surface of the steel plate and the concrete element must be prepared properly. The concrete contact area should be sandblasted or some other method used to remove the weak external layer of laitance and to expose a clean and sound surface. The epoxy can be applied to the steel and the plate gradually compressed against the existing element to spread the epoxy uniformly and to squeeze out extra epoxy. For flexural members, the ends of the steel element should be fixed with a dowel to prevent debonding at these locations and development of a crack along the epoxy layer (Reference 41). Although these techniques have been used in many repair situations, very little test data has been reported.

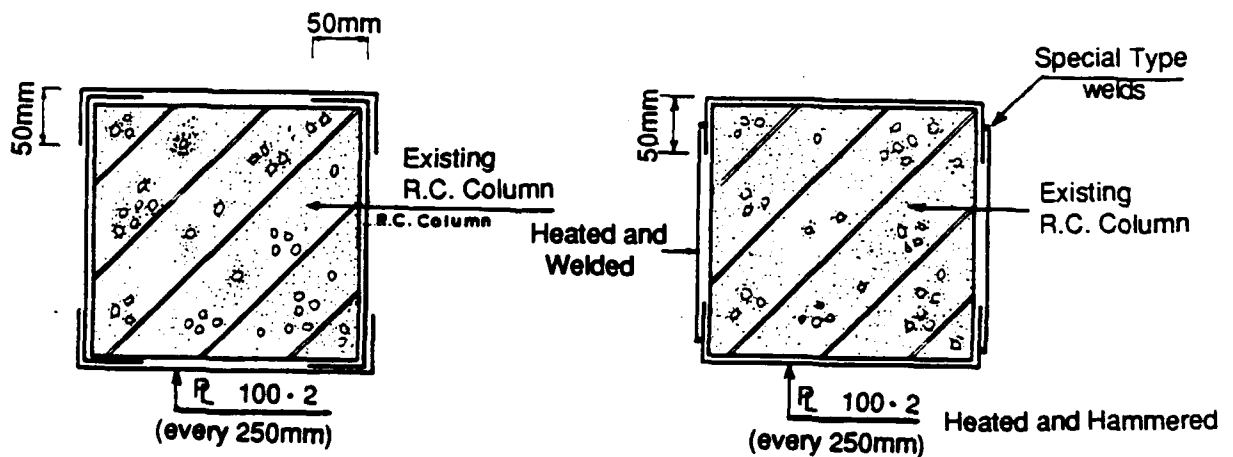
(1) Columns. The jacket can be formed by a skeleton of steel angles connected by means of steel straps or round bars (Figure 40a). To enhance the confinement provided by the jacket, the angles should be clamped and pressed into position or the steel straps should be preheated before welding to create tension after cooling (References 11 and 14).

In some cases the whole column surface can be covered with thin steel plates (Figure 40 b and c). If the plates are bonded with epoxy, the concrete and steel surfaces must be cleaned as discussed before. Scales, oxides, grease and oil must be removed from the steel surface



1 - existing column; 2 - steel angle profile; 3 - steel plate;
4 - supporting plate; 5 - angle profile

(a) Use of Angles and Straps (Reference 14)



(b) Bonded (by resin mortar)
steel sheets (Reference 11)

(c) Heated, welded and bonded
(by injection) steel sheets
(Reference 11)

Figure 40. Steel Jacketing for Columns (Reference 11)

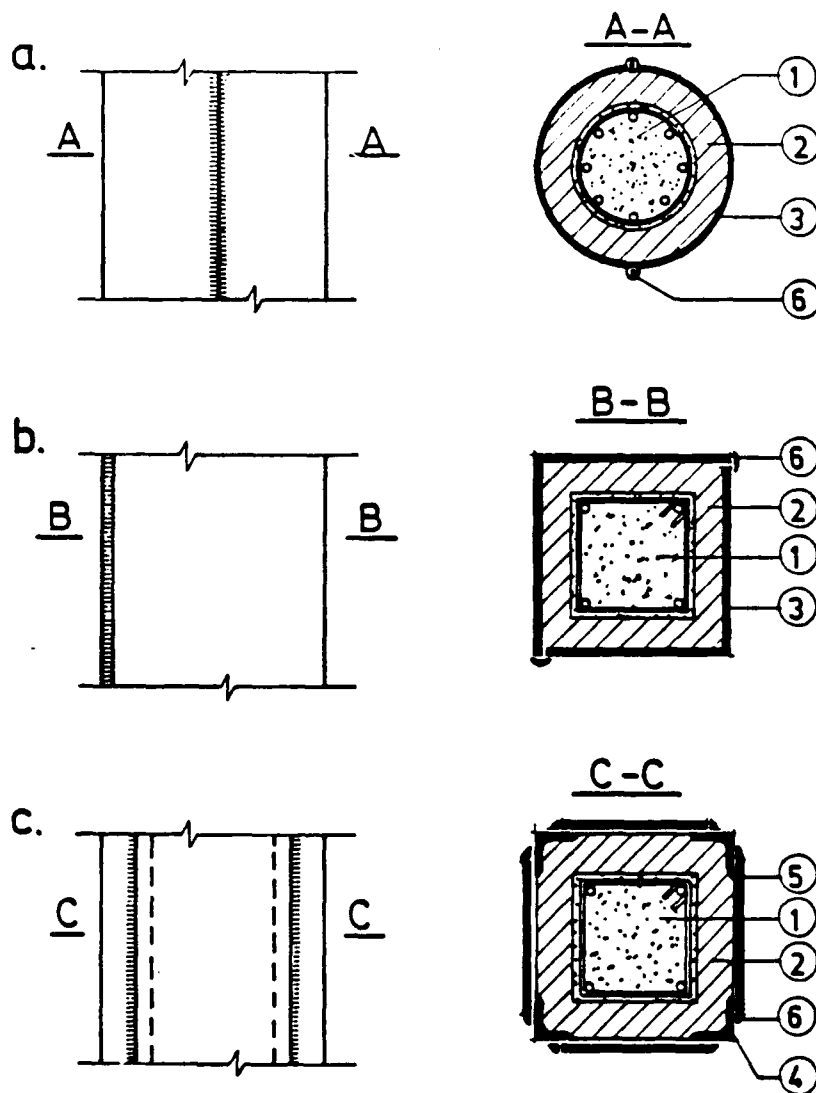
by means of any mechanical or chemical procedure available. Normally the adhesive is smeared on the steel sheets to attach them to the concrete surface. However, the steel sheets can be attached to the concrete surface with small anchors and then bonded with resin injection. In a few cases steel sheets have been preheated and welded into place to provide enough confinement. Figure 41 illustrates one variation of these techniques. Steel plates are welded to provide a casting which is larger than the reinforced concrete column. The space between the steel casing and the column is filled with nonshrinkage or expansive cement grout (References 11 and 14).

Special attention must be focused on the contact surface between the jacket and the slab to avoid shear or punching failures. This is usually solved by means of a collar. The space between the jacket and the column should be grouted. A concrete casing or jacket must be provided to protect the steel from corrosion and fire. Due to the impossibility of making the jacket continuous through several stories, the technique is limited to enhancing or restoring axial and shear capacity of the columns (References 11, 12, 14, and 23). Tests have shown that the ductility of the column can be greatly enhanced and the strength increased moderately by steel encasement (Reference 18). Tests have shown that steel straps provide added shear capacity and delay concrete crushing (Reference 42).

(2) Beams and Slabs. Attaching steel straps or plates to a damaged element by means of epoxy resins (Figure 42) and/or mechanical connectors is one way to upgrade the shear and/or flexure capacity of a beam. The contact surfaces of the concrete and steel must be prepared as mentioned before. Attaching plates to the sides of the beam enhances the shear capacity while attaching the plates to the bottom of a beam enhances flexural capacity. Figure 43 illustrates a beam with shear and flexural capacities enhanced (References 11 and 12).

Exterior post-tensioned ties can also be used to accomplish the same purpose (Figure 44). The ties consist of steel rods with threaded ends surrounding the damaged element and tightened using bolts. Steel plates must be provided to support and distribute the stresses induced on the concrete surface by the steel bolts once the ties are stressed. The ties can be vertical or diagonal. In the first case, steel angles must be provided in the bottom part of the beam to provide a larger contact area between tie and beam to avoid crushing of the concrete. In the second case, the tie must be welded to the longitudinal reinforcement of the beam to be able to resist the horizontal component of the force. Although not mentioned in the available literature, the flexural capacity can be enhanced using the first solution if adequate anchorage is provided to the steel angles in the bottom face of the beam (Figure 44a). Figure 44b shows a beam repaired using these procedures. Figure 45 shows the construction detail for two intersecting repaired beams (References 12, 23, and 36).

The flexural capacity of slabs can be also restored or increased using these techniques (Reference 41). Epoxy bonded steel plates have been reported as a reliable, economical and fast way to repair structures subjected to noncyclic loading (References 11, 14 and 41).



1 - existing column; 2 - new concrete or grout; 3 - steel encasement;
4 - steel angle profiles; 5 - steel plate; 6 - welding

Figure 41. Steel Jacketing of Column with Steel Case and Expansive Concrete or Grout (Reference 14)



Figure 42 . Strengthening of Beam with Steel Straps Attached with Epoxy Resins (Reference 36)

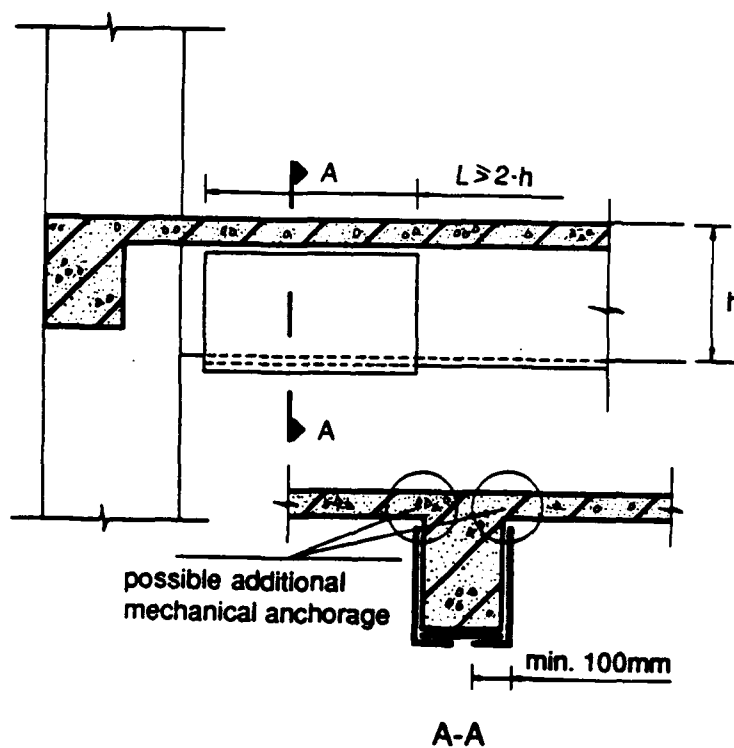
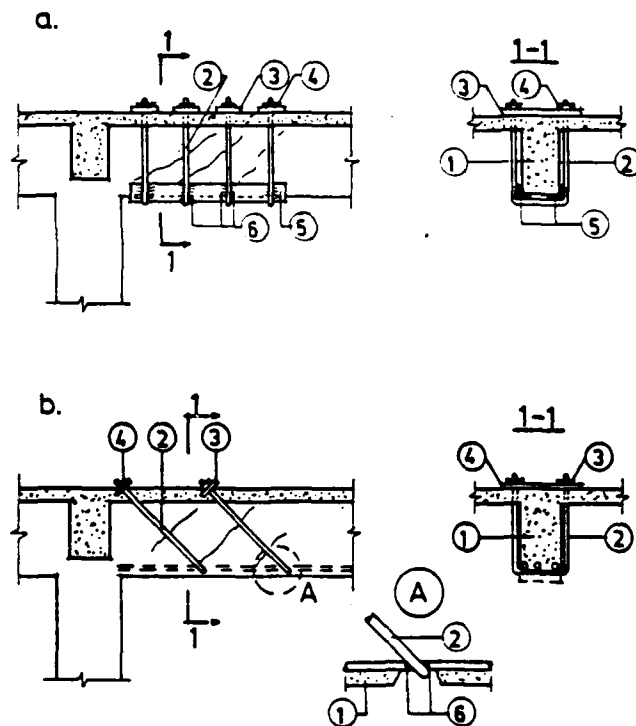
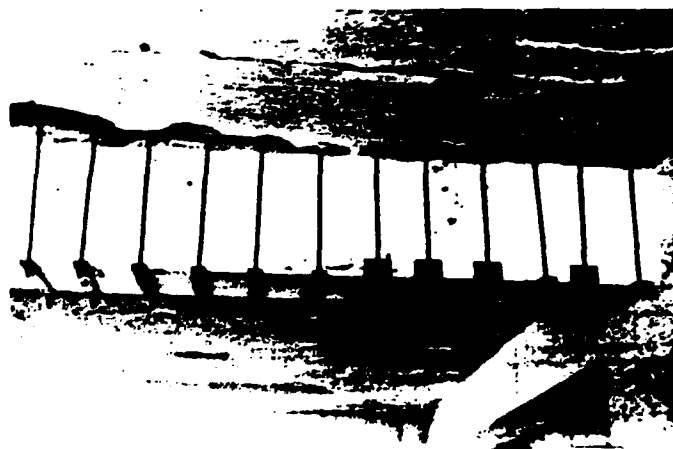


Figure 43. Strengthening by Means of Glued Thin Steel Sheets (Reference 11)



1 - existing beam; 2 - steel clamp; 3 - steel plate; 4 - nut;
5 - angle profile; 6 - welding

(a) Techniques (Reference 14)



(b) Applications (Reference 36)

Figure 44. Steel Jacketing of Beams with External Post-tensioned Steel Rods

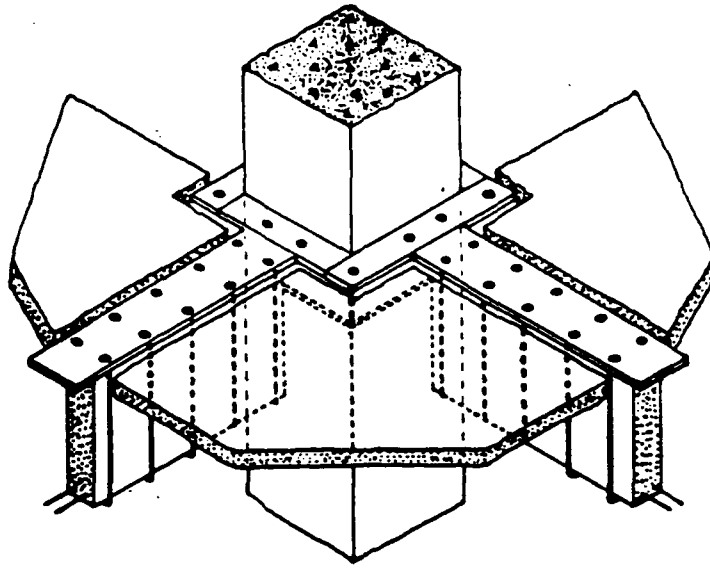


Figure 45 Detail for the Intersection of Two Perpendicular Jacketed Beams (Reference 23)

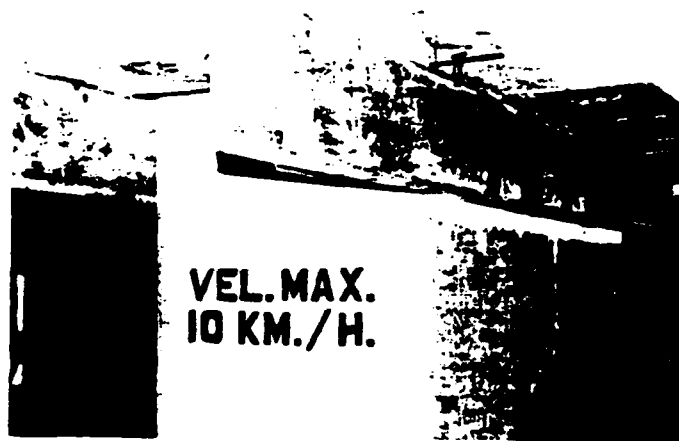


Figure 46 Strengthening of Column Capital (Reference 36)

In slabs with damaged column capital, the shear (punching) capacity can be upgraded by repairing the damaged part of the joint and attaching new steel elements with mechanical anchors as shown in Figure 46 (Reference 36). The joint shear capacity in planar frames can be enhanced by the use of post-tensioned collars as shown in Figure 47. Thin steel plates or high strength steel threaded bars are secured into vertical, horizontal or diagonal position and then tightened through bolts and nuts by means of a wrench (Reference 11). Corner joints can be strengthened by means of steel plates attached to the joint with epoxy resins or mechanical connectors (Figure 48).

e. Special Techniques.

U-shaped metal units with small legs known as stitching dogs can be used to prevent crack growth in slightly damaged concrete (Figure 49). Holes must be drilled and cleaned on both sides of the crack and stitching must be grouted in place to bridge the crack. Stitching dogs can vary in size to prevent the creation of a new failure line. Spacing must be reduced at the crack ends. Holes drilled at the crack ends will relieve stress concentrations. The dogs must be protected from corrosion (Reference 37).

Cracked reinforced concrete flexural elements can be repaired with epoxy and extra reinforcement bar insertion as shown in Figure 50. The shear cracks are externally sealed with gel-type epoxy, inclined holes are drilled through the element to cross the crack at approximately 90°. Steel bars must be inserted in the holes to bridge the crack on each side sufficiently to permit development of the bar tensile capacity. Epoxy is injected at low pressures to fill the cracks and bond the reinforcement to the concrete. The method has been used in practice with good results to repair bridge girders (Reference 37).

