World Housing Encyclopedia

*an Encyclopedia of Housing Construction in
Seismically Active Areas of the World*

an initiative of
Earthquake Engineering Research Institute (EERI) and
International Association for Earthquake Engineering (IAEE)

HOUSING REPORT

Street front building with arcade at the first floor (contemporary construction)

Report #	62
Report Date	05-06-2002
Country	TAIWAN
Housing Type	RC Moment Frame Building
Housing Sub-Type	RC Moment Frame Building : Designed for gravity loads only, with URM infills
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Reviewer(s)	Craig D. Comartin

Summary

This building type is common in many Taiwanese cities and towns. The street-front buildings are medium-rise, reinforced concrete frames with infill brick masonry walls serving as partitions. Usually, the first floor (typically 4 m high) is used for commercial purposes while the upper stories (typically 2 to 4 stories above, floor height 3 m) are used for storage and residences. Neighboring units of similar design have been constructed together to form a corridor for pedestrians to walk in.

Connected units vary in number from 6 to 10 and they may be built in a row, in an L shape, or in the U shape. There are several structural deficiencies associated with this building type: (1) the weak and soft first story can result from a large opening at the street level for commercial use; (2) a typical building layout has walls in one direction only, perpendicular to the street; as a consequence, there are few earthquake-resisting elements in the other direction; (3) extra rooftop additions increase loads. Also, building owners tend to reduce the number of columns for a wider storefront view. Many buildings of this type collapsed in the Chi-Chi earthquake of 1999.

1. General Information

Buildings of this construction type can be found in almost all cities and towns on the island. This type of housing construction is commonly found in both rural and urban areas. This construction type has been in practice for less than 100 years.

Currently, this type of construction is being built. .

Figure 1A: Typical Building

Figure 1B: Typical Building (Source: EERI 2001)

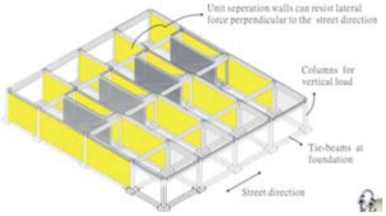


Figure 2: Key Load-Bearing Elements

2. Architectural Aspects

2.1 Siting

These buildings are typically found in flat terrain. They share common walls with adjacent buildings.

2.2 Building Configuration

Rectangular shape is most common. Walls perpendicular to the street (side walls) are mostly used to separate building units, therefore these walls do not have any openings. Other walls may have openings, but the openings were not the major cause of capacity reduction. Major seismic problems are due to the architectural layout of these buildings, characterized with the total absence of walls or a very few walls in the direction parallel to the street. As a consequence, columns are the only elements resisting earthquake forces in the direction parallel to the street. This structural deficiency has led to a significant damage or even collapse of the columns in the 1999 Chi-Chi earthquake.

2.3 Functional Planning

The main function of this building typology is mixed use (both commercial and residential use). In a typical building of this type, there are no elevators and 1-2 fire-protected exit staircases. Usually only one stairway is designed for a housing unit, therefore there is only one means of escape.

2.4 Modification to Building

Typical patterns of modification include: addition of one or more floors (vertical expansion), demolishing the interior walls at the ground floor level for the commercial space. Initially, building permits are originally given for 3 or 4 story construction. However, most owners build 1 or 2 extra stories without seeking the permit for vertical expansion after the original building permit has been approved by the local government.

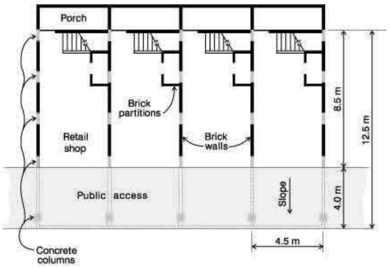


Figure 3A: Plan of aTypcial Building

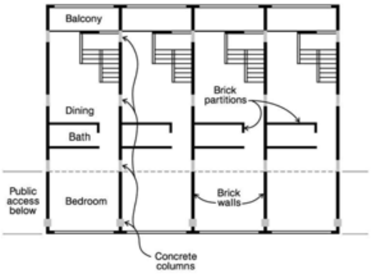


Figure 3B: Typical Floor Plan -Past Practice (Source: EERI 2001)

