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EARTHQUAKE DAMAGE OF WINDOW GLASS AND DOOR OF A HOTEL DAMAGED IN THE 1999 CHI-CHI TAIWAN EARTHQUAKE

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SUMMARY

On September 21,1999,an earthquake with magnitude M=7.3 occurred in the central area of Taiwan , in the earthquake more than 100,000 buildings were completely or partially destroyed. Even the buildings suffered slight structure damage , the non-structure were still serious.

In this paper , the damage of window glass and door for a hotel located in the epicentral area are investigated after earthquake. The main purpose of this investigation is to understand the damage factors that worth to be learned by the architect or building designer.

For the exit and door , followings are observed:

(1) Lower story obtained higher damage than higher story.
(2) Usually the damaged door seriously has surround brick wall with damage level higher than III or crack wider than 2.0mm.
(3) Deformed steel doors are more difficult to opened than wooden doors.

For the window , it is observed that most of damage are occurred at fixed window glass , and the window glass with slim-shape appears less damage than short-squat shape. Also , it is found that in this hotel almost all the glass with 3.0mm thickness are broken to piece , however only a very low percentage of 5.0mm reinforced glass are seriously damaged.

During earthquake , besides the structural safety , non-structural safety must also be well considered by the building designer. The damages of window glass and door of this hotel provide a good lesson for practical design.

I.INTRODUCTION

In view of the experience of all previous earthquakes , the damage of non-structure , especially the distortion of door frame , and the damage of panel and lock may cause the main exit could not be opened after earthquakes , and make the building loose its normal function and also cause casualty. In addition , the exit and fixed window glass was broken to pieces and flied or fell .These pieces not only directly hurt people but also hampered from rescuing.

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The data of this study is according to the investigation from 1999 Chi-Chi earthquake. We inquired into a hotel which retained the damaged condition after Chi-Chi earthquake in Zu-Shan. We surveyed and drew the detail dimensions of the exit and fixed window glass , and compared the material as well as construction between damaged and undamaged , and analyzed the reason of damage in the earthquake and influence parameter.

The detail of exit door include (a) the material and shape of the door, (b) the construction and location of the lock, (c) the type of the hinge, (d) the spare space between door panel and frame, (e) the fixed mode of the frame. The damage mode of the exit doors included: (a) whether the door lock could be opened or not , (b) whether the door panel extruded frame or not , (c) the damage of the frame, (d) the damage of the panel, (e) the damage situations of the hinge in the connection. The detail of fixed window glass included: (a) the dimension of the window, (b) how to fix the window on the wall, (c) the types and thickness of the glass, (d) the spare space between glass and frame. The damaged items included: (a) the window frame, (b) glass, (c) the material for fixed the window.

II.THE DAMAGE EXAMPLE FROM 1999 CHI-CHI EARTHQUAKE

2-1Experience of earthquake damage of exit

The hotel in Zu-Shan is a five-story building. The building plan is L type. The building can be divided A , B structures , that connected with expansion joint. The height of the first story was 4.3m and the standard story was 3.2m. There are more than two hundred rooms in the hotel. Even the buildings suffered slight structure damage , the non-structure were still serious like the ceiling and slate of the wall falling down , the partition walls being crack , the fixed window glass breaking.

Fig1~fig4 show the damage of the brick partition wall in the first story of building A . In figure1 , the brick wall had a shear crack on the 45° , and the crack had pass through the wall. Because the slide bricks extruded door frame and caused the deflection of the door , the panel and the lock damaged. For example , the door of No.123 and No.126 rooms could not been opened after earthquake.

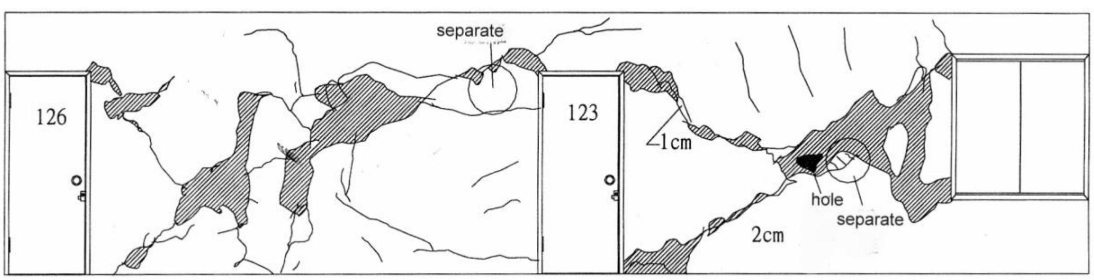

fig.1 brick walls were seriously damaged, the doors couldn’t be opened(damage degree V)