2. Masonry

a. General

To enhance the lateral load-carrying capacity of a masonry wall structure, the walls must be tied together and to the roof system to prevent failure of a wall in a direction perpendicular to the plane of the wall. Vertical reinforcement is generally needed to increase its deformation capacity.

b. Injection

The injection technique is used to restore the capacity of masonry elements with cracks up to 10 mm wide, with no loose bricks and no heavily damaged parts. Fluid cement mortar can be used to inject cracks exceeding 0.3 mm and up to 3.0 mm. For crack widths ranging from 3.0 mm to 10 mm, cement grout injection can also be used (Reference 14).

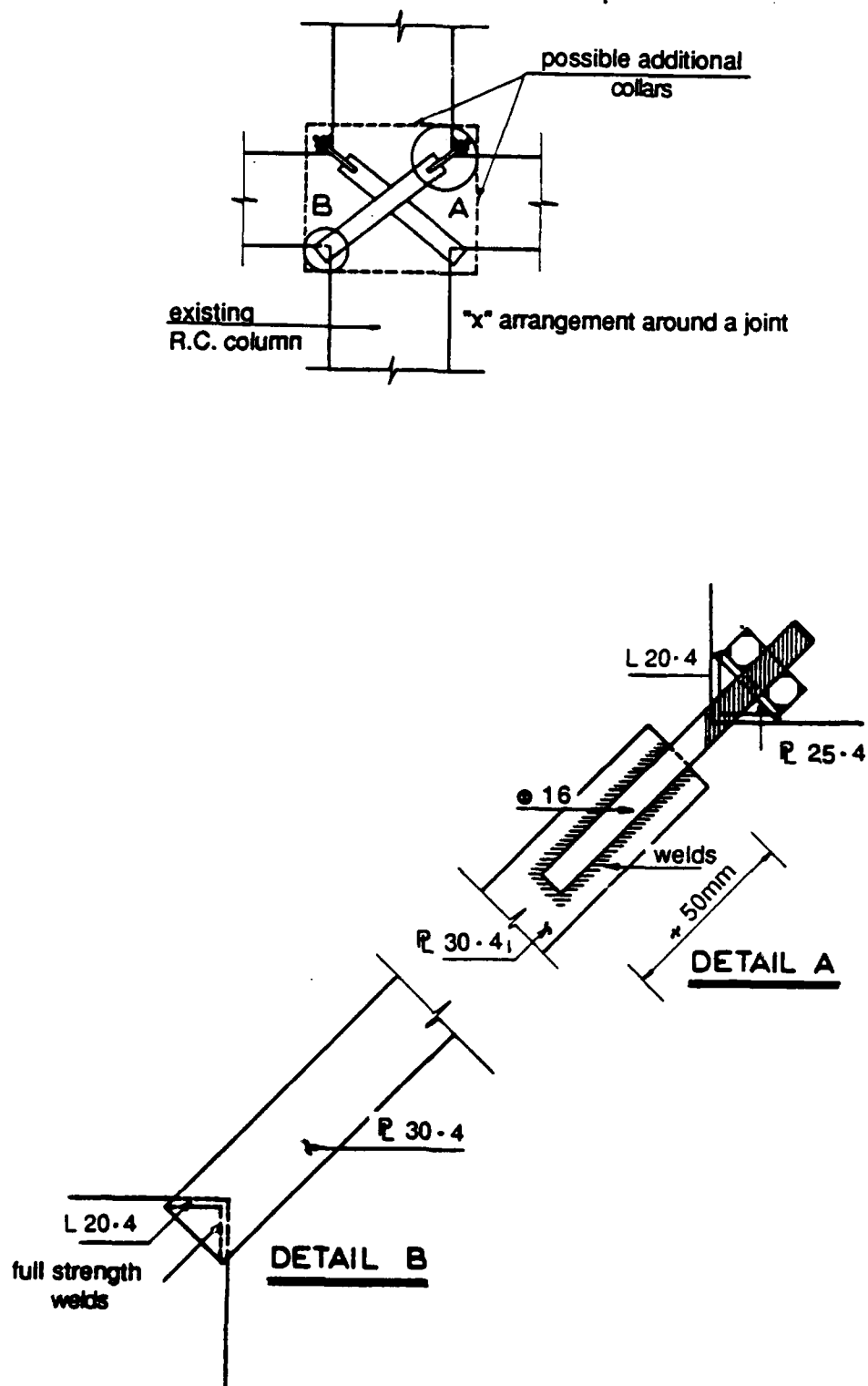


Figure 47. Tensioned and tightened collars for confinement of planar frame joint region (Reference 11)

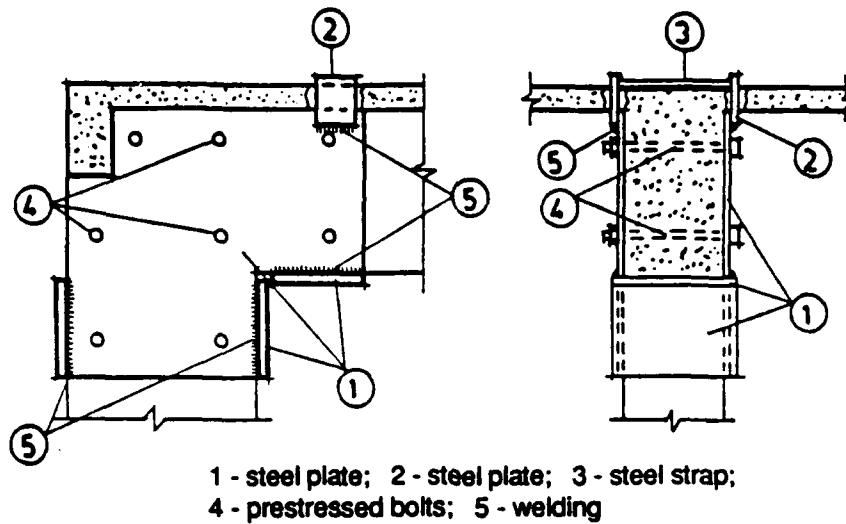


Figure 48. Steel Jacketing of Corner Joint (Reference 14)

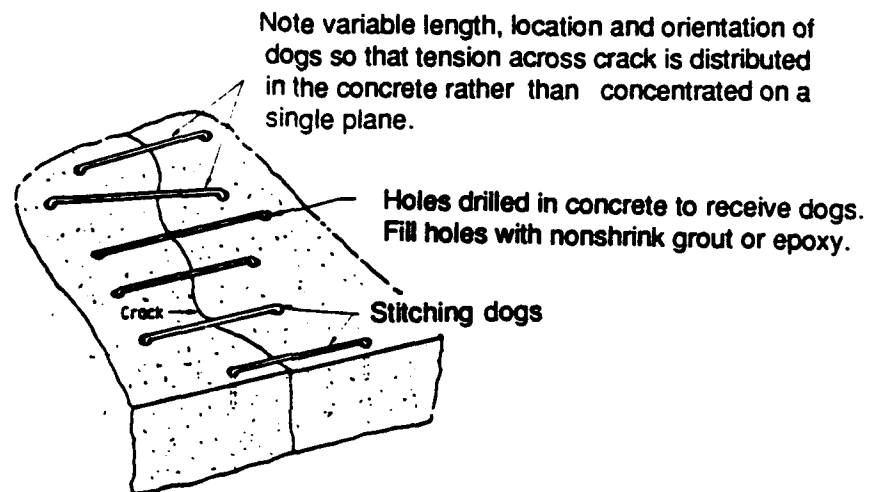


Figure 49. Repair of Crack by Stitching (Reference 37)

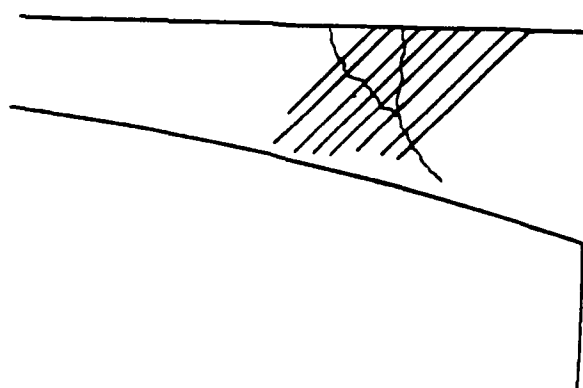


Figure 50. Reinforcing Bar Orientation Used to Effect the Repair (Reference 37)

The procedure to repair crack damage in a masonry element is very similar to that discussed for concrete elements with some differences. Finish or surface coatings must be removed from the damaged zone and the cracks cleaned with air or water. Intervals between nipples or ports depend on the cracks' width – distances are typically between 30 to 60 cm. The nipples are placed in bored holes and attached with mortar. Cracks can be sealed with cement- mortar to contain the injected fluid. In structures where the walls do not carry high axial loads, large cracks can be filled by trowelling or similar procedures (Reference 14).

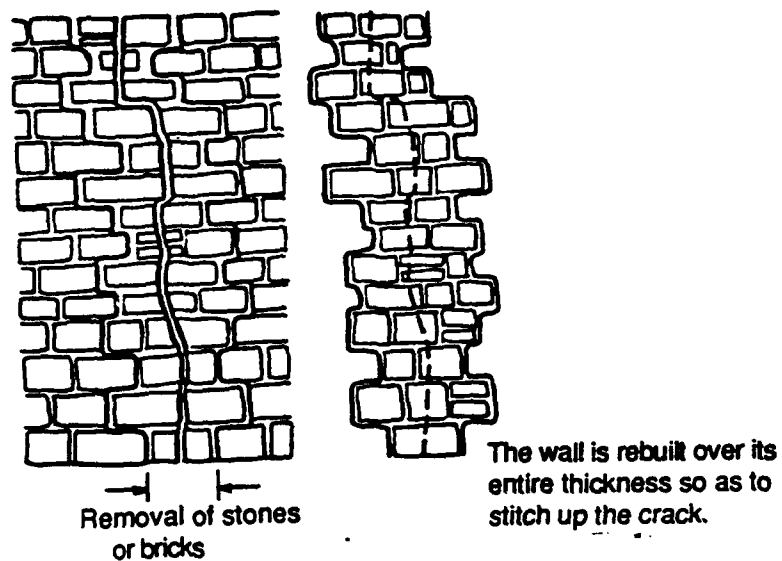
c. Replacement

In masonry elements with cracks greater than 10 mm wide or with loose bricks, damaged bricks should be replaced by new repair materials. Three methods are discussed for the repair of vertical cracks:

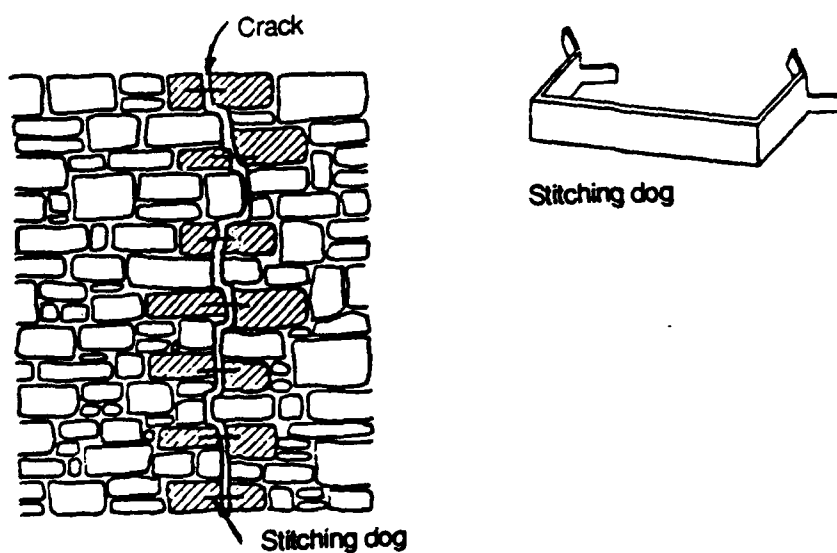
- Bricks within a distance of 15 to 20 cm on each side of the crack can be removed and replaced by elongated masonry elements that bridge the crack zone (Figure 51a). A high cement content mortar is recommended (Reference 14).
- Loose bricks next to the crack should be removed and new bricks substituted on each side. Stitching dogs or steel bars connect the new bricks (Figure 51b). The remaining crack can be filled with a cement rich mortar (Reference 14).
- A more substantial wall is produced if the bricks removed are replaced with an equivalent reinforced concrete column or wall (Reference 14). This does not constitute just a repair scheme but strengthens and greatly enhances the behavior of the wall. Experience gathered in many countries shows properly located reinforced concrete columns will prevent the collapse of masonry buildings. Practice in China includes the use of a steel tie rod, placed horizontally from the upper end of one column to the upper end of the next column to enhance the behavior of the building (References 14, 43, 44, and 45).

d. Strengthening

In some cases, masonry walls cannot develop their full in-plane shear capacity if a premature out-of-plane failure occurs. Steel sections can be used to enhance the wall resistance to force perpendicular to the plane of the wall. The steel elements are tied to the floor diaphragms and confine or "basket" the masonry elements. The steel sections are attached vertically to the wall by means of steel ties that pass through holes as illustrated in Figure 52a. The steel elements must be adequately anchored to the floor system on top and bottom of the masonry wall to effectively contain and brace the wall. Steel elements can be attached on both or only on one side of the wall. In the latter case, nuts and washers or plates must be used on the opposite side. Adding elements



(a) Substitution of damaged elements on a masonry wall (Reference 14)



(b) Use of stitching dogs to repair cracks in masonry walls (Reference 14)

Figure 51. Replacement of Material along Crack in Masonry Wall

to both sides of the wall confines the masonry elements and provides a better solution. Figure 52b illustrates details of the repair procedure for corners or intersections (Reference 14).

A similar procedure to that described for concrete columns can be used to strengthen masonry piers, as shown in Figure 52c.

e. Repair and Strengthening of Intersections

To repair small vertical cracks within the intersection, the techniques mentioned in b and c above can be used. For bigger cracks or separation of wall from adjoining elements, the wall must be tied by means of one of the following techniques:

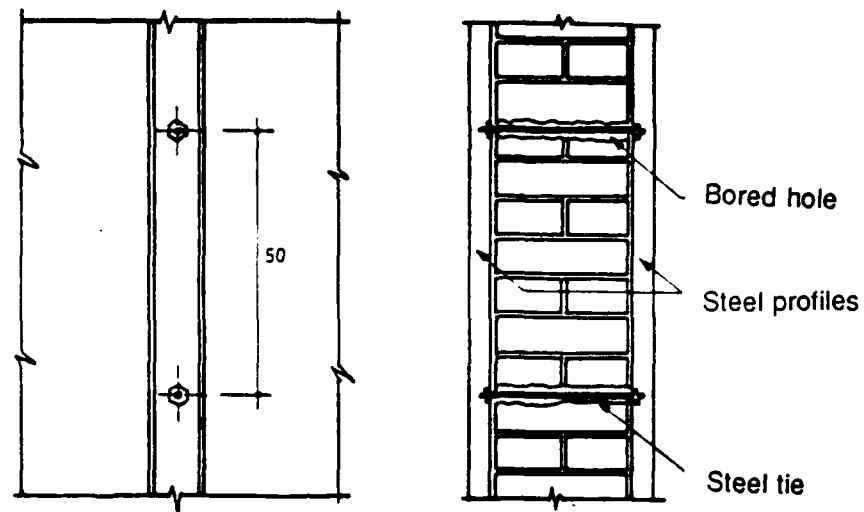
- Steel plates can be inserted between two layers of both walls to bridge the separation or crack zone. The plates are attached with mortar or other adhesive as illustrated in Figure 53a. To allow insertion of the plates, bricks must be removed and be placed. The method will not close the crack so the remaining gap or crack between both walls must be filled (Reference 14).
- To avoid the removal of bricks at the intersection, holes can be bored horizontally all along and perpendicular to the crack. Steel rods must be inserted to bridge the gap between both walls. The rods are attached with grout or epoxy resin (Reference 14).

If the separation between the walls is significant, the gap must be closed before the intersection is repaired. The loose wall can react against a steel channel attached to the perpendicular wall by means of tie rods anchored at both sides of the perpendicular wall, as shown in Figure 53b. The wall can be straightened by tightening the bolts with a wrench. After the gap has been closed, the remaining cracks should be repaired as mentioned above. The tie bars and channel should be protected against corrosion (Reference 14).

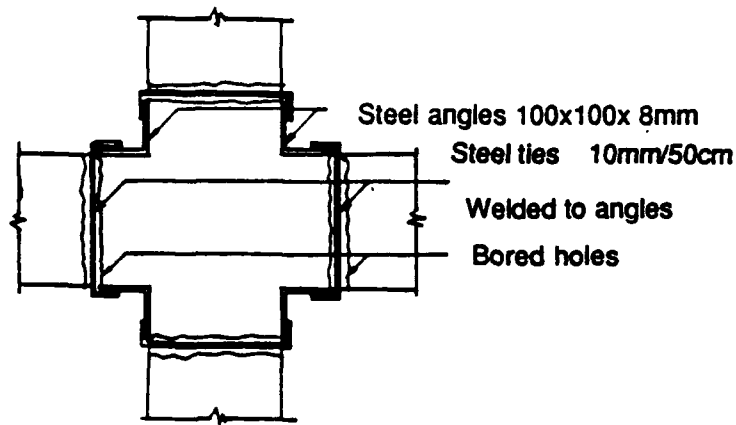
E. ADVANCED TECHNIQUES FOR REPAIR

The techniques described here to restore (or upgrade) the damaged element strength and stiffness require more time and effort. The technical background and preparation of the people that are needed to implement advanced solutions is considerably higher than needed for the solutions described previously.

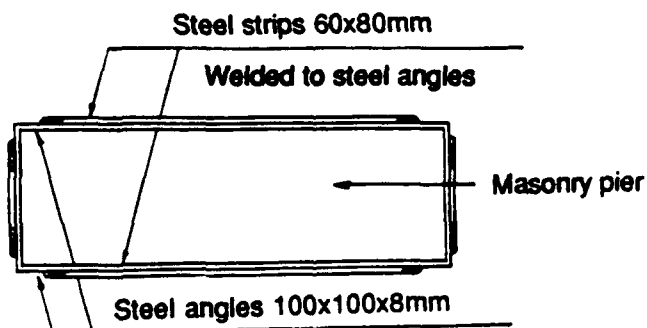
A repair or strengthening scheme is classified as advanced when its implementation alters the overall structural behavior under severe loads. Special care must be focused on avoiding the creation of weak links while repairing the structure. Basic knowledge of the behavior of the structure before and after the implementation of the strengthening scheme is essential to prevent further problems in the structure.