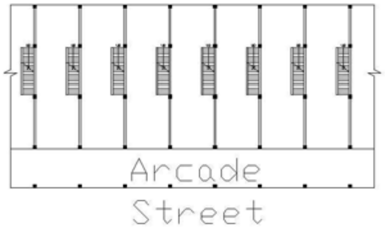


Figure 3C: Typical Ground Floor Plan- Past Practice (Source: EERI 2001)

3. Structural Details

3.1 Structural System

Material	Type of Load-Bearing Structure	#	Subtypes	Most appropriate type
Masonry	Stone Masonry Walls	1	Rubble stone (field stone) in mud/lime mortar or without mortar (usually with timber roof)	
		2	Dressed stone masonry (in lime/cement mortar)	
	Adobe/ Earthen Walls	3	Mud walls	
		4	Mud walls with horizontal wood elements	
		5	Adobe block walls	
		6	Rammed earth/Pise construction	
	Unreinforced masonry walls	7	Brick masonry in mud/lime mortar	
		8	Brick masonry in mud/lime mortar with vertical posts	
		9	Brick masonry in lime/cement mortar	
		10	Concrete block masonry in cement mortar	
	Confined masonry	11	Clay brick/tile masonry, with wooden posts and beams	
		12	Clay brick masonry, with concrete posts/tie columns and beams	
		13	Concrete blocks, tie columns and beams	
	Reinforced masonry	14	Stone masonry in cement mortar	
		15	Clay brick masonry in cement mortar	
		16	Concrete block masonry in cement mortar	
	Moment resisting frame	17	Flat slab structure	
		18	Designed for gravity loads only, with URM infill walls	
		19	Designed for seismic effects, with URM infill walls	
		20	Designed for seismic effects, with structural infill walls	
		21	Dual system – Frame with shear wall	
			Moment frame with in-situ	

Structural concrete	Structural wall	22	shear walls	
		23	Moment frame with precast shear walls	
	Precast concrete	24	Moment frame	
		25	Prestressed moment frame with shear walls	
		26	Large panel precast walls	
		27	Shear wall structure with walls cast-in-situ	
		28	Shear wall structure with precast wall panel structure	
Steel	Moment-resisting frame	29	With brick masonry partitions	
		30	With cast in-situ concrete walls	
		31	With lightweight partitions	
	Braced frame	32	Concentric connections in all panels	
		33	Eccentric connections in a few panels	
	Structural wall	34	Bolted plate	
		35	Welded plate	
Timber	Load-bearing timber frame	36	Thatch	
		37	Walls with bamboo/reed mesh and post (Wattle and Daub)	
		38	Masonry with horizontal beams/planks at intermediate levels	
		39	Post and beam frame (no special connections)	
		40	Wood frame (with special connections)	
		41	Stud-wall frame with plywood/gypsum board sheathing	
		42	Wooden panel walls	
Other	Seismic protection systems	43	Building protected with base-isolation systems	
		44	Building protected with seismic dampers	
	Hybrid systems	45	other (described below)	

3.2 Gravity Load-Resisting System

The vertical load-resisting system is others (described below). Floor weight on different stories is transferred to solid RC floor slabs (usually 120 mm thick), which are supported by RC beams (typically 400 to 600 mm deep and 300 mm wide). Loads are then transferred from the beams to the brick masonry walls, usually 120 mm thick, and RC columns, with dimensions ranging from 300 X 500 mm to 400 X 500 mm. Transverse column reinforcement (ties) are usually spaced at 300 mm on centre which is less than the current code requirement for ductile columns that prescribes 100 mm c/c tie spacing for columns end zones. The reinforcement is usually terminated outside the beam-column joint. Longitudinal column reinforcement ratio varies from 1 to 2.9 %, depending on the design or floor height. Concrete strength varies from 10 to 20 MPa and was mostly pre-mixed in plant and delivered to site. Reinforced concrete slabs were cast monolithically with beams and columns on each floor. As a result, honeycombing can be observed on the column surface if concrete was not sufficiently vibrated during the construction. The foundations are mostly shallow spread footings connected with tie-beams.