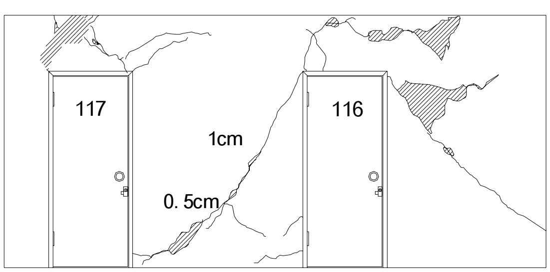

fig.2 shearing cracks appeared on the brick walls, the doors were compressed and couldn’t be opened (damage degree IV)

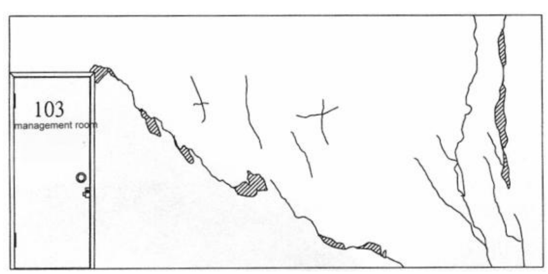

fig.3 oblique cracks occurred on the brick wall , the plaster flaking off (damage degree III)

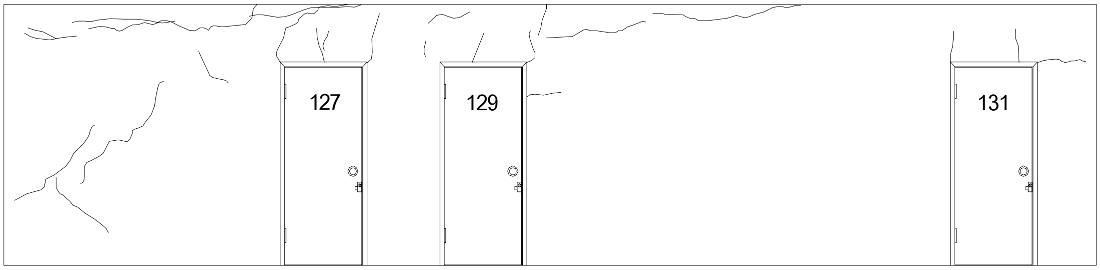

fig.4 the width of crack was under 2mm, damage was slighter(damage degreeII) , the No.131 was on the level of damage degree I

We divided the damage into three types: “O” meant the door opened smoothly , and “D” meant to open the door have a little difficult but still can be opened , and”X” meant the door was unable to be open(Table.1). The number of door , including rooms and exit , total is 222. According to the records showing in Fig.1, there were 92 doors (41 %) unable to open , and 62 doors (28 %) opened hardly , and only 68 doors (31 %) can be open smoothly. Fig.5 showed that if the exits were in the lower story , the doors which opened hardly or couldn’t opened would get higher percentage.

In addition , for the damage of 17 steel doors a more detail investigation was conducted(there are 13 Emergency doors in the staircase among they). As fig.2 shown , only 3 doors were unable to be opened. This also indicates that steel doors are better than wooden doors in earthquake-resistancy.

Table.1¡B The doors damaged statistics of the hotel’s exits in Zu-shan(including wooden doors and steel doors)

floor	Building A 135 doors			Building B 87 doors			Total 222 doors		
	O	D	X	O	D	X	O	D	X
1F	8 (35%)	4 (17%)	11 (48%)	1 (6%)	0 (0%)	16 (94%)	9 (23%)	4 (10%)	27 (67%)
3F	10 (25%)	11 (28%)	19 (47%)	5 (24%)	4 (19%)	15 (57%)	15 (25%)	15 (25%)	31 (50%)
4F	11 (29%)	11 (29%)	16 (42%)	4 (19%)	10 (48%)	7 (33%)	15 (25%)	21 (36%)	23 (39%)
5F	15 (44%)	9 (26%)	10 (30%)	9 (43%)	11 (52%)	1 (5%)	24 (44%)	20 (36%)	11 (20%)
6F				5 (71%)	2 (29%)	0 (0%)	5 (71%)	2 (29%)	0 (0%)
subtotal	44 (33%)	35 (26%)	56 (41%)	24 (28%)	27 (31%)	36 (41%)	68 (31%)	62 (28%)	92 (41%)

<remark> O:The exits could be opened smoothly D:The exits were opened hardly
X:The exits unable be opened