(a) Out-of-plane strengthening of masonry wall.

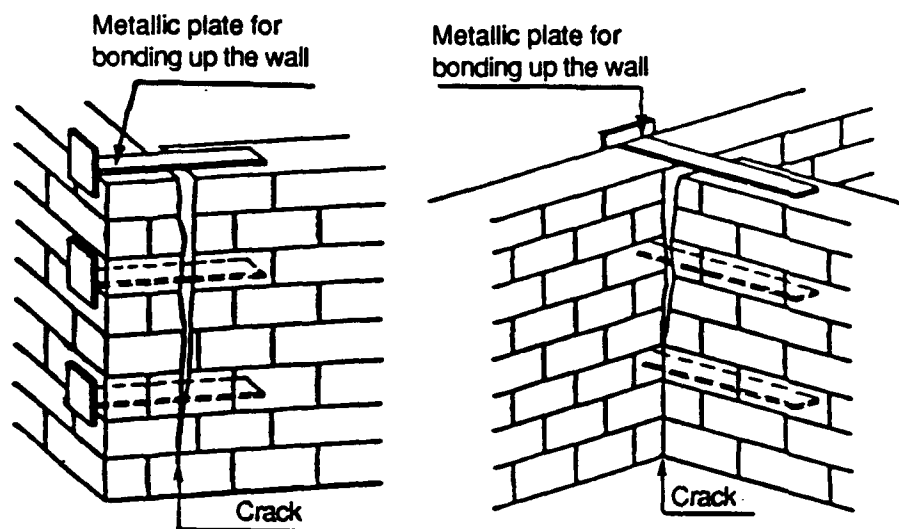


(b) Intersection detail for perpendicular walls, out-of- plane strengthening of masonry walls

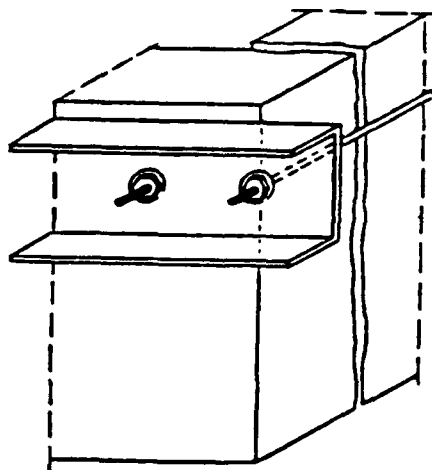


(c) Steel jacketing of masonry pier

Figure 52. Strengthening Masonry Walls with Steel Elements (Reference 14)



(a) Repair of wall intersection with steel plates



(b) Attachment of untied masonry wall to perpendicular wall

Figure 53. Repair of Wall Separations (Reference 14)

1. Repair and Strengthening of Existing Elements.

Perhaps the most important aspect involved in the repair and strengthening procedures to be described in this section is the achievement of adequate bond between old and new materials (See Section IV.D.1.a.)

a. Increase in Thickness (Walls and Slabs)

Damaged large plane elements such as structural walls and slabs can be repaired or strengthened by this procedure. When a wall is damaged or has insufficient strength, the section of the wall can be increased. To enhance the shear capacity of the wall, new material must be added to make it thicker, as shown in Figure 54. For flexure, the new material should be added at the flanges. Both shear and flexural capacity can be upgraded simultaneously by thickening or increasing the entire wall.

Monolithic behavior is achieved by properly preparing the contact surface, and by adequately tying new steel to the existing wall (welding existing steel or using steel anchors). Figure 54 illustrates a common procedure using steel epoxied bars or expansion inserts with 90° hooks (Reference 14).

Normally new concrete is shotcreted; however, cast-in-place procedures can be used. Due to the basketing effect achieved, better behavior of the wall is obtained when the section is increased on both sides. The structural wall must have continuous reinforcement over the height of the building. To achieve a proper transfer of forces between the slab and the wall, holes must be drilled into the slab to allow the placement of continuous longitudinal reinforcement bars and to permit the placement and compaction of new concrete as shown in Figure 55. Data available from different tests suggest that the strength and stiffness of a wall upgraded by this technique can be as high as that of a monolithic wall if adequate anchorage is provided between the new and old material (References 14, 30, and 36).

In case of a damaged or undamaged slab with insufficient strength or stiffness, an increase in section can be accomplished by adding concrete and reinforcement on the top and/or the bottom surfaces of the slab, as illustrated in Figure 56a. Normal cast-in-place procedures are usually used unless the concrete is added at the bottom part, in which case shotcrete is used. Shear transfer capacity must be enhanced to assure monolithic behavior of the slab (Figure 56b) (Reference 14).

b. Concrete Jacketing

The purpose of concrete jacketing is to enhance the axial, flexural and shear strength and stiffness of any element by wrapping it with an additional steel cage that could be formed either by new longitudinal steel plus ties or by welded wire fabric, and new cast-in-place or shotcreted

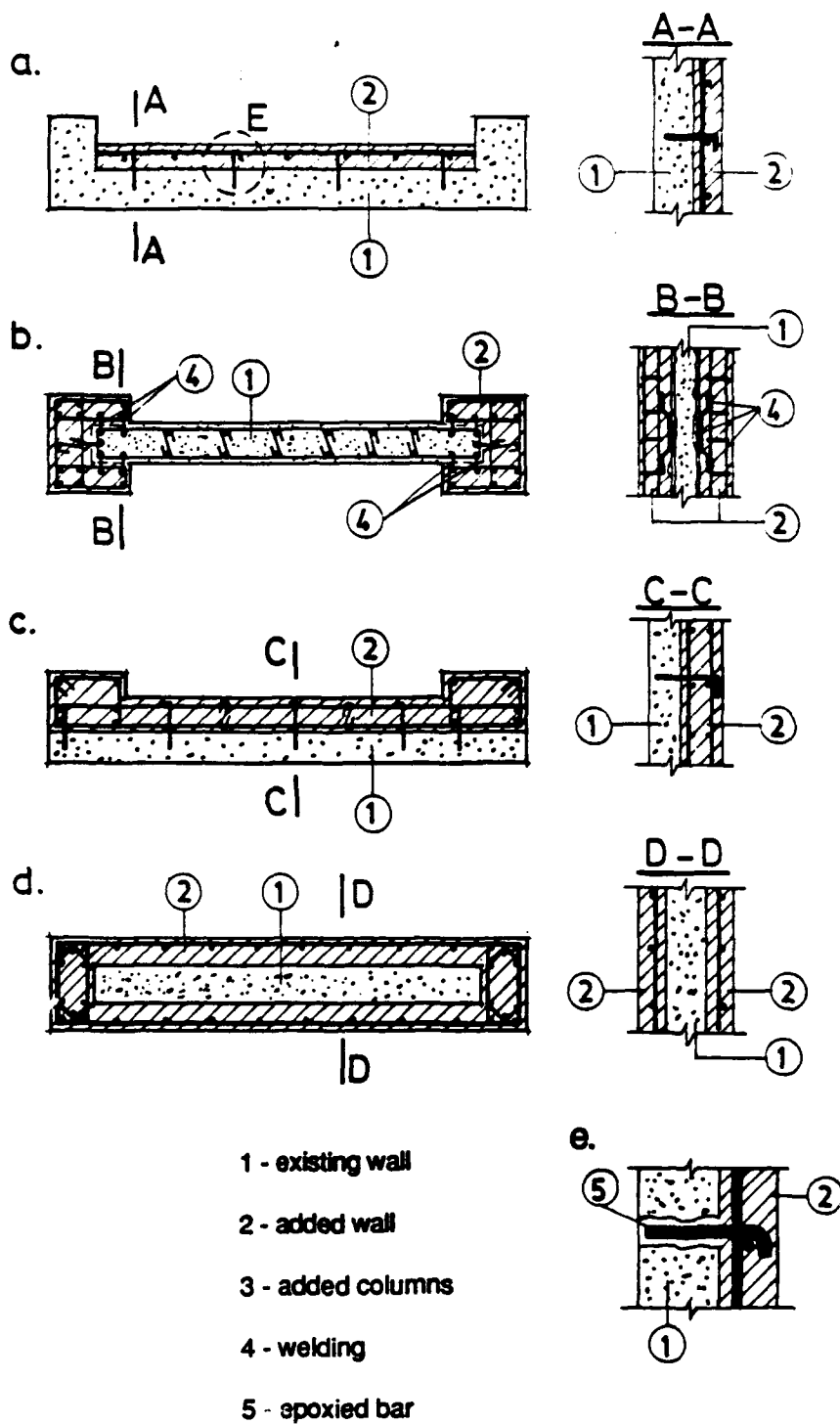
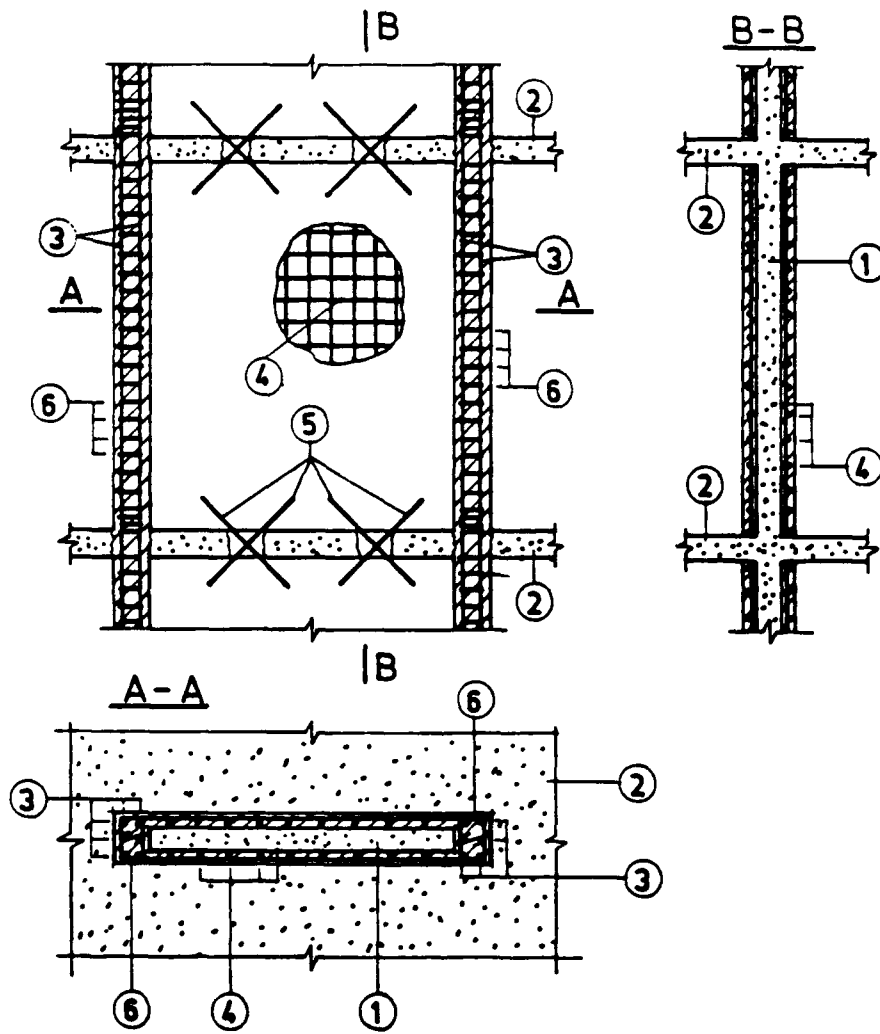
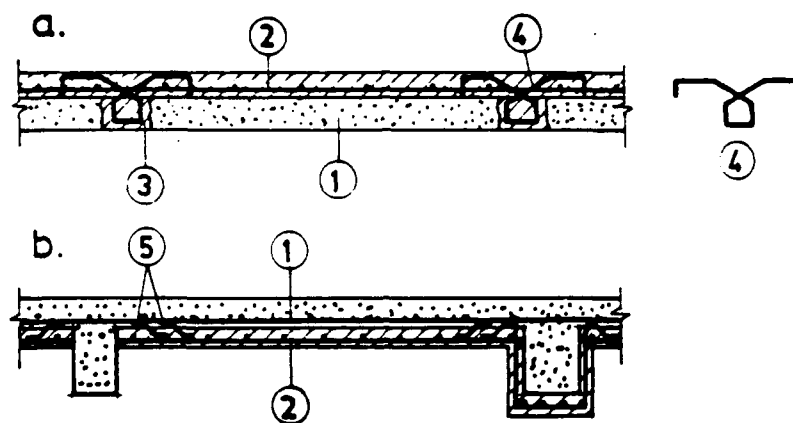


Figure 54 . Strengthening of Concrete Structural Walls (Reference 14)



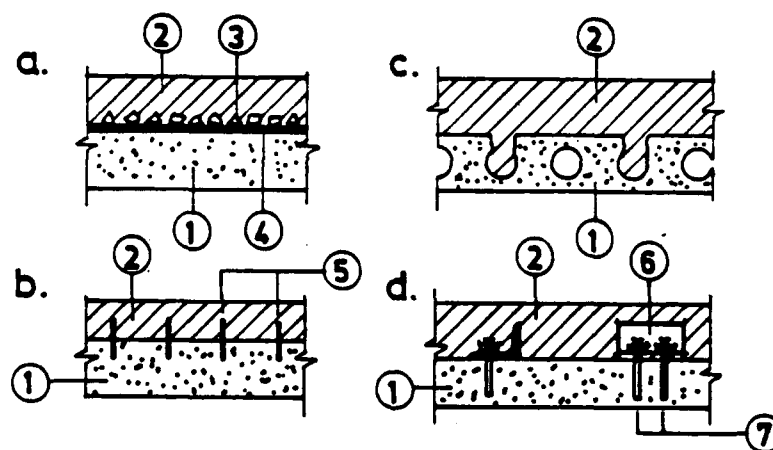
1 - existing wall; 2 - existing slab; 3 - added longitudinal reinforcement; 4 - added wire fabric; 5 - diagonal connecting bars; 6 - added ties

Figure 55. Strengthening of Structural Wall (Reference 14)



- 1 - existing slab
- 2 - added reinforcement
- 3 - dowel
- 4 - anchoring bent bars
- 5 - welded connecting bars

(a) Strengthening of concrete slabs



- 1 - existing slab; 2 - new slab; 3 - sand corner; 4 - epoxy glue;
- 5 - epoxied bolts; 6 - angle profile; 7 - anchor bolts or shoot nails

(b) Shear transfer mechanisms in concrete slabs

Figure 56 Slab Repair Procedures (Reference 14)

concrete cover. For flexural capacity, the jackets should be made continuous using holes drilled in the structure to allow the passage of the transverse and longitudinal reinforcement.

The contact surface between old and new material must be prepared and cleaned. It is important to have an irregular surface, normally attained by chipping or sandblasting to assure satisfactory monolithic behavior of the new and old concrete.

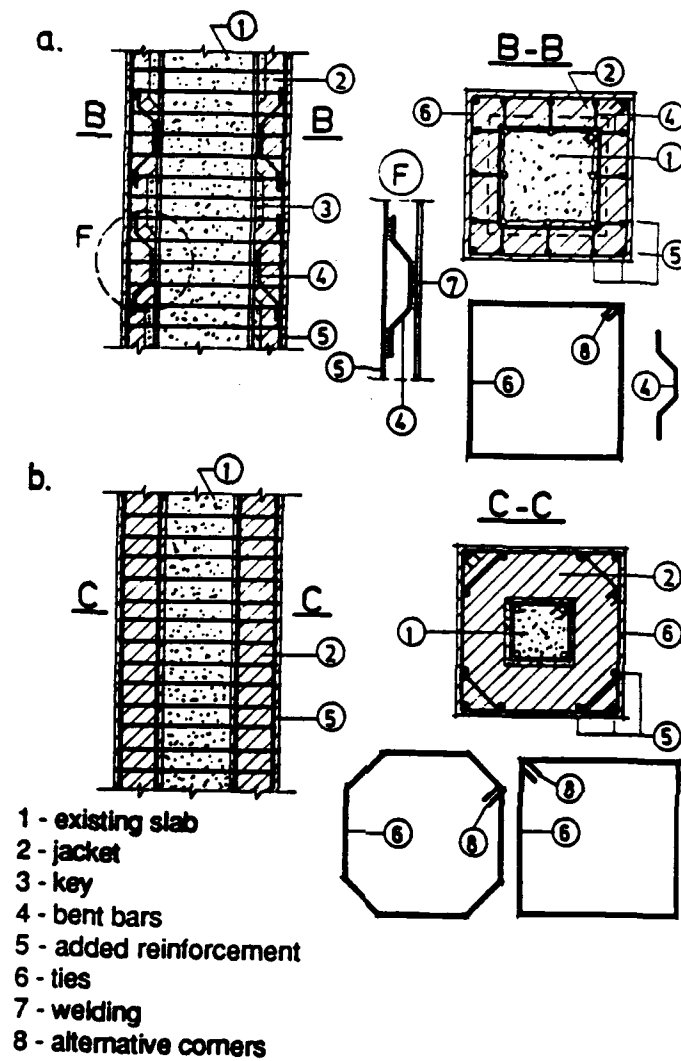
(1) Columns. The most common jacketing encases the whole column (four sides) and provides good bond and structural behavior. Longitudinal steel can be added at the corners to hold the ties in place. If the bars pass through the floor system the flexural strength is improved. The best behavior is obtained by distributing longitudinal reinforcement uniformly around the perimeter of the columns. However, this requires removing concrete from the beams - a difficult task. Figure 57 shows several alternatives for tie arrangement and for connecting old and new sections.