3.3 Lateral Load-Resisting System

The lateral load-resisting system is others (described below). The main lateral load resisting system in these buildings consists of reinforced concrete frames with infill brick masonry walls serving as partitions. Key load bearing elements are illustrated in Figure 2. Columns are designed for seismic effects, however due to the inadequate construction and the lack of the seismic detailing, these columns have demonstrated inadequate seismic resistance (especially in the 1999

Chi Chi earthquake). Due to the fact that the quality control of the brick walls had not been stringent, these infill walls have a limited ability to resist seismic forces. However, the walls certainly contribute to structural stiffness and strength in these buildings. For low-rise buildings it is considered to err on the safe side if the effect of infills is neglected in the structural analysis. Most of the walls are made of brick masonry (typical wall thickness 120 mm); however, in the last decade, some builders have used 120 mm thick RC walls instead of the traditional brick walls. Some walls at the rear side (kitchen area) are not full height. Sometimes windows are cut through the walls, and ventilation equipment or pipes may pass through these walls. As a result, the rear walls have a limited contribution to lateral load resistance in these buildings. Wall layout is a critical factor that influences the seismic resistance of these buildings. In each housing unit, two end walls separate different units. Majority of the walls run only perpendicular to the street. Such structural characteristics make these buildings very strong for the seismic effects in the wall direction (perpendicular to street). However, due to the lack of lateral load-resisting elements in the other direction (parallel to the street), seismic resistance of these buildings is inadequate. Typical floor plans are illustrated in Figure 3A and 3B. In some buildings, walls are laid out parallel to the street direction due to the layout of stairways (which is also parallel to the street), as illustrated in Figure 7B. These buildings have demonstrated better seismic performance as compared to the buildings with different wall layout, as observed in the 1999 Chi-Chi earthquake.

3.4 Building Dimensions

The typical plan dimensions of these buildings are: lengths between 10 and 10 meters, and widths between 4.5 and 4.5 meters. The building has 4 to 5 storey(s). The typical span of the roofing/flooring system is 4.5 meters. Typical Story Height: Usually story height is 4 m at the first floor level and 3 m at upper stories. The typical storey height in such buildings is 3 meters. The typical structural wall density is up to 5 %. The wall density perpendicular to the street direction at the first floor level is approximately 5%. The wall density in the direction parallel to the street may range from 0.3 to 1%.

3.5 Floor and Roof System

Material	**Description of floor/roof system**	**Most appropriate floor**	**Most appropriate roof**
Masonry	Vaulted		
	Composite system of concrete joists and masonry panels		
Structural concrete	Solid slabs (cast-in-place)		
	Waffle slabs (cast-in-place)		
	Flat slabs (cast-in-place)		
	Precast joist system		
	Hollow core slab (precast)		
	Solid slabs (precast)		
	Beams and planks (precast) with concrete topping (cast-in-situ)		
	Slabs (post-tensioned)		
Steel	Composite steel deck with concrete slab (cast-in-situ)		
Timber	Rammed earth with ballast and concrete or plaster finishing		
	Wood planks or beams with ballast and concrete or plaster finishing		
	Thatched roof supported on wood purlins		
	Wood shingle roof		
	Wood planks or beams that support clay tiles		
	Wood planks or beams supporting natural stones slates		
	Wood planks or beams that support slate, metal, asbestos-cement or plastic corrugated sheets or tiles		
	Wood plank, plywood or manufactured wood panels on joists supported by beams or walls		
Other	Described below		