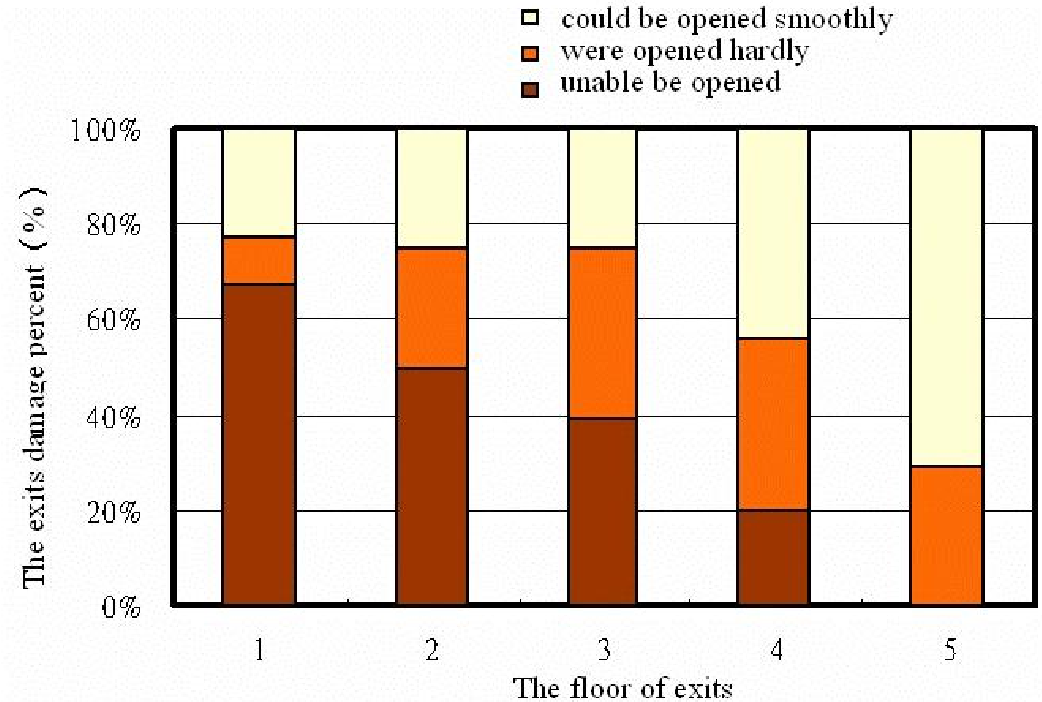

fig.5 The relationship between exits damage and floor

Table.2.The steel doors damaged statistics of the hotel

floor	Building A ¡]12 doors¡^			Building B ¡]5 doors¡^			Total ¡]17 doors¡^		
	O	D	X	O	D	X	O	D	X
1F	1	1	0	1	0	0	2	1	0
3F	1	3	1	1	0	0	2	3	1
4F	1	1	1	1	0	0	2	1	1
5F	1	0	1	1	0	0	2	0	1
6F				1	0	0	1	0	0
subtotal	4 (33%)	5 (42%)	3 (25%)	5 (100%)	0 (0%)	0 (0%)	9 (53%)	5 (29%)	3 (18%)
<remark> O:The exits could be opened smoothly D:The exits were opened hardly X:The exits unable be opened									

2-2 The earthquake damage experience of fixed window glass

Fixed windows were the main part in damage; on the contrary, only few destructed examples found in the movable windows except those in seriously deformed or nearly collapsed structures. The investigation shows that the upper fixed window glass of main entrance was apt to shatter; besides, the ordinary glass came to sharp pieces after shearing , and glass crack is generally in the direction of 45^o.

5mm thick ordinary glass was adapted in part of court skylights in this hotel , and it could be a great menace to human life if the sharp pieces falling down from top. Especially the glass of main entrance and surroundings was mostly designed as large area of fixed glass window adapted ordinary glass. We found that smaller area of unit glass(under 90cm*90cm)was directly fixed by Silicon(fig.7), but some area reached $1.5m^2$ was barely fixed by Silicon.; As to larger area, some was broken by being compressed directly since it was fixed by layering, but the down edge of glass did not be separated by elastic gasket(fig.6). The figure.8 is the standard construction of fixed window glass.