The use of welded wire fabric is limited to enhancing the shear strength and deformation capacity of the column due to the impossibility of passing it through the slab (Figure 57b). If construction space is limited, 1, 2, or 3 sides can be jacketed. Longitudinal steel must be confined by new ties, or attached to the old steel using welded connectors as shown in Figure 58 (Reference 12, 14). Tests have shown that the ductility of a column is greatly enhanced with a moderate increase in strength by jacketing. In these tests a gap was provided at the column end to avoid a significant flexural capacity increase (References 18, 42, 47, and 48).

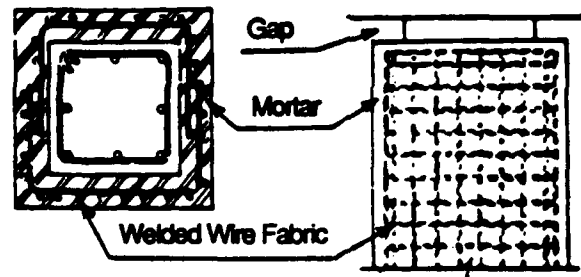
For flexural upgrade of columns, the reinforcement must be made continuous through holes drilled in the slabs. On the top column, the steel is usually anchored by welding it to a steel plate provided for this purpose and shown in Figure 18. In many cases, it is important to add transverse steel that crosses the beam at the joint to achieve good confinement in this critical region.

(2) Beams. In a similar way, beams can be jacketed to enhance their flexural and shear capacity. To upgrade the positive flexural capacity of a beam, the beam must be jacketed only on its bottom face, as can be seen in Figure 59. The new longitudinal reinforcement is normally attached to the original bars by means of welded connectors. To provide confinement, new ties are welded to existing ties. In order to reach yield of the new longitudinal bars adequate anchorage must be provided at both ends of the beam. This is frequently attained by anchoring the reinforcement to a angle collar placed around the column or by making continuous the reinforcement through holes drilled in the columns. Other anchorage methods are shown in Figure 18.

To enhance the shear properties as well as the flexural properties, 3 or 4 face jackets must be used as illustrated in Figure 59. If a 4 face jacket is used, the possible addition of top longitudinal steel would enhance the beam negative flexural strength. Some openings must be bored through the slab to allow the passage of new ties and the new concrete (References 12 and 14).



(a) Use of reinforcement (Reference 14)



(b) Use of welded wire fabric

Figure 57. Column Jacketing (Reference 14)

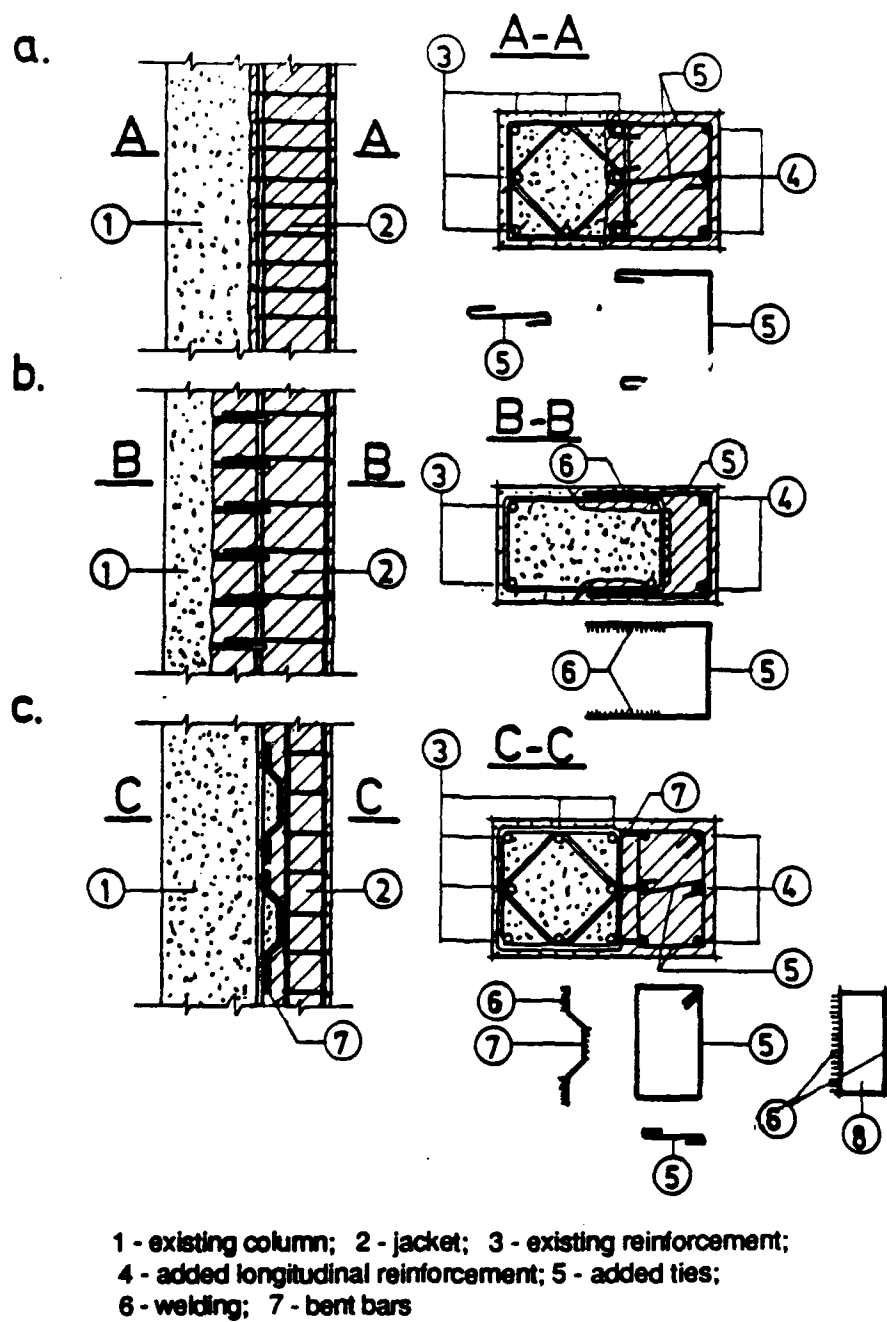
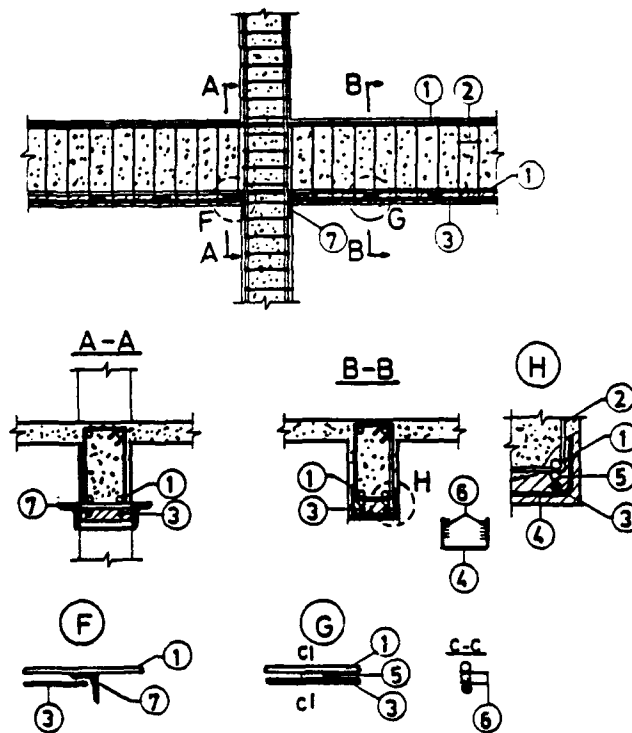
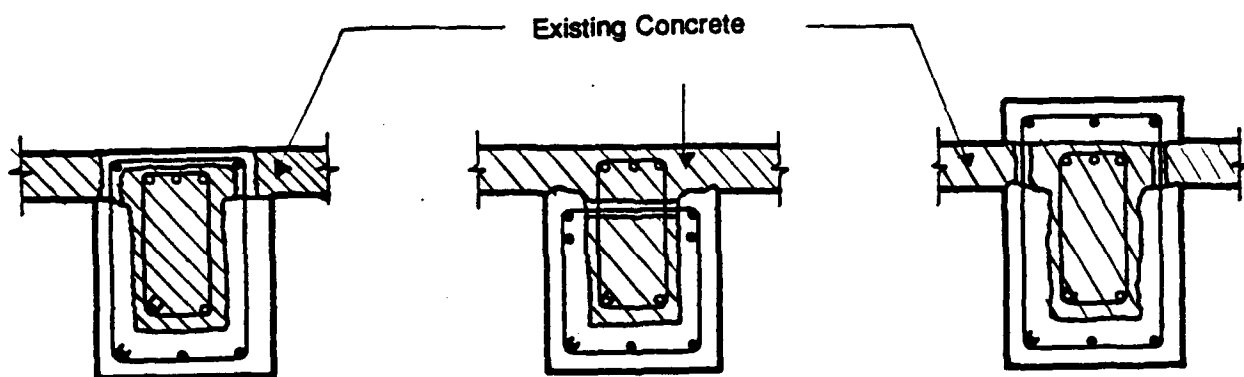


Figure 58. Jacket on One Side of Column (Reference 14)



1-existing reinforcement; 2-existing stirrups; 3-added longitudinal reinforcement; 4-added stirrups; 5-welded connecting bar; 6-welding; 7-collar of angle profiles

(a) Bottom face jacket



(b) Three and four face jacket

Figure 59. Interior Face Jacketing of Concrete Beam (Reference 14)

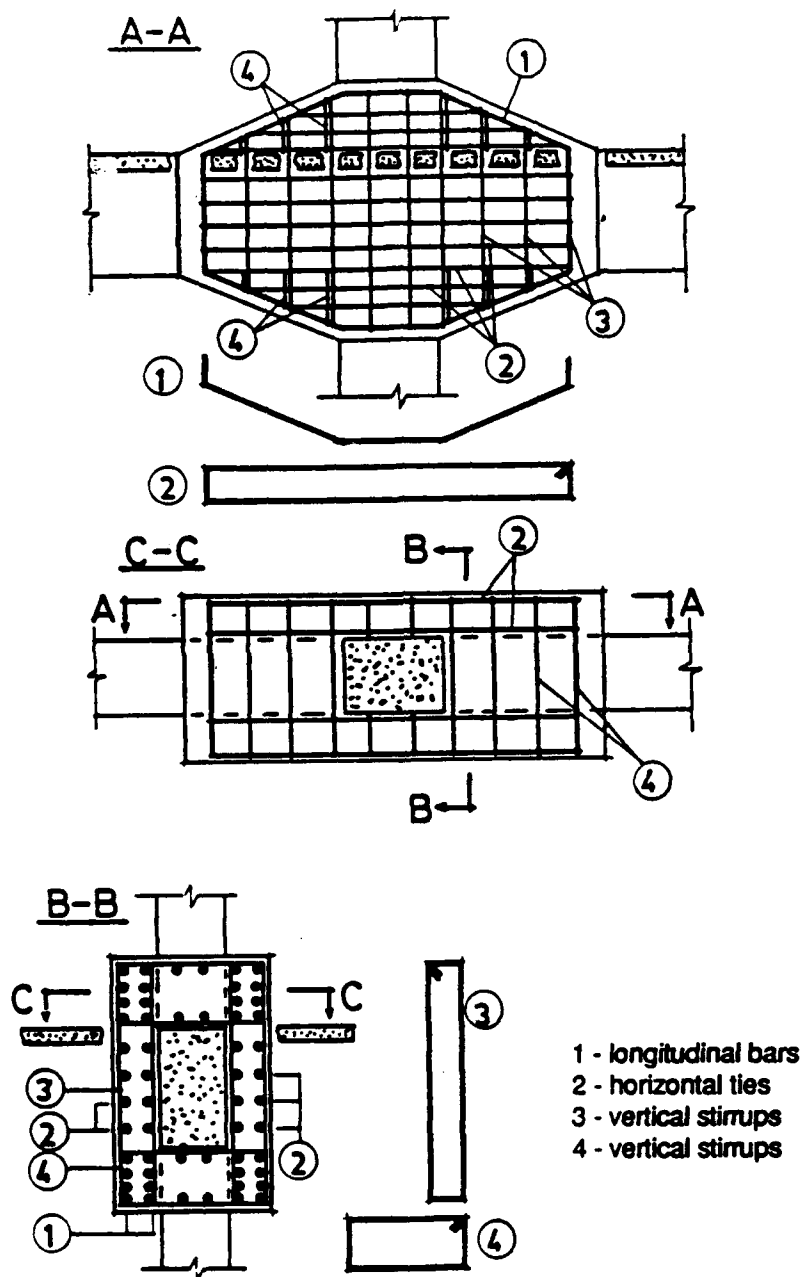


Figure 60. Local Jacketing of Joint (Reference 14)

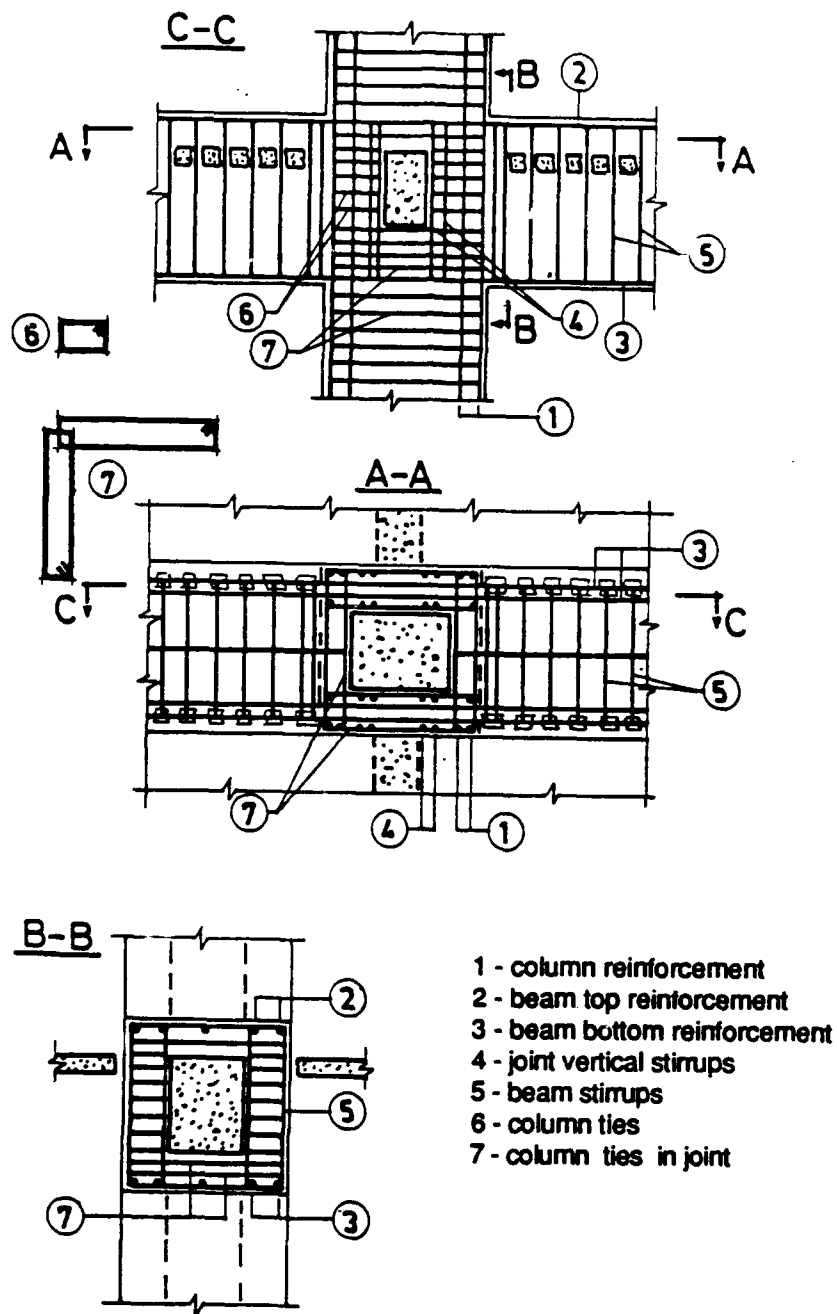


Figure 61. Global Jacketing of Joint, Columns and Beams (Reference 14)

(3) Joints. The joint can be locally repaired as shown in Figure 60 or from part of an overall jacketing scheme that includes beams and columns as shown in Figure 61. In both cases, it is important to provide enough horizontal and vertical transverse reinforcement to assure an adequate level of confinement. Holes must be drilled through the slab and sometimes through the beams to allow transverse reinforcement to effectively surround the joint (References 5, 12, and 14).

c. Masonry Walls.

If the masonry is severely damaged, the wall can be jacketed to restore and/or upgrade its vertical and lateral load-carrying capacities. The jacket can be added to one or both sides. If one side is jacketed, special care must be taken to adequately attach the jacket to the masonry wall. The jacket will also support the masonry against out-of-plane forces. Different materials have been used successfully to strengthen and repair masonry walls. Glass-reinforced concrete and steel-fiber-reinforced concrete have given satisfactory results.

Normally a reinforced concrete jacket is used. If the jacket is strong enough, the masonry wall does not need to be repaired prior to the jacketing. All the plaster, finishes and loose bricks must be removed and the masonry surface must be cleaned with air or water for a dust-free surface. The jacket is usually shotcreted; however, other manual procedures can be used to place conventional concrete. The masonry surface can be wetted to avoid absorbing water from the fresh shotcrete. If the masonry is sensitive to the addition of water, the surface can be prepared with a coat of cement milk or epoxy before the application of shotcrete.

The jacket should be reinforced with steel bars or welded wire fabric as appropriate. The reinforcement should be lapped with dowels into the foundation wall and concrete ring beams. Holes are bored in the masonry at regular intervals in horizontal and vertical directions to allow the passage of steel ties that tie the reinforcement on one or both sides, as illustrated in Figure 62. Figure 63 shows details for corners and intersections. The technique can be used for local repairs of masonry walls with openings, such as windows and doors, without jacketing the whole wall.