3.6 Foundation

Type	Description	Most appropriate type
Shallow foundation	Wall or column embedded in soil, without footing	
	Rubble stone, fieldstone isolated footing	
	Rubble stone, fieldstone strip footing	
	Reinforced-concrete isolated footing	
	Reinforced-concrete strip footing	
	Mat foundation	
	No foundation	
Deep foundation	Reinforced-concrete bearing piles	
	Reinforced-concrete skin friction piles	
	Steel bearing piles	
	Steel skin friction piles	
	Wood piles	
	Cast-in-place concrete piers	
	Caissons	
Other	Described below	

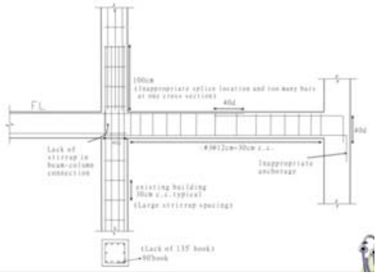


Figure 4: Critical Structural Details - RC Frame Reinforcement Details

4. Socio-Economic Aspects

4.1 Number of Housing Units and Inhabitants

Each building typically has 5-10 housing unit(s). 6 to 10 units in each building. The number of inhabitants in a building during the day or business hours is 11-20. The number of inhabitants during the evening and night is others (as described below). More than 50 live in the building: Grandparents and parents may live with two or three children, so there may be 5-8 family members. Also, in some cases rooms may be rented to tenants for the extra income.

4.2 Patterns of Occupancy

Usually one family per housing unit.

4.3 Economic Level of Inhabitants

Income class	Most appropriate type

a) very low-income class (very poor)	
b) low-income class (poor)	
c) middle-income class	
d) high-income class (rich)	

A typical annual income for a middle class family is $US 25, 000 to $US 60,000; however, the income varies depending on the location.

Ratio of housing unit price to annual income	**Most appropriate type**
5:1 or worse	
4:1	
3:1	
1:1 or better	

What is a typical source of financing for buildings of this type?	**Most appropriate type**
Owner financed	
Personal savings	
Informal network: friends and relatives	
Small lending institutions / micro-finance institutions	
Commercial banks/mortgages	
Employers	
Investment pools	
Government-owned housing	
Combination (explain below)	
other (explain below)	

In each housing unit, there are 2 bathroom(s) without toilet(s), no toilet(s) only and 1 bathroom(s) including toilet (s).

Usually there are 2-3 bathrooms in one housing unit. .

4.4 Ownership

The type of ownership or occupancy is renting, outright ownership , ownership with debt (mortgage or other) and individual ownership.

Type of ownership or occupancy?	**Most appropriate type**
Renting	
outright ownership	
Ownership with debt (mortgage or other)	
Individual ownership	
Ownership by a group or pool of persons	
Long-term lease	
other (explain below)	

5. Seismic Vulnerability

5.1 Structural and Architectural Features

Structural/ Architectural Feature	Statement	Most appropriate type		
		True	False	N/A
Lateral load path	The structure contains a complete load path for seismic force effects from any horizontal direction that serves to transfer inertial forces from the building to the foundation.			
Building Configuration	The building is regular with regards to both the plan and the elevation.			
Roof construction	The roof diaphragm is considered to be rigid and it is expected that the roof structure will maintain its integrity, i.e. shape and form, during an earthquake of intensity expected in this area.			
Floor construction	The floor diaphragm(s) are considered to be rigid and it is expected that the floor structure(s) will maintain its integrity during an earthquake of intensity expected in this area.			
Foundation performance	There is no evidence of excessive foundation movement (e.g. settlement) that would affect the integrity or performance of the structure in an earthquake.			
Wall and frame structures-redundancy	The number of lines of walls or frames in each principal direction is greater than or equal to 2.			
Wall proportions	Height-to-thickness ratio of the shear walls at each floor level is: Less than 25 (concrete walls); Less than 30 (reinforced masonry walls); Less than 13 (unreinforced masonry walls);			
Foundation-wall connection	Vertical load-bearing elements (columns, walls) are attached to the foundations; concrete columns and walls are doweled into the foundation.			
Wall-roof connections	Exterior walls are anchored for out-of-plane seismic effects at each diaphragm level with metal anchors or straps			
Wall openings	The total width of door and window openings in a wall is: For brick masonry construction in cement mortar : less than ½ of the distance between the adjacent cross walls; For adobe masonry, stone masonry and brick masonry in mud mortar: less than 1/3 of the distance between the adjacent cross walls; For precast concrete wall structures: less than 3/4 of the length of a perimeter wall.			
Quality of building materials	Quality of building materials is considered to be adequate per the requirements of national codes and standards (an estimate).			
Quality of workmanship	Quality of workmanship (based on visual inspection of few typical buildings) is considered to be good (per local construction standards).			
Maintenance	Buildings of this type are generally well maintained and there are no visible signs of deterioration of building elements (concrete, steel, timber)			
Other				

5.2 Seismic Features

Structural Element	Seismic Deficiency	Earthquake Resilient Features	Earthquake Damage Patterns
Wall	Unreinforced brick masonry walls are laid out in one direction only, resulting in the increased vulnerability in the other direction due to the absence of vertical elements of lateral-load resisting system, as illustrated in Figure 2.		In a major earthquake (of intensity similar to or larger than the design level earthquake), collapse of buildings is expected to take place due to the lack of structural strength in the weak direction.
Frame consists of columns and beams.	- Column reinforcement is usually spliced at the top of the slab where the column bending moments are the largest (see Figure 4). As a result of this poor construction practice, seismic capacity of the columns is largely reduced. Majority of the buildings that collapsed in the Chi-Chi earthquake were constructed this way. - Lack of the 135 degree stirrup hook was another major defect in building construction (see Figure 5C). - Widely spaced column ties, usually spaced at 300 mm on centre which is less than the current code requirement for ductile columns that prescribes 100 mm c/c tie spacing for columns end zones. (see Figure 5B)		Collapsed columns
	No major deficiencies		
	The open front at the bottom story is the most obvious configuration irregularity characteristic for this construction type. This feature creates undesirable soft-story and torsional effects, as illustrated in Figure 5A. (Source: EERI 2001)		Extensive damages and building collapses due to the large demands on the bottom story columns caused by soft story and torsional effects (see Figures 6A, 6B, 6C, 6D, 6E, 6F)

5.3 Overall Seismic Vulnerability Rating

The overall rating of the seismic vulnerability of the housing type is *C: MEDIUM VULNERABILITY (i.e., moderate seismic performance)*, the lower bound (i.e., the worst possible) is B: MEDIUM-HIGH VULNERABILITY (i.e., poor seismic performance), and the upper bound (i.e., the best possible) is *D: MEDIUM-LOW VULNERABILITY (i.e., good seismic performance)*.

Vulnerability	high	medium-high	medium	medium-low	low	very low
	very poor	poor	moderate	good	very good	excellent
Vulnerability Class	A	B	C	D	E	F

5.4 History of Past Earthquakes

Date	Epicenter, region	Magnitude	Max. Intensity
1999	Chi-Chi, Taiwan	7.3	X

Although many buildings of this construction type sustained significant damage in the 1999 Chi Chi earthquake, most of them performed satisfactorily. Earthquake damages are illustrated in Figures 6A, 6B, 6C, 6D, 6E, and 6F. The main causes for damage observed after the earthquake are (EERI, 2001): 1) Poor configuration attributable to the open front combined with inadequate column lateral reinforcement (ties). The large displacement demands from the soft-story and torsional effects often damaged the plastic hinge regions of the columns at the open front. All damaged columns were observed to have non-ductile confinement reinforcement details consisting of widely spaced horizontal hoops, more than 300 mm apart, and 90 degree hooks. Usually, the lack of confinement reinforcement in the plastic hinge regions resulted in brittle failure. In some cases, hinge rotation caused buildings to permanently lean out of plumb. In other cases, buildings with no signs of earthquake damage remained standing next to the seemingly identical buildings that sustained the total collapse of entire bottom stories. 2) There was also widespread damage to the unreinforced brick partitions and perimeter walls. Although partitions are usually considered nonstructural elements, the collapse of or damage to unreinforced brick partitions represents a significant falling hazards, and it forced many people out of their homes. 3) Performance of this construction type in the earthquake was significantly influenced by the infill wall layout. Because brick infills significantly influence the structural characteristics and yet are not considered in the design, the seismic performance of this building type is highly unpredictable.