Appropriate curing must be provided to prevent excessive cracking or debonding of the shotcrete from the wall. Additional bars at the opening and at the edges of walls will enhance the scheme. For improved behavior the jacket should be continuous at corners, and the reinforcement must be adequately tied to the wall to prevent it from buckling or to separate from the wall (References 12, 14, 15, 19, 49, and 50).

Tests have shown good behavior for one and two-face jacketing of masonry walls with different materials by enhancing and rehabilitating the load-carrying capacity, improving initial stiffness and ductility. Two-side jackets ensure stability for in-plane and out-of-plane loading. Thin fiber reinforced coatings with hand application techniques show potential for a quick and economic solution (References 19, 49, 50, 51, and 52).

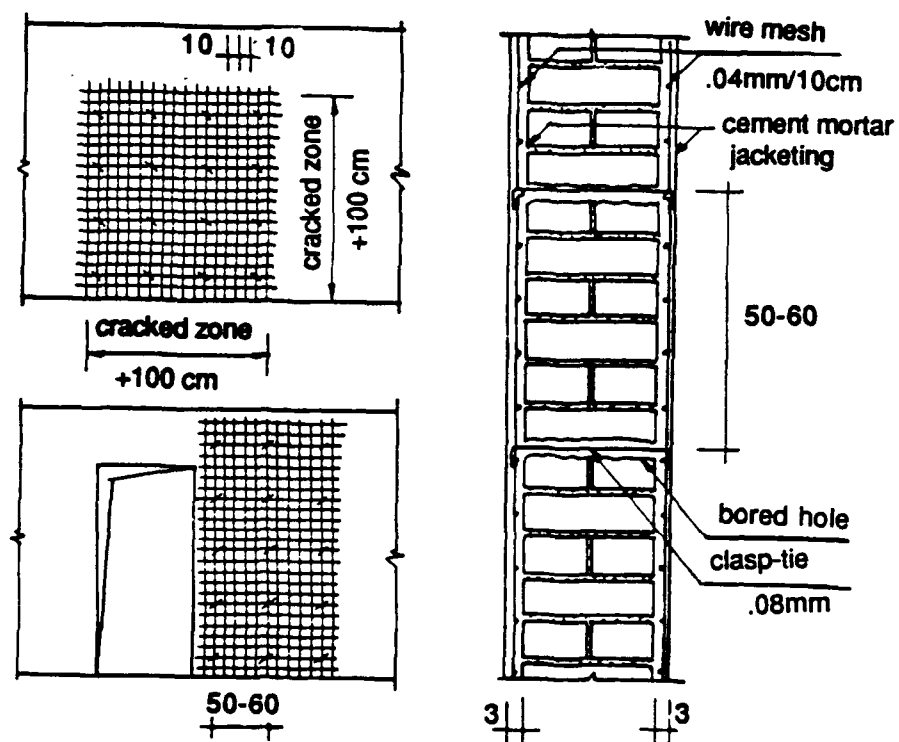


Figure 62. Jacketing Two Sides of Masonry Wall (Reference 14)

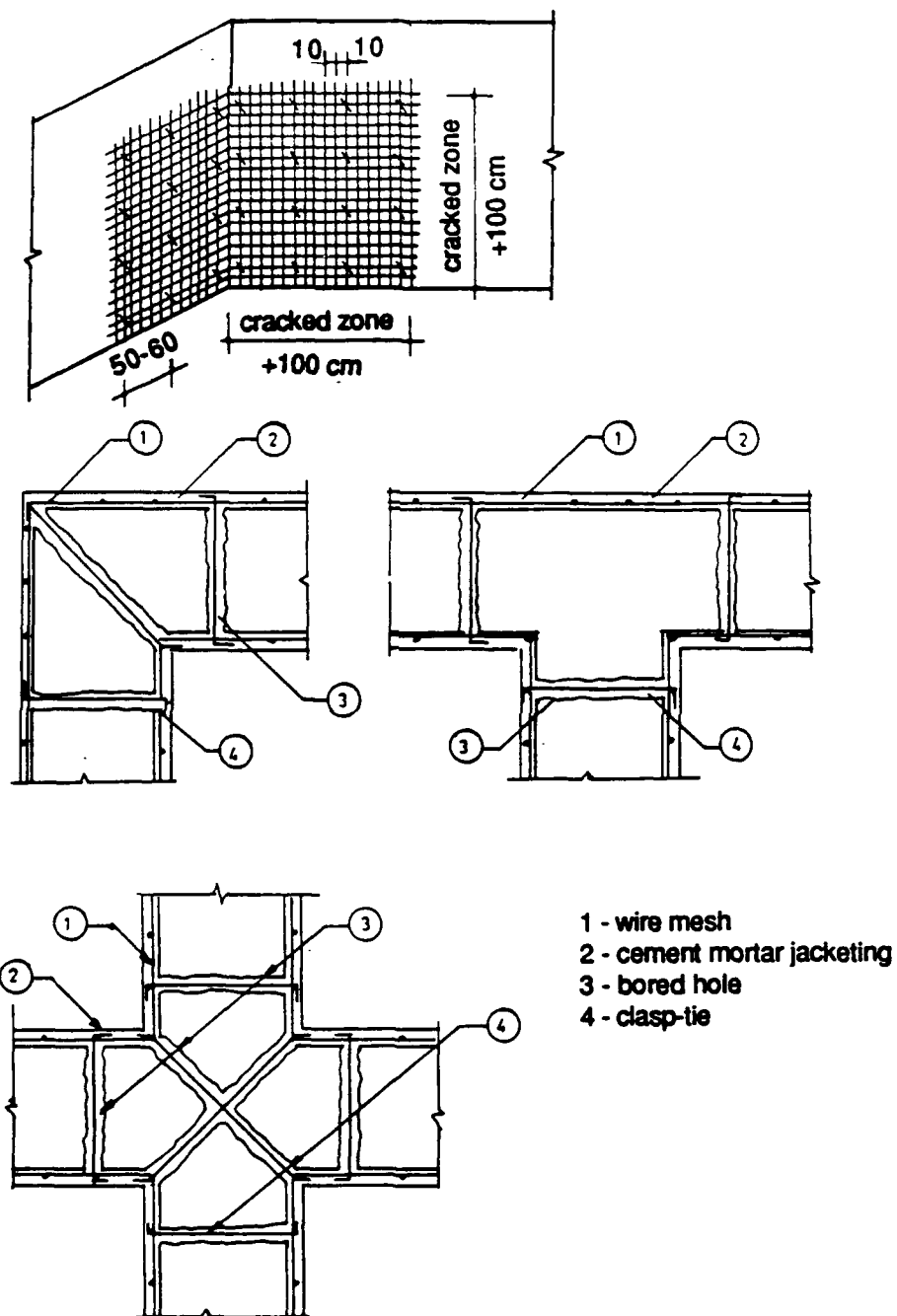


Figure 63. Details of Jacket on Two Sides of Masonry Walls for Corners and Intersections (Reference 14)

New Zealand practice includes the use of timber structural walls attached to the masonry wall inner face as a strengthening scheme. The studs of the wood wall are attached by means of grouted ties. Plywood sheeting is fixed to the studs to resist in-plane loading (Reference 50).

Similar methods to those mentioned in Section IV.D.2.e. can be used to strengthen wall intersections. To enhance the lateral load-carrying capacity of a masonry structure, the walls must be tied together and to the roof system to prevent them from falling in a plane perpendicular to that of the wall. Vertical reinforcement must be provided to confine the masonry. Three methods will be mentioned (References 12, 14, 15, 49, and 50).

- Prestressed tie rods attached at the upper part of both faces of the wall, properly anchored to a perpendicular wall as shown in Figure 64. Additional vertical rods, tied to the foundation, placed at corners and openings enhance the behavior of the system, compressing the masonry to minimize tension failures. Prestressing is a suitable solution for masonry structures, where no creep or shrinkage problems are expected (References 12, 49, and 52).
- Timber or reinforced concrete ties can be used to confine a masonry structure as shown in Figure 65. Vertical columns at corners and surrounding the wall openings will greatly enhance the scheme (References 12 and 49).
- External belts of reinforced mortar to provide adequate confinement. The method is similar to wall concrete jacketing mentioned above. Instead of jacketing the whole wall, only strips are jacketed at corners, openings and floor levels (Figure 66). Special care must be given to continuity of the welded wire fabric around the corners (Reference 12).

d. Special Techniques

The versatility of post-tensioning allows its application to the strengthening of different kinds of structural elements, mainly concrete floor systems or masonry walls. The repair procedure can be done while the structure remains essentially in operation (References 11, 29).

To strengthen or close cracks on a flexural element, different post-tensioning schemes can be used (Figure 67a). In concrete elements the prestressing cables can be placed on a vertical or horizontal position. The cables can be placed against the surface of the element and fixed in place by covering them with concrete. Usually, external prestress is used, in the latter case, suitable and adequate deviators and anchoring devices must be provided (Figure 67b). The external tendons can be covered with cast-in-place concrete or shotcreted to protect them from corrosion and fire.

Stress losses can be expected due to creep of the concrete and slip in the anchorage devices, especially in the case of short spans and heights. The compression force introduced,

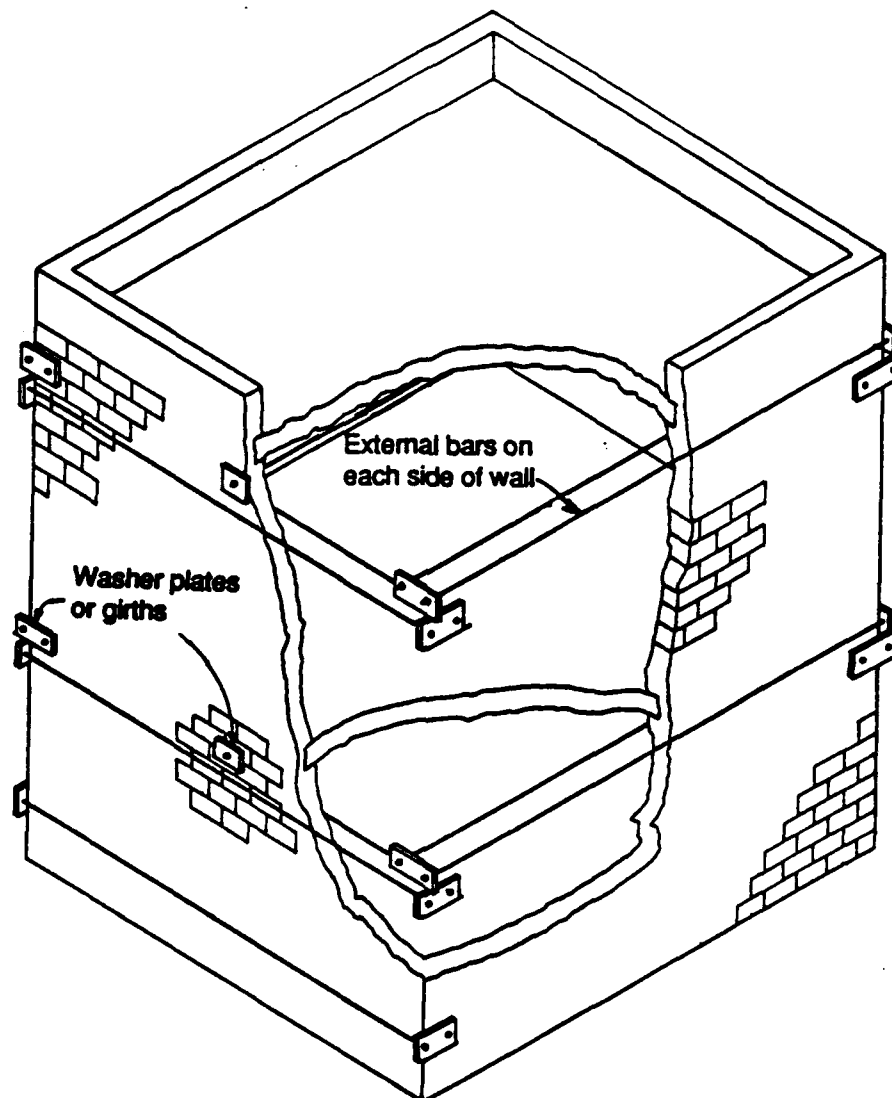


Figure 64. Strengthening of Wall Intersections with Post- tensioned Tie Rods (Reference 52)

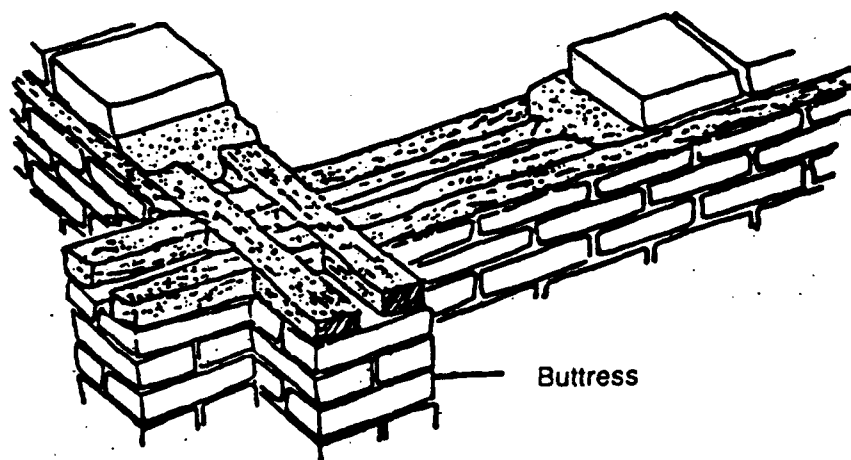


Figure 65. Strengthening of Wall Intersections with Perimeter Ties (Reference 12)

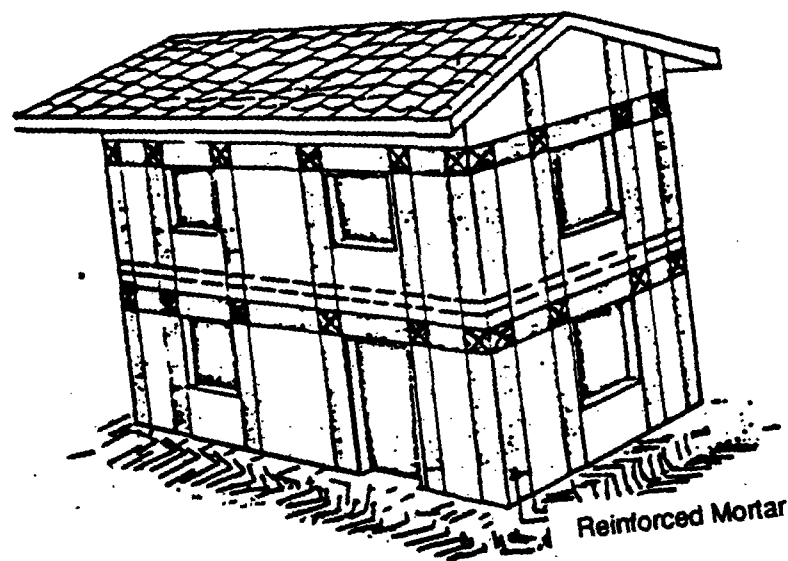
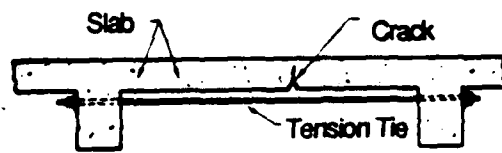
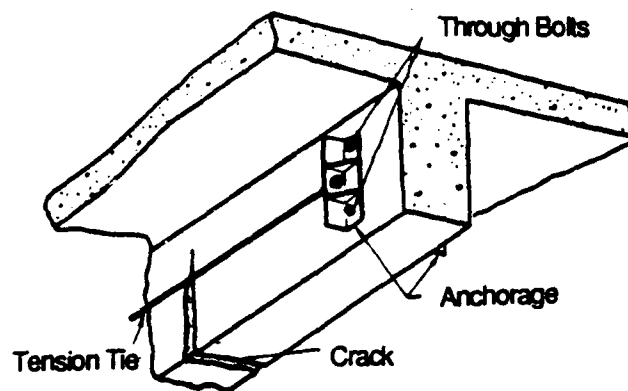


Figure 66. Strengthening of Masonry Structure with External Belts of Reinforced Mortar (Reference 12)

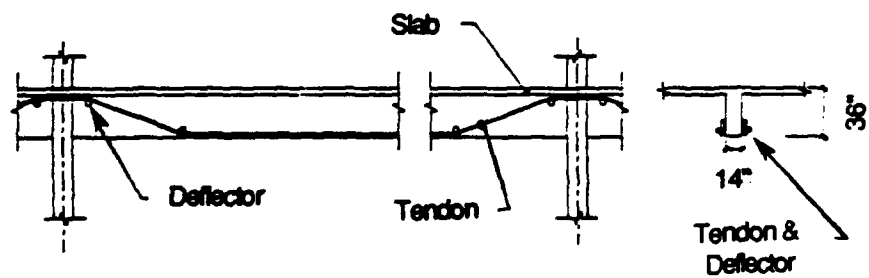


To Correct Cracking of Slab



To Correct Cracking of Beam

(a) One span (Reference 37)



(b) Multiple spans (Reference 29)

Figure 67. Strengthening with External Prestressing

changes in shear stress, effects due to creep, secondary moments and induced reactions must be carefully studied to avoid damage to the existing structure (References 11, 15, 29, and 37).

In case of damaged precast buildings, the joints can be reinforced by means of short steel bars embedded in grooves made in the panels and filled with resin mortar. See Figure 68 (Reference 11).

2. Structure Strengthening by Addition of New Elements.

The addition of new elements must be considered when the lateral force carrying capacity of a damaged or undamaged structure is not able to resist the expected lateral forces, or when the damage is extensive and existing elements are not capable of being repaired to satisfy failure loading demands.

The new elements must be placed within the structure to correct existing deficiencies without creating new problems. In each case the solution depends on the type of structure and loading anticipated. The behavior of the existing structure under extreme loads must be understood clearly by the designer to improve performance and to avoid creating weak links in the existing structure when new force paths are developed using the added elements.