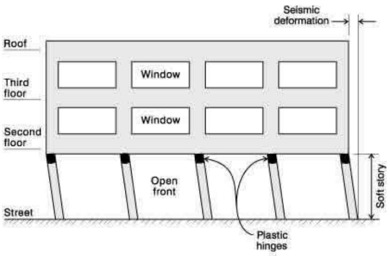


Figure 5A: Seismic Deficiency: Soft-story deformation of open front at the street level

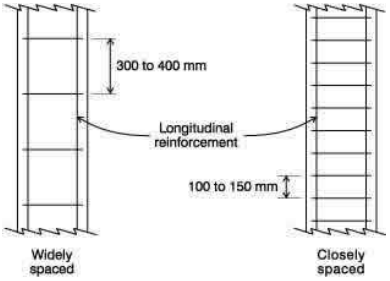


Figure 5B: Seismic Deficiency - Widely spaced hoop reinforcement (Source: EERI 2001)

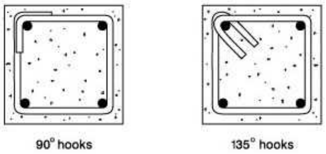


Figure 5C: Seismic Deficiency: Column ties -90 degree hook were used instead of 135 degree hooks (Source: EERI 2001)

Figure 6A: A Photograph Illustrating Typical Earthquake Damage

Figure 6B: Earthquake damage-Collapsed Three-story building in the 1999 Chi Chi earthquake (Source: EERI 2001)

Figure 6C: Earthquake Damage - Partial Collapse of a Three-story building in the 1999 Chi Chi Earthquake (Source: EERI 2001)

Figure 6D: Earthquake Damage - Pancake Collapse of an Entire City Block in the 1999 Chi Chi earthquake (Source: EERI 2001)

Figure 6E: Earthquake Damage - Opening of 90 degree column hooks in the 1999 Chi Chi earthquake (Source: EERI 2001)

Figure 6F: Collapse of a Concrete Frame Building in the 1999 Chi Chi Earthquake (Source: EERI 2001)

6. Construction

6.1 Building Materials

Structural element	**Building material**	**Characteristic strength**	**Mix proportions/dimensions**	**Comments**
Walls	Brick wall	Compression: 110 kg/cm² Tension: 33 kg/cm²	Brick dimensions: 50 X 110 X 230 mm	
Foundation	Reinforced concrete	fc'=210 kg/cm² fy=4200 kg/cm²	plant -mixed concrete	
Frames (beams & columns)	Reinforced concrete	fc'=210 kg/cm² fy=4200 kg/cm²	plant -mixed concrete	
Roof and floor(s)	Reinforced concrete	fc'=210 kg/cm² fy=4200 kg/cm²	plant -mixed concrete	

6.2 Builder

This construction is mostly built by developers. Builders do not necessarily live in these buildings.

6.3 Construction Process, Problems and Phasing

In the contemporary (post-1980) construction of this type which is described in this contribution, RC frame structure is constructed first, and the brick walls are then built as an infill. Therefore, brick walls are not tightly connected to the RC frames. However, in the older buildings of this type (of the pre-1970s vintage) which are described in another contribution by the same authors, the brick walls were constructed first, and RC frames were subsequently constructed around the brick walls. The construction of this type of housing takes place in a single phase. Typically, the building is originally designed for its final constructed size.

6.4 Design and Construction Expertise

Due to the absence of major earthquakes before the 1999 Chi-Chi earthquake in Taiwan, contractors were reluctant to make extra effort into workmanship related to the seismic detailing. Therefore, in most of the construction sites, seismic detailing for RC structures is inadequate. All buildings in Taiwan need the signature of a registered architect before government approval granted. However, some architects may not have adequate knowledge for the latest development in seismic design. Developers have the tendency to choose whichever A/E that would compromise structural design to the sales strategy. As a consequence, building code requirement becomes the upper bound for structural design in many recent projects.