To properly design the additional elements, compatibility of the stiffness of the original structure and the new elements must be considered so that the distribution of the loads can be determined. The load-carrying elements of the existing structure must be able to deform without failure when the modified structure is subjected to lateral deformations.

Connection details between the new elements and the original structure must be carefully designed and constructed to achieve proper force transfer and for the new elements to be fully effective. Special attention must be focused on the forces introduced by the new elements on the existing foundation. In some cases, the foundation must be strengthened and the possibility of building new foundation members must be considered to support such forces.

Particular care must be exercised in tying the horizontal floor diaphragms to the new lateral load resisting elements. In some cases, the slab may have to be strengthened for adequate transfer of forces (Reference 15).

Numerous alternatives can be implemented to provide resistance to lateral loads such as structural walls, precast units, different kinds of braces and masonry walls. In all cases, the new elements must be properly attached and the stress transfer behavior of various components in the system must be understood (Reference 30).

Figure 69 shows qualitative sketches of the efficiency of different infill schemes to improve the strength and deformation capabilities of an existing structure (Reference 42).

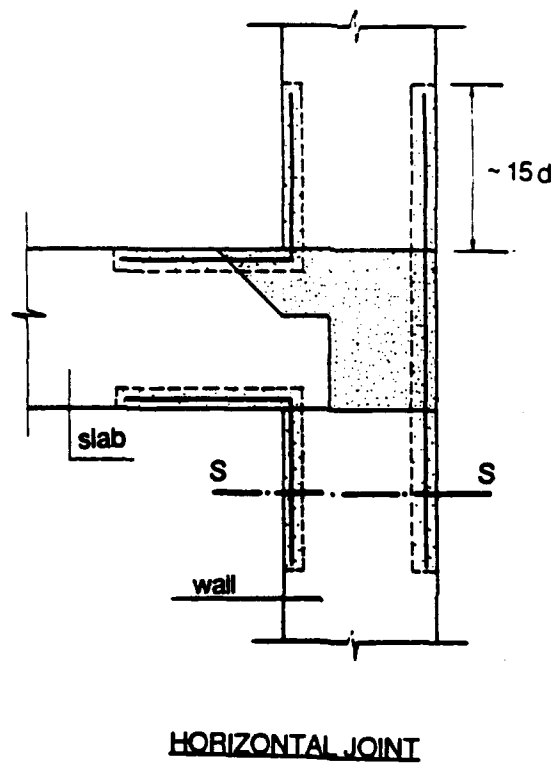
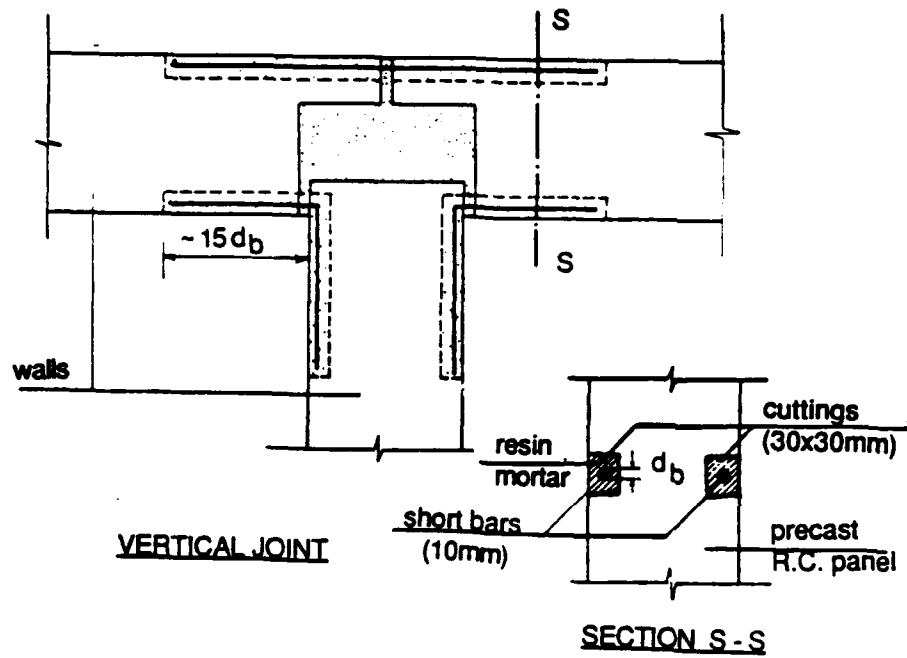


Figure 68. Strengthening of Precast Concrete Structure Joints (Reference 11)

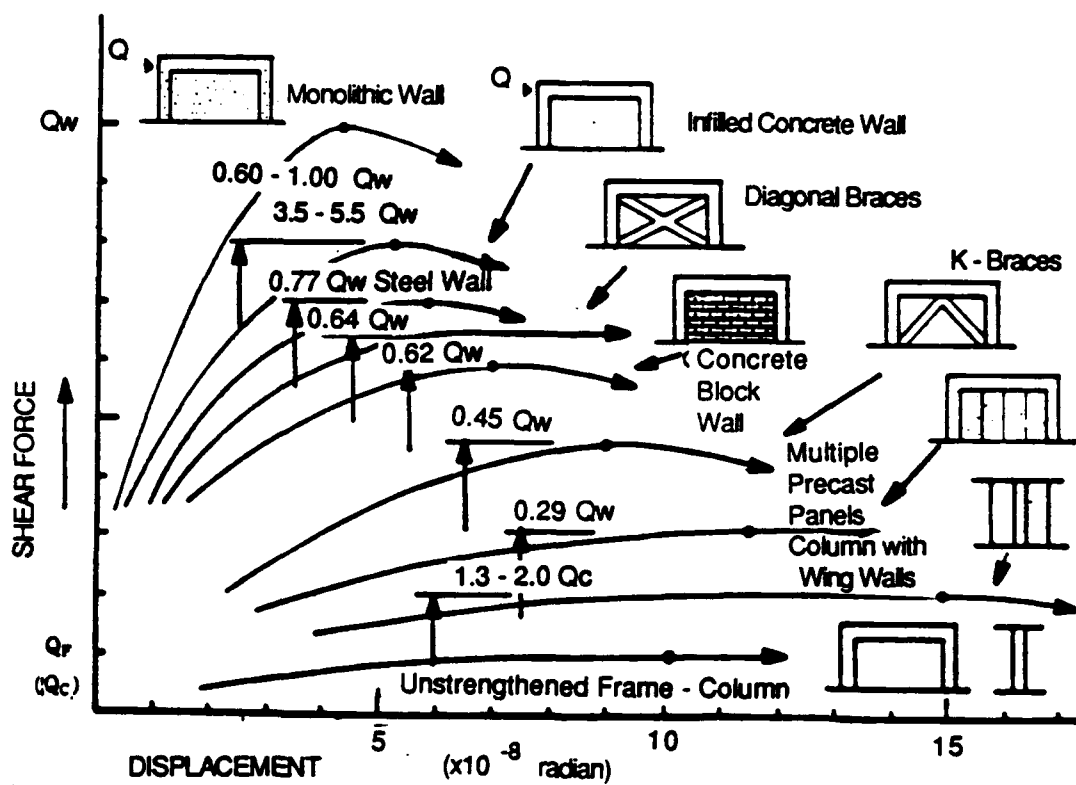
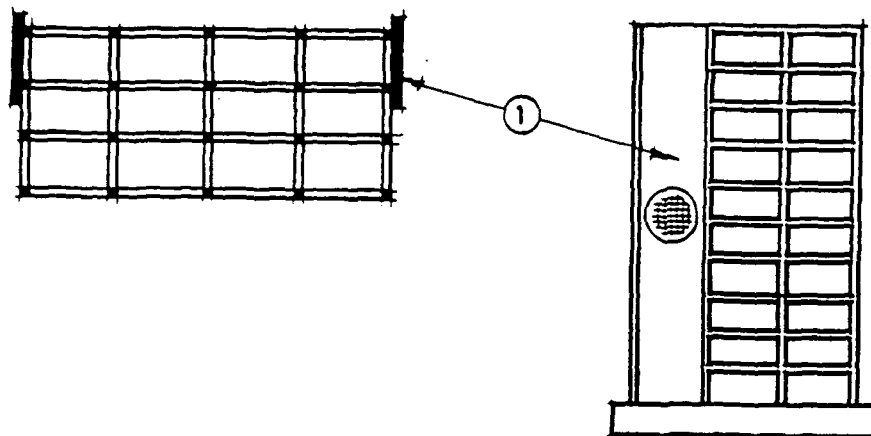
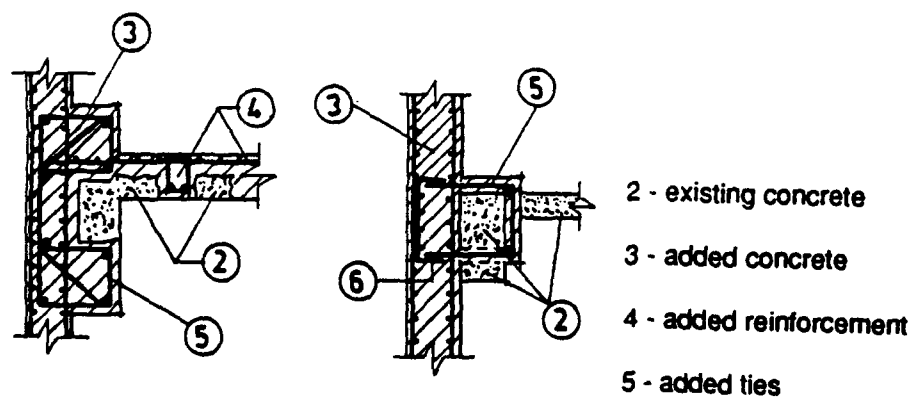


Figure 69. Typical Load-displacement Relationships for Different Strengthening Techniques (Reference 42)



1 - added shear wall

(a) Addition of external structural walls to existing structure



(b) Connection details between new structural wall and existing structure

Figure 70. Addition of Shear Walls (Reference 14)

a. Structural Walls

The addition of structural walls to a structure is one of the most common procedures used to enhance lateral force capacity (Figure 70). The walls are normally cast-in-place or shotcreted. Prefabricated concrete elements are difficult to use because economic and adequate connection details do not exist and prefabricated units are not frequently used (References 14, 27, 33, and 34). Normally, new walls are added on the external face of perimeter frames to avoid creating interference to the normal functioning of the building. Flexural and vertical web shear reinforcement must be continuous over the height of the wall. The wall must be properly attached to the structure to allow the wall to develop its full design capacity without damaging the existing floor diaphragms and/or foundation. Some methods used to attach walls to the existing structure are illustrated in Figure 20 (References 12, 14, 27, and 50). If beams are present in the floor system, shear walls should be offset from the frame girds to allow continuity of the wall reinforcement. In such cases, eccentric effects on columns must be considered (Reference 50).

When the wall must be added inside the structure, holes must be drilled in the slab to allow the passage of the longitudinal reinforcement, to allow the placement of diagonal shear reinforcement and to allow the placement and compaction of the new concrete during casting operations (Figure 71). Special care must be placed on adequate contact between the bottom surface of the slab and the top surface of the new wall beneath the slab. To reduce the shrinkage of the wall, expansive or shrinkage compensating concretes can be used. Common practices involve the use of dry pack or injection of epoxy resins or resin mortar in the existing gap. Enough transverse steel must be provided at the base of the wall to improve ductility and prevent buckling of the longitudinal flexural steel. The wall must be attached to existing columns whenever possible, so that vertical gravity loads counter the uplift at the ends of the wall under lateral loading (References 11, 14, 23, 27, 53, and 54).

b. Infill Walls

Reinforced concrete, steel or masonry infill walls in a frame structure enhance its stiffness and lateral load-carrying capacity (Figure 72). Concrete infill walls are normally cast-in-place or shotcreted. If the connection between the infill and the surrounding elements is appropriate, the wall can achieve a strength equal to a monolithic wall with the existing columns as flanges. Such infills significantly increase the strength of the existing frame (References 14, 18, 42, 47, 48, 53, and 55).

If the old elements and the wall do not behave as monolithic units due to improper connection details, the wall will act as a rigid diaphragm that introduces high local stresses to the surrounding elements. Special care must be taken to anchor the infill wall properly. Normally, dowels are used at the interfaces between the frame and infill. The column axial capacity (including

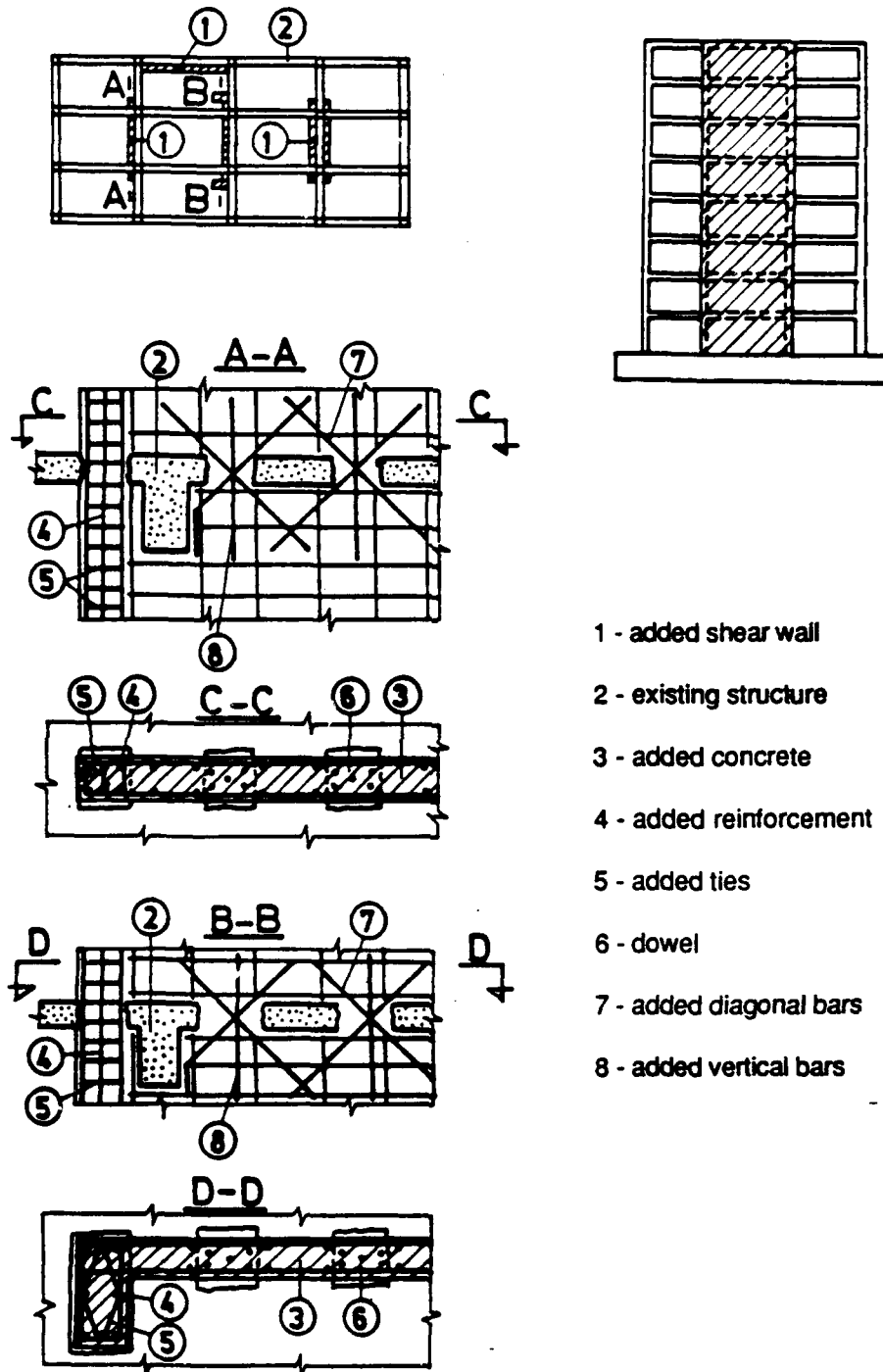
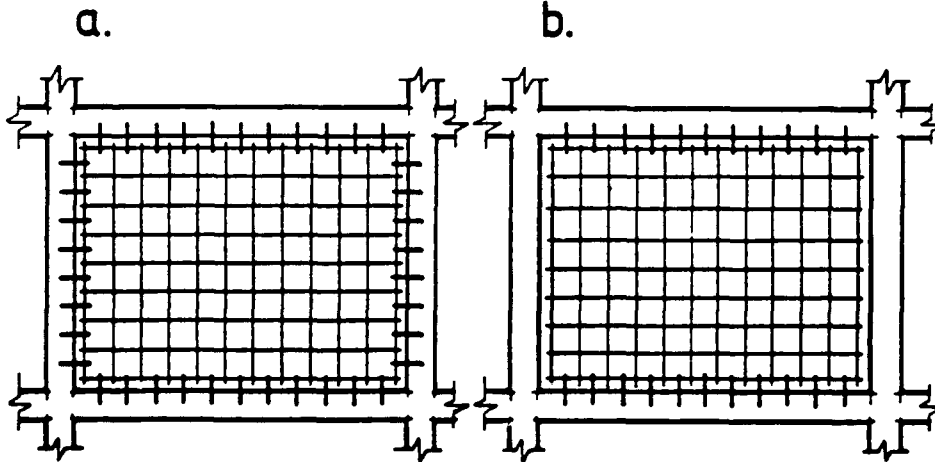
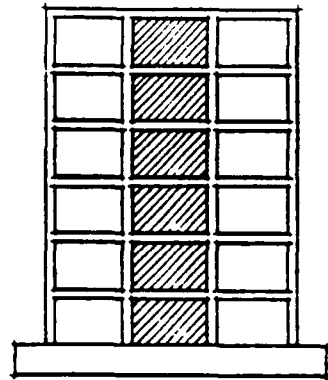
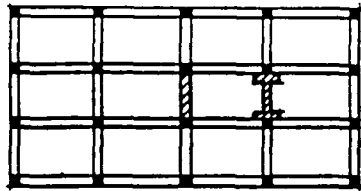


Figure 71. Addition of Internal Structural Walls to Existing Structure (Reference 14)



a - cast-in place infilled shear wall

b - cast-in-place infilled shear wall separated from columns

Figure 72. Addition of Infill Walls to Existing Structure (Reference 14)

splices) must be sufficient to resist the tension forces at the boundaries of the structural wall (Reference 12).