6.5 Building Codes and Standards

This construction type is addressed by the codes/standards of the country. Title of the code or standard: Building construction technique code in 1974 first addressed the seismic force and wind force for building design. Year the first code/standard addressing this type of construction issued: 1974 When was the most recent code/standard addressing this construction type issued? 1998.

Building permits are granted after the architectural drawings are reviewed to satisfy building codes. Construction work proceeds afterwards. At this stage, the design architect is usually responsible for monitoring that appropriate construction methods and materials are being used in the construction. After the construction is finished, government official inspects the building to ensure that everything is built to the design drawings before a permit of occupancy is issued.

6.6 Building Permits and Development Control Rules

This type of construction is an engineered, and authorized as per development control rules. Building permits are required to build this housing type.

6.7 Building Maintenance

Typically, the building of this housing type is maintained by Owner(s).

6.8 Construction Economics

To include the material (for all the structural and nonstructural components) and labor: 300 $US/ m² (contemporary construction). Usually, it takes 10 days to build one story (structural part only), including the bar installation, forming, and pouring of concrete.

7. Insurance

Earthquake insurance for this construction type is typically unavailable. For seismically strengthened existing buildings or new buildings incorporating seismically resilient features, an insurance premium discount or more complete coverage is unavailable.

8. Strengthening

8.1 Description of Seismic Strengthening Provisions

Strengthening of Existing Construction :

Seismic Deficiency	**Description of Seismic Strengthening provisions used**
Lack of walls at the ground floor level in the direction parallel to the street	- Installation of new walls near the rear door or staircase to increase seismic strength in the direction parallel to the street, as illustrated in Figure 7A. - Installation of new steel braces.
Weak columns	-Steel jacketing or fiberwrap

Strengthening of New Construction :

Seismic Deficiency	**Description of Seismic Strengthening provisions used**
Planning of stairways and walls parallel to the street direction	Walls laid out parallel to the street direction due to the layout of stairways, as illustrated in Figure 7B.

8.2 Seismic Strengthening Adopted

Has seismic strengthening described in the above table been performed in design and construction practice, and if so, to what extent?

Yes. Seismic strengthening is generally accepted by builders. However, recent economic downturn may weaken the will to retrofit.

Was the work done as a mitigation effort on an undamaged building, or as repair following an earthquake?

Both.

8.3 Construction and Performance of Seismic Strengthening

Was the construction inspected in the same manner as the new construction?

Less stringent in retrofit work.

Who performed the construction seismic retrofit measures: a contractor, or owner/user? Was an architect or engineer involved?

Contractors performed retrofit construction. Only small percentage of the work involved architects or engineers.

What was the performance of retrofitted buildings of this type in subsequent earthquakes?

Yet to be discovered by the next major earthquake.

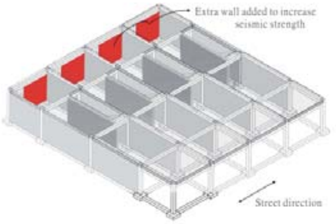


Figure 7A: Illustration of Seismic Strengthening Techniques

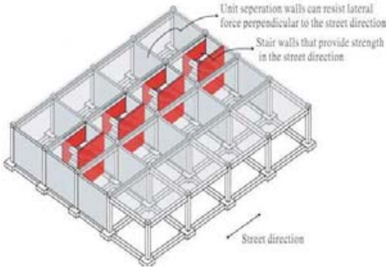
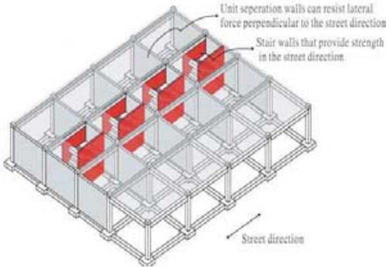


Figure 7B: Seismic Strengthening (New Construction) - Wall Layout in the Street Direction



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