Figure 72 shows the two ways to attach an infill wall to the existing structure. If columns are strong enough to resist the axial forces introduced, dowels at all edges as shown in Figure 72a can be used. In the second case, ductile behavior can be achieved if space is provided between the new wall and the existing column (References 14 and 42).

Steel dowels and concrete shear keys are the most common methods to provide shear transfer capacity between the wall, columns and beams. Sometimes the vertical as well as the horizontal reinforcement of the wall is anchored to the previously uncovered reinforcement of the existing elements. Figure 16 illustrates possible connection details for infill walls and surrounding columns and beams. Although these shear transfer mechanisms are extensively used, a reliable design method is not currently available. The design of details such as dowel anchorage length and surface roughness is often an intuitive process rather than an established procedure. Special care must be taken to provide good contact between the upper part of the new wall and the bottom surface of the beam (References 12, 14, 23, 24, and 25).

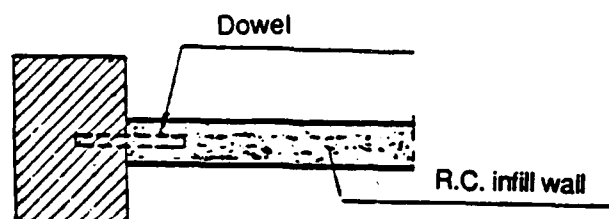
An alternative is to jacket the beams and columns of the existing frames when the wall is added. The addition of extra reinforcement in the jacketed elements (Figure 73) helps to diminish problems in the transferring shear between existing frame and new wall. The new column longitudinal reinforcement must be continuous through the height of the building (Reference 23).

The repair scheme can include the use of prefabricated walls attached to existing elements. Such elements provide an economical solution for quick repair whenever the strengthening of the structure must be restored as fast as possible without interfering in operational functions.

Steel shear panel is formed by steel plates with stiffeners, adequately spaced ribs in both directions to avoid buckling of the wall. The steel walls can be attached to the existing structure with anchor bolts. Protection against corrosion and fire must be provided. Test data for frames strengthened by means of steel shear walls show that the walls have adequate energy dissipation, improved strength and high ductility (References 11, 56, and 57).

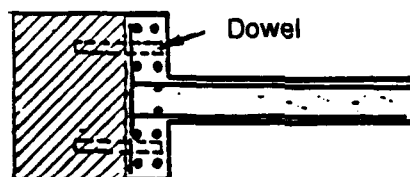
Multiple precast elements connected or separated can be used to fill the whole bay or a portion of it. Test data regarding the use of multiple precast panels show ductile behavior with a moderate to small strength increase. To enhance the ductile behavior of the system, a narrow gap must be provided between the panel and the existing columns (Reference 11, 18, 42, 55, 58, and 59).

Masonry infills, normally bricks or concrete block walls, can be used when the presence of large shear forces is not expected. The masonry must be confined to achieve better behavior. A concrete jacket on one or both sides (normally shotcreted) can be used (References 11 and 53).



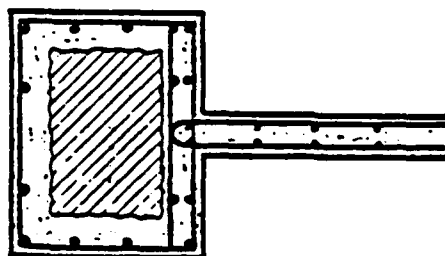
a)

if sufficient reinforcement
in the existing column



b)

If supplementary vertical rein-
forcement has to be added



c)

if the column has to be
strengthened for compression

Figure 73. Infill Wall Connection to Existing Column (Reference 14)

c. Wing Walls

When a bay can only be infilled partially, the use of cast-in-place or precast wing walls should be considered. Wing walls are a special variant of infill walls, in which the additional wall is added at both sides of the existing column, as shown in Figure 74. The new wall elements must be attached to the existing frame with procedures similar to those illustrated in the previous section. Wing walls are generally placed symmetrically about the existing column. They normally have less thickness than the existing column.

The effects of the wing wall on the structure must be studied carefully. The wing wall can introduce high negative moments near the midspan of the beam where only positive moment capacity has been provided in the original frame. The use of wing walls to stiffen and enhance the lateral force capacity of a structure may not be as efficient as the methods described in the previous two sections (References 11, 12, and 60). Test data show that wing walls can be used successfully to increase moderately the strength of a frame and its deformation capacity (References 42, 47, and 61).

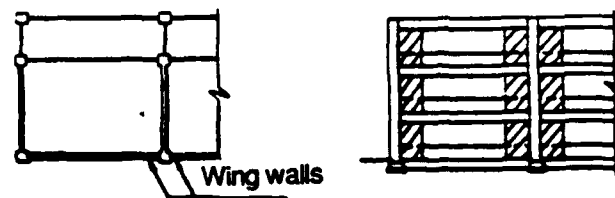
d. Braces, Frames and Trusses

If the available space within the structure is limited, the use of internal or external reinforced concrete frames and/or braces must be considered, as shown in Figure 75. The use of concrete elements in the repair scheme of the structure may be limited due to the increased dead loads that in some cases require expensive or impractical strengthening of the existing foundation. In such cases the use of lighter elements such as steel frames, trusses and braces is an adequate solution. Steel elements are more expensive and special techniques must be used to attach the new elements to the existing concrete. Connection details strongly influence the overall behavior of the strengthening scheme (References 53, 56, 57, 60, 61, 62, and 63).

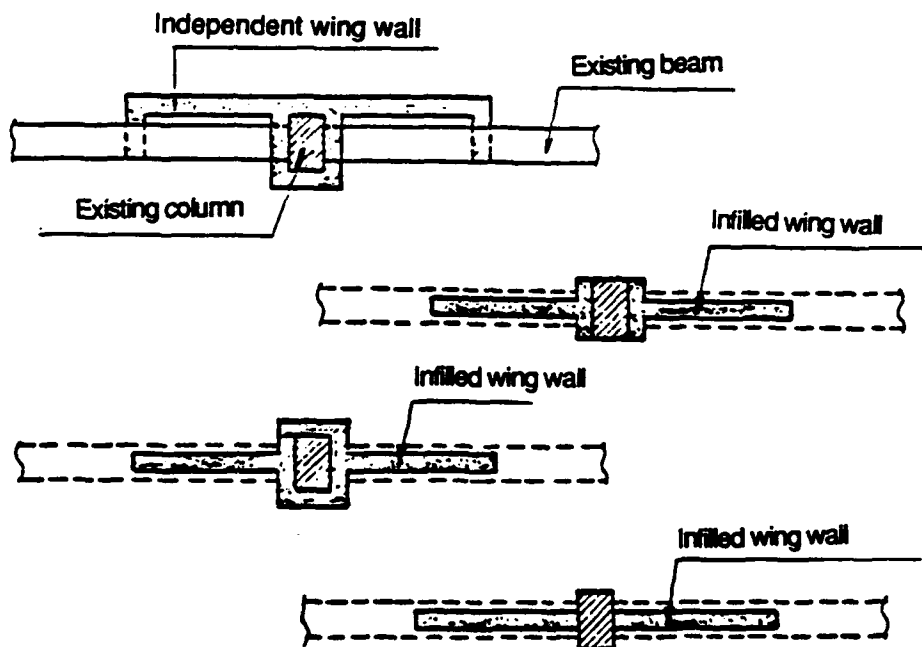
Diagonal steel bracing is a versatile technique which combines moderate strength, adequate energy dissipation, improved strength and high deformation capabilities. The bracing system is typically added on the perimeter frames. When required, the slab may need to be strengthened to transmit lateral shear forces from the structure to the bracing system (References 18, 42, 53, 55, 56, 57, 60, 61, 64, and 65).

The addition of infill braces can be considered when the beams and columns of the original structure have enough shear capacity to transfer the lateral force component from the brace to the floor diaphragm. If the shear capacity is not sufficient, the original elements must be strengthened or an internal frame must be provided to transfer the force between the brace and the floor system, as shown in Figure 76.

The use of steel braces to strengthen and stiffen a structure is a very common solution. The brace configuration can go from a simple diagonal or crossing diagonal (Figure



(a) Wingwall placement (Reference 42)



(b) Wingwall details (Reference 14)

Figure 74. Addition of Infill Walls to Existing Structure

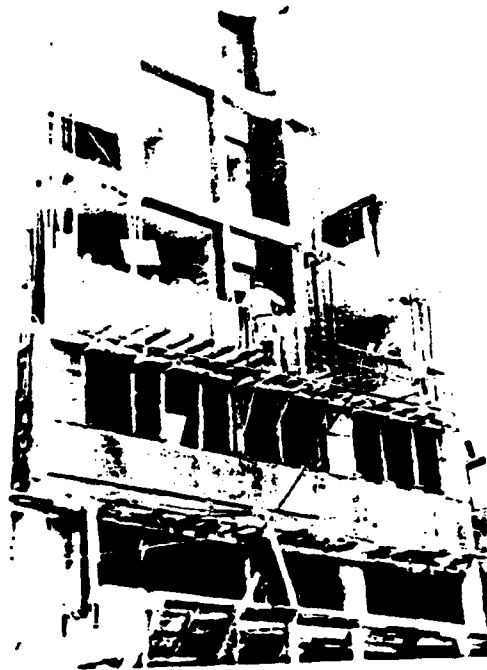


Figure 75. Addition of New Concrete Frame to Existing Structure (Reference 36)

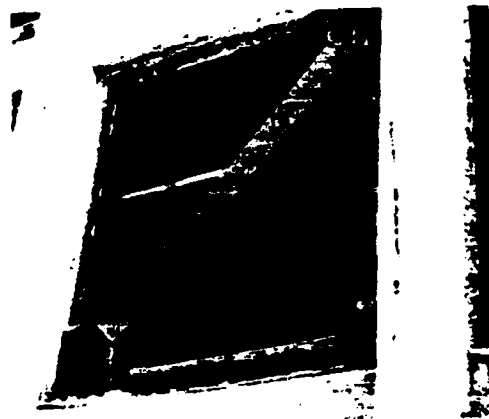
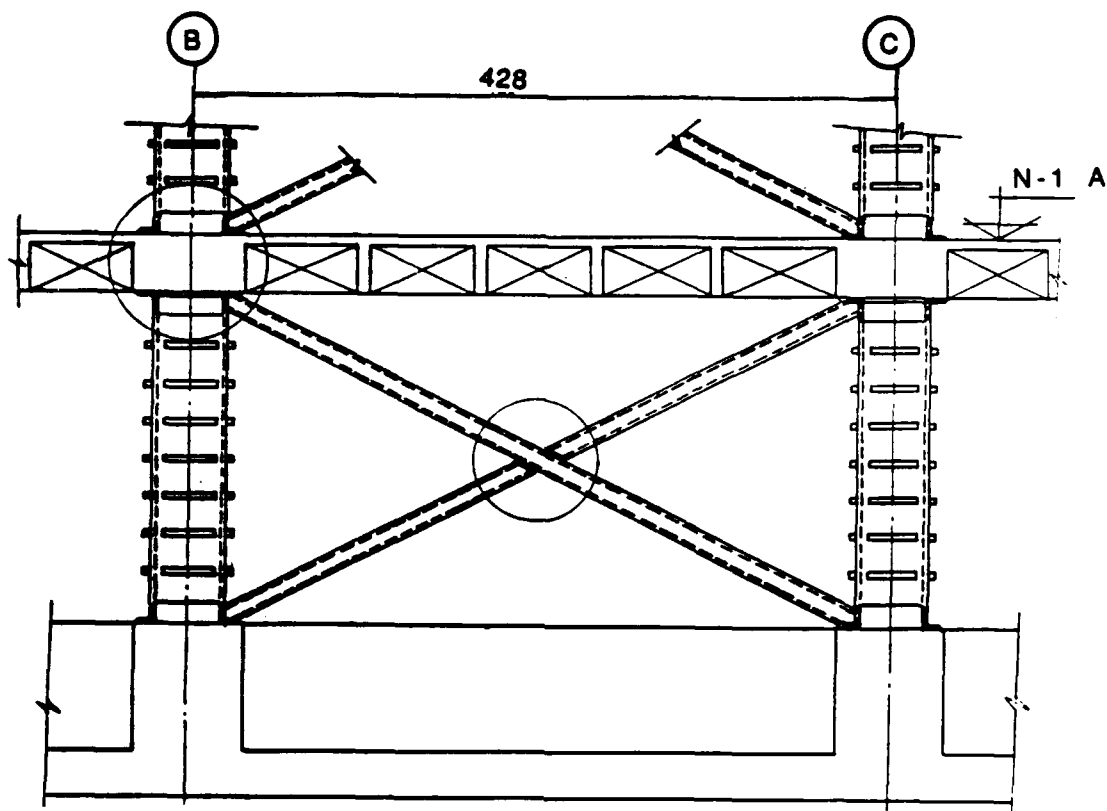
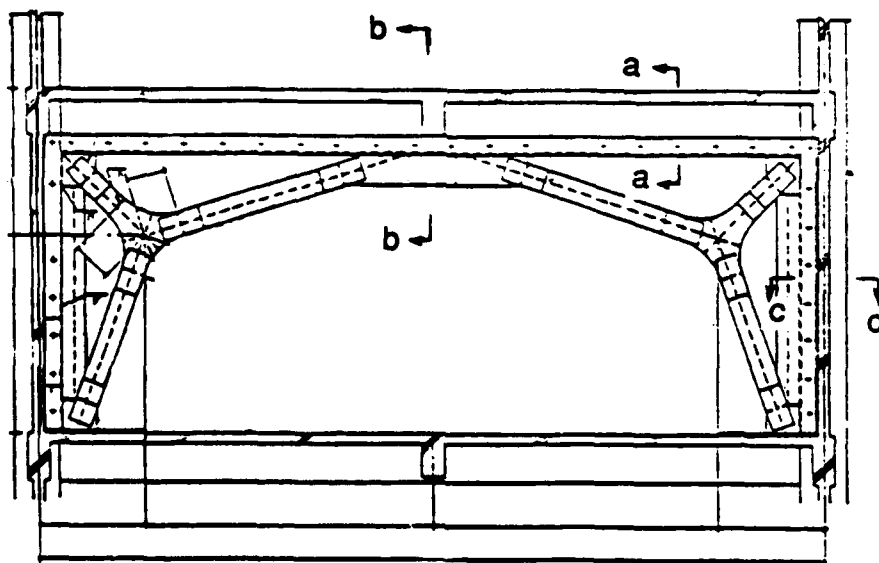


Figure 76. Diagonal Steel Compressive Brace (Reference 64)

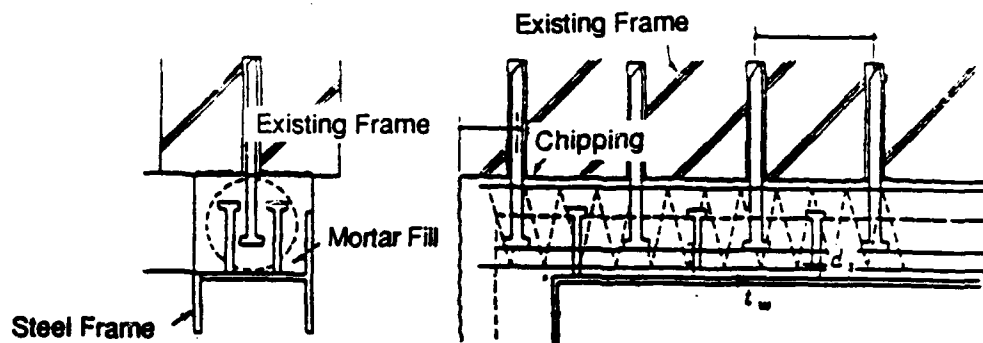


(a) Two-diagonal steel compressive braces (Reference 28)



(b) Arch-type brace (Reference 57)

Figure 77 . Types of Steel Bracing Systems



(a) Connection of peripheral frame of the bracing scheme and existing concrete (Reference 57)



(b) View of connection of peripheral frame and existing structure (Reference 23)

Figure 78. Use of Peripheral Frames in Bracing Schemes

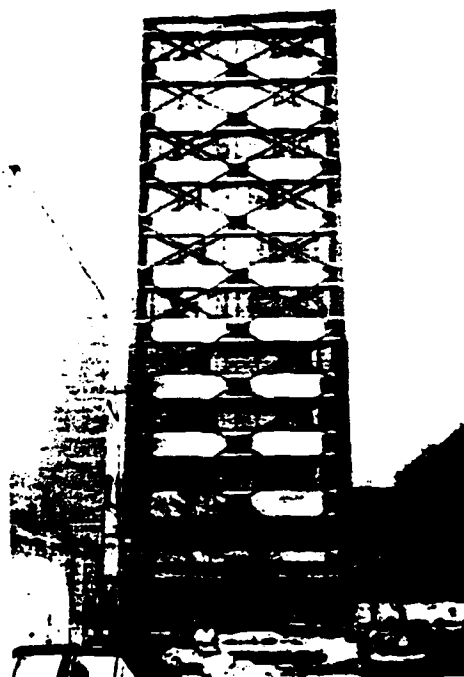
77a) to very complex forms such as shown in Figure 77b. The members of the brace system are usually welded; however, they can be bolted. On a cross brace configuration, the elements can be independent or welded to each other. The configuration chosen and the assembly technique used depend on the operational constraints of the structure (e.g., window openings) or the construction requirements (e.g., limited access or large dimensional variability).

There are many methods to attach infill braces to the existing structure. In some cases steel tension or compression braces are bolted or welded to the perimeter steel frame. Dowels can be attached to existing concrete elements to provide force transfer. The bracing system is connected by means of nonshrink mortar in the space between existing frame and the new bracing scheme. Spiral reinforcement can be placed in the grout filler to enhance the shear connection and to prevent splitting of the mortar interface. The connection is illustrated in Figure 78a. In some cases the perimeter steel frame is bolted directly to the concrete elements as shown in Figure 78b. The braces can also be attached by welding them to a steel jacket on the column, as shown in Figure 77a (References 23, 36, 56, 57, and 64).

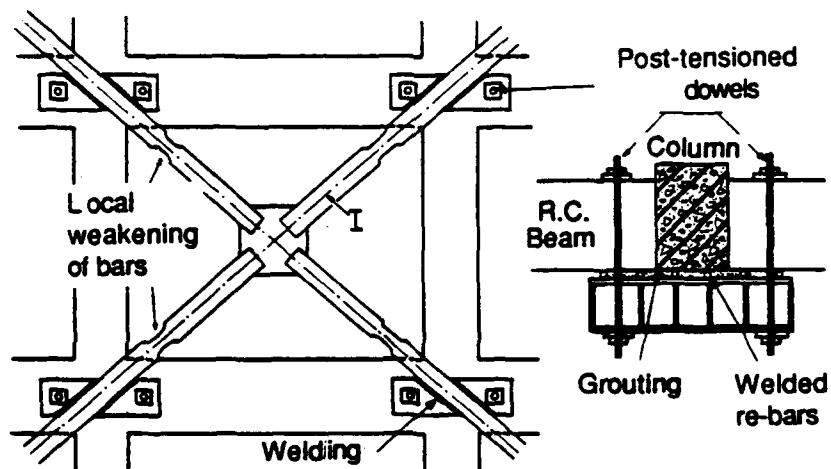
Steel braces can also be attached at the floor level to the external face of the columns in the perimeter frame (Figure 79). Normally, the external braces are attached with friction bolts to steel plate bases adhered to the concrete surface with epoxy and post-tensioned steel rods passing through bored holes in the beams. The concrete and steel surfaces must be cleaned by abrasion methods such as sandblasting before applying epoxy to the steel-concrete interface. Shear keys can be used to enhance shear transfer between the plate and the concrete. Test results show that the use of epoxy to fill the gap between the steel rods and the oversized holes improves the stiffness and overall behavior of the connection. Torsion and shear forces on the existing columns produced by eccentric bracing must be carefully studied (References 11, 56, 57, 61, 62, 63, and 66).

One important aspect in brace system design is to assure that braces can yield in axial tension and compression and to avoid inelastic buckling of the brace. The braces can be designed with small slenderness ratios to encourage compression yielding of the section rather than buckling. In some cases, necks (reduced sections) are formed in the steel elements by cutting or perforating the section to achieve this purpose. Tension braces, normally prestressed to enhance their performance, can be used to avoid the problem. Braces must be designed or restrained to avoid out-of-plane buckling. Sometimes, horizontal steel elements are provided at floor levels and connected to the braces to "collect" the shear force of the story and transfer it to the bracing system (References 11, 56, 54, 64, and 66).

A new variation of bracing has been recently tested in Japan. The steel braces are connected to a steel damper, consisting of an H-shaped steel plate. The damper is designed to buckle in shear before compressive buckling of the braces is reached. Test data show that the system is able to withstand severe lateral deformations with minor damage to the system. The design procedure for the damper is simple; if it is damaged, the replacement cost is low (Reference 67).



(a) View of external bracing (Reference 64)



In order to avoid the buckling of compressed bars, a local weakening (neck) has been introduced: Thus, eccentric compression has alleviated the buckling effects.

(b) Attachment of external braces (Reference 11)

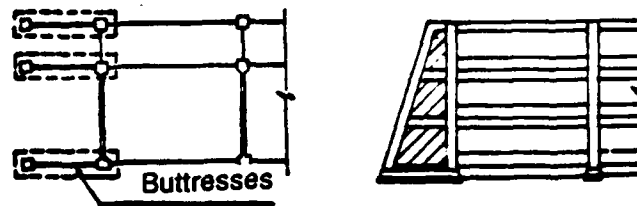
Figure 79. External Steel Braces

e. Buttresses

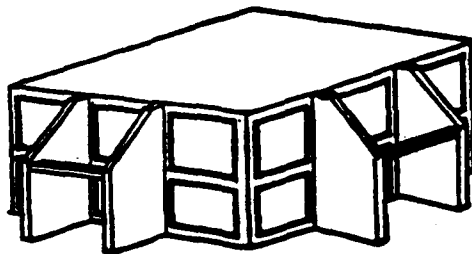
The use of external reinforced concrete buttresses (Figure 80) to resist the lateral forces acting on structures of small height must be considered when enough space is available outside the structure. The concrete buttresses must be properly anchored to the soil and connections to the old structure carefully designed. Some buttresses are much stiffer than the frames in the building, the columns are expected to resist very little lateral load (References 12 and 68).

f. Masonry Walls

In some cases masonry structures can be strengthened by adding new masonry walls. The connection between new and old walls must be designed to assure desired behavior. One solution is shown in Figure 81 where connectors are attached to the existing wall and grouted into the bed joint of the new masonry wall. The horizontal reinforcement is then continuous between the new and existing walls (Reference 12).



(a) External Reinforced Concrete Buttresses (Reference 42)



(b) Layout of Buttresses
(Reference 12)



(c) View of structure with buttresses
(Reference 68)

Figure 80. Use of Buttresses

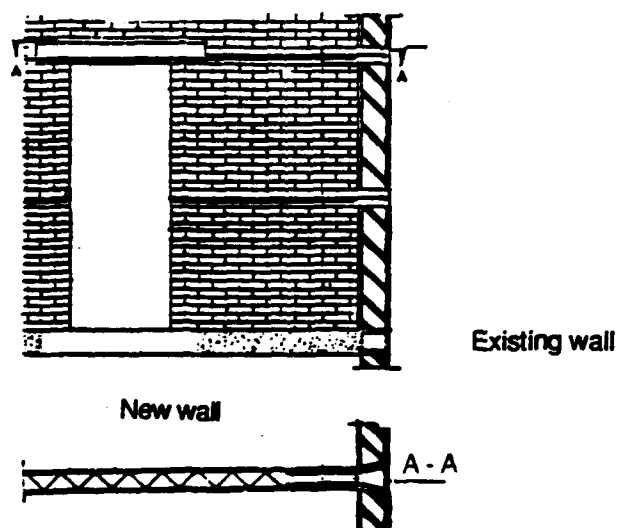


Figure 81. Strengthening of Masonry Structures with New Walls (Reference 12)

SECTION V

ASSESSMENT OF TECHNIQUES

A. SELECTION OF REPAIR TECHNIQUES

From the earthquake damage repair perspective, the techniques which appear to be most advantageous are generally those which are least expensive. In many cases, the primary objective is stabilization of the structure by techniques which do not provide a permanent solution, but rather protect the public and the occupants or contents until more extensive repairs or demolition are possible. In the case of damage due to blast effects, the critical nature of the facilities makes expedient repairs of prime importance. Because operational functions carried out in the structure are likely to be critical, a repair solution which does more than stabilize the structure will be needed. Expedient repair procedures will have to be conducted primarily by personnel on the site using stockpiled materials.

To make the repair process function properly and quickly, the following activities should be carried out and the information developed should be readily available in time of emergency.

- Inventory of critical structures and details of the structural systems, non-structural systems, utilities, and equipment. In the long term, computer-based data systems will be needed to maintain this information and to assist personnel in developing repair strategies.
- Development of a guide to assist field personnel in assessing the degree of damage to structural components. Such a guide could be used to correlate appropriate techniques with damage level.

B. CATEGORIZATION OF TECHNIQUES

The most promising techniques will depend heavily on the degree of damage and expertise and materials available at the site. It is likely that the materials most commonly stockpiled will include wood (dimensioned lumber, poles, railroad ties) and common structural steel shapes. Therefore, basic repair techniques should be developed using such materials. For more sophisticated, more permanent repairs, the use of jacketing and substituting or adding critical elements has considerable merit. By adding material or constructing new load-resisting elements, the structure generally will be strengthened during the repair process. A brief discussion of the options available and the personnel and equipment needed will illustrate the preceding points. Table 6 summarizes the pertinent considerations in selecting a repair procedure for expediently returning the structure to use.

TABLE 6. SUMMARY OF REPAIR TECHNIQUES - CONSTRUCTION NEEDS

Level	Personnel		Training	Materials	Special Equipment
	Supervisory	Construction			
Basic	Technician	Semi-Skilled	Supervisor only - supplement with "How-to" Manual	lumber, structural steel shapes or rods; fasteners (bolts, expansion anchors), banding materials	saws, drills, hydraulic jacks, hand pumps
	Engineer	Semi-skilled Welder Concrete worker	Design Guidelines Manual - Short-course or workshop on design and construction	lumber, structural steel, concrete materials (cement, aggregate), adhesives (epoxy, polyester), grouting materials	saws, drills, hydraulic jacks and pumps, gas and/or arc welders, grouting equipment, concrete production equipment (small mixers)
Advanced	Structural Engineer	Full range of construction workers	Course in evaluation of damaged buildings and structural repair and/or strengthening	lumber, structural steel, concrete materials, reinforcing steel, adhesives, grouting materials	Full range of power equipment, as mentioned above. Large concrete production equipment (ready-mix plant on site or nearby) or development of shotcreting techniques. Hoists and cranes

1. Basic Techniques

Basic techniques can be implemented using a relatively unstrained labor force and common, inexpensive building materials. Basic repairs to stabilize the structure and maintain operations could be accomplished using lumber, structural steel shapes or rods, and common fasteners such as threaded rods, expansion anchors, and banding materials. The only power tools required would include drills and saws. Hydraulic jacks and pumps (hand operated) could assist the workers in realigning damaged elements. A supply of wooden wedges should be available to "snug" elements in place where compression forces must be transferred to fill gaps between repair elements and existing surfaces.

The advantage of the basic techniques discussed in Section IV - REPAIR TECHNIQUES is that the labor forces does not have to have specialized training. Simple, straightforward manuals could be developed to provide guidance as to techniques available, materials stockpiled, and methods for carrying out rudimentary calculations for sizing and placing repair elements. A small number of people at each installation would need to be trained to use the manuals and supervise construction.

Finally, the material utilized in the basic measures can be stored for long periods. With proper protection, there is essentially no limit to their "shelf life". In addition, the common materials can be used for other emergency operations and stocks replenished easily.

2. Intermediate Techniques

Various techniques described in Section IV - REPAIR TECHNIQUES call for greater engineering judgment and design, and a more skilled work force. As opposed to basic measures, the intermediate techniques are intended to provide permanent repairs and restore the integrity and function of building elements.

The work force would be required to have at least basic construction skills including the ability to weld, to use portland cement grout or concrete, to handle epoxy adhesives, and to reconstruct elements where damage was severe. A major feature of the intermediate techniques, is the use of structural steel components (plates, angles, channels) to jacket heavily damaged elements or to replace such elements. Such components would need to be fabricated in place, hence the need for welding ability. For continuity, it may be necessary to assure force transfer between steel components and structural concrete or masonry elements. Such transfers can be made through the use of adhesives or the concrete surface or dowels embedded into the existing elements.

The equipment needed will include electric or gas welders, and special tools for mixing and/or pressure grouting epoxy compounds or portland cement grouts. Materials to be stockpiled would include structural steel shapes, fasteners, and epoxy adhesives. The main problem with the adhesives is their relatively short shelf life and the need for careful handling, mixing and placing.

Careful inventories would be needed and outdated materials discarded and replaced with fresh adhesives. Small amounts of concrete may need to be produced where replacement of damaged elements is required.

While manuals could be developed for intermediate techniques, it is expected that the work would need to be designed and supervised by an engineer with some specialized training in repair procedures. In turn, each installation would need to have personnel trained in the different construction operations required to complete the repair process.

Intermediate repair procedures should be completed in about the same time as basic measures. However, the work force, equipment, and materials must be more sophisticated to enable such procedures to be successfully applied.

3. Advanced Techniques

Advanced techniques require skilled engineering personnel and trained construction workers. The time involved in completing such repairs will be considerably greater than for basic or intermediate techniques. Therefore, it is not expected that advanced techniques will generally be considered for expedient "first" repairs but will be used to make permanent repairs to heavily damaged structures or to upgrade structures that provide inadequate protection.

The methods described in Section IV are such that a whole range of construction skills will be needed and the work will have to be preceded by a thorough engineering design process.

All the materials and tools described in the previous sections will be needed and one major additional material, concrete, will have to be produced, placed, and cured, possibly in large quantities. It is likely that the capability to produce will be needed on site so that concrete materials (aggregate and cement), mixing and placing equipment, and formwork materials will have to be stockpiled.

A variety of shotcreting processes are being developed and may hold considerable promise for use in repair work requiring fresh concrete on site.

SECTION VI RECOMMENDATIONS

A. GENERAL TOPICS FOR FURTHER STUDY

Much of the research on repair of structures in zones of high seismic risk is aimed toward strengthening to mitigate earthquake damage. While the techniques have wide applicability to repairing earthquake damage, the applicability to blast or impulse loading damage has not been demonstrated. Several general topics would appear to have broad applicability to the critical structures studied in this project and should be studied.

- **Assessment of degree of damage in ordinary (nonhardened) structures subjected to high-impulse loads.**
- **Development of special techniques for restoring integrity of large planar elements (especially structural or nonstructural walls) under lateral overpressures (impulse loads acting normal to the plane of the wall). Selected techniques should be studied under static and blast loadings and on initially damaged or undamaged elements.**
- **Development of procedures for intermediate or advanced repair techniques which utilize on-site manufacture or delivery of materials at a low-cost with good quality control and reduction of construction time. Shotcrete and polymer resins appear to be particularly attractive.**

B. RESEARCH AND DEVELOPMENT - SPECIAL TOPICS

During the course of this research program, a number of research needs were identified. The following topics are recommended for further study:

- **Expand critical facility list**

Only a few airbases were represented in the list of critical facilities. More effort is needed to define typical structural, architectural, roofing and mechanical systems in critical facilities.

Both upgrade and repair procedures are needed for all systems.

- **Define damage mechanisms for double layer masonry walls**

There is a paucity of information on blast damage to masonry walls. Virtually no information was found on double layer (composite) walls subjected to short duration blast loads which can be expected from conventional bombs. This lack of information requires repair techniques to be developed based upon expected damage rather than observed damages.

- Quantify reserve strengths of various structural members (frames, walls, roofs)

Proper selection and design of repair procedures should be based upon the ability of the repaired member to resist subsequent loadings. Reserve strengths of the damaged members must be known to accurately assess their resistance to further loadings.

- Define lateral load resistances of masonry wall perimeter beams

In this study masonry walls were considered to respond as if supported on either two or four sides. The supports were considered to be rigid. Actual supports will have some flexibility depending upon the lateral stiffness of the perimeter beams. If the lateral stiffness and strength are low enough, the wall system can fail by breaking of the perimeter beam from lateral loads.

- Develop techniques for increasing masonry wall blast resistance

Masonry walls are inherently very weak against lateral loadings. This weakness makes them extremely vulnerable to conventional bomb attack. However, techniques could be developed to reinforce the masonry walls against lateral loadings and greatly increase their resistance to lateral overpressures. Such measures are preventive rather than repair procedures.

- Quantify repaired member residual strengths

A number of repair procedures have been suggested within this study. Assessment and comparison of the various procedures can only be accomplished from a subjective basis since there is little or no information available on the member strengths afforded by the repairs. Residual strength information is needed to aid in selecting repair methods, improving the various techniques, and optimizing repair procedures.

- Characterize blast effects on structures similar to those of the predominant critical facilities described

No experimental data were found for blast damage to structures with descriptions as defined for the predominant critical facility. Damage mechanisms to the structure and structural members were defined based upon testing of the individual elements or experiences with other structures which employed similar structural elements. Experimental data are needed for complete structural systems representing the predominant critical facilities.

- Upgrade structural hardness of critical facilities

Surprisingly, the critical facilities identified in the AFESC list were of common construction rather than protective construction. Efforts should be made to upgrade the protection levels of the critical facilities by hardening the existing facilities or moving the support functions to hardened facilities.

- **Develop more precise guidelines for repairing various elements**

The methods and procedures described in this study are presented as general guidelines for repair. Detailed procedures should be developed based upon the structural element, degree of damage, desired level of restored strength, etc.

- **Develop methods to characterize cumulative damage from repeated loadings**

The damage mechanisms described in this study were based upon experience of damage to structural elements from single event loadings. In an actual attack, a structural element could experience multiple loadings from detonation of more than one bomb. These multiple loadings can vary in intensity and direction of loading, thus subjecting the element to multiple responses and an accumulation of damage. Very little is known concerning cumulative damage from such extreme loadings. A basic data base is needed to help define expected damage mechanisms and resulting element conditions.

- **Characterize progressive collapse mechanisms**

Most bomb damage studies concentrate on the damage expected on specific structural elements subjected to specific bomb loadings. However, the response of the overall structural system can depend on the accumulation of damage to the entire structural system from individual structural elements. Partial or total loss of essential support elements can lead to collapse of other parts of the structure which themselves did not suffer substantial damage from the bomb loading. More emphasis should be placed on considering the overall response of the entire structural system based upon the responses of the individual elements.

SECTION VII CONCLUSIONS

The large volume of work reported in the literature and the ongoing repair and strengthening of structures damaged in earthquakes provide a wealth of information for expedient repair of structural facilities.

A thorough review of the literature reveals a number of techniques which can be easily and inexpensively used for expedient repairs. The basic repair measures outlined require only common construction materials, a work force with only limited construction experience, and technician level supervision, provided that simple manuals are developed to guide the repair work.

Intermediate and advanced techniques are also available but may require more time and skill than can be permitted for expedient repair. A number of research and development topics are identified. The studies outlined would permit employment of advanced techniques and better quality repairs involving basic or intermediate procedures.

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