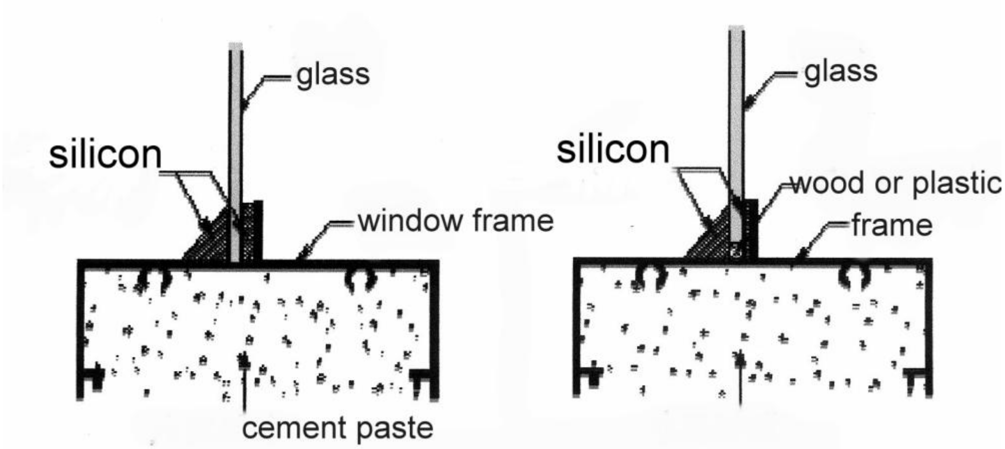

fig.6. Frequently used glass-fixed construction _1 and 2

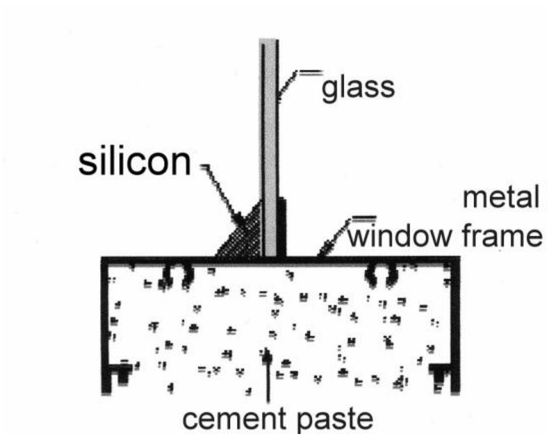

fig.7.Frequently used glass-fixed construction _3

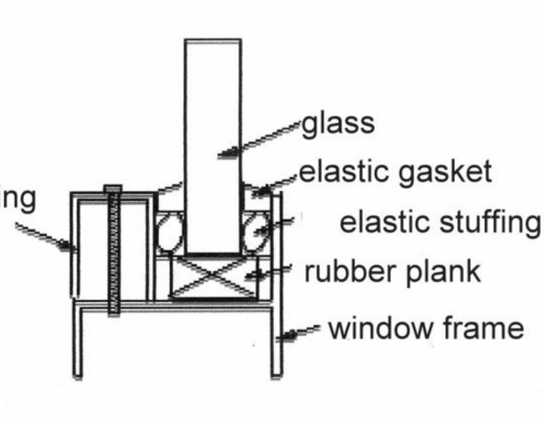

fig.8.standard construction of fixed window glass

III. EARTHQUAKE DAMAGE FACTORS

3-1 Damage of Exits

The relationship between the damage degree of brick and exits

There were 203 exits have been listed for figuring out the relation between the damage degree of brick and exits that could not be opened. Furthermore, we listed three kinds of doors open phenomena to analysis(Table.4)by different damage degree of brick(Table.3).

The distribution of the brick walls damage degree(above III)declined with the increasing of floors. In damage degree IV , V, over 90% of brick walls caused the exits couldn't be open at all; there were also 46 exits of 68% brick walls in damage degree III acted in the same way. We could figure out that the exits would be seriously destroyed to prevent people form fleeing when the brick walls reached damage degree III or above by synthesizing the above-mentioned statistics.

Table.3 Damage degree of brick

Damage degree of brick	The brick damage condition
I	Visible cracks were appeared on brick walls and the interface of beam-column; fine cracks appeared on upper edge of the openings
II	Apparent cracks were appeared on brick walls and the interface of beam-column; oblique cracks occurred on the corners of brick walls or the plaster flaking off; oblique cracks also appeared on upper edge of the openings
III	oblique cracks occurred on the brick walls or sliding along cracks, the plaster of corners or middle parts flaking off; many cracks surrounding the openings occurred
IV	clear two-direction shearing cracks occurred on the brick walls sliding along cracks, large-area plaster flaking off, obviously brick walls broken condition took on; and the broken brick walls obviously compressed the openings.
V	large cracks that could be seen through occurred on the brick walls, and could collapse out-of-plane possibly; the openings deformed by great compression.

Table.4 Statistics of brick walls damage degree surrounding the openings

floor	brick walls damage degree surrounding the openings															Sub-total
	I			II			III			IV			V			
	○	D	X	○	D	D	○	D	X	○	D	X	○	D	X	
1F	0	0	0	5	0	0	1	1	10	1	0	11	0	0	5	24
2F	4	0	0	6	7	1	2	5	20	0	1	7	0	0	1	54
3F	3	0	0	7	14	5	3	6	10	0	0	6	0	0	1	55
5F	7	1	0	13	17	3	2	2	6	0	0	2	0	0	0	53
6F	2	0	0	3	2	0	0	0	0	0	0	0	0	0	0	7
Sub-total	16 (94%)	1 (6%)	0 -	34 (41%)	40 (48%)	9 (11%)	8 (12%)	14 (21%)	46 (68%)	1 (4%)	1 (4%)	26 (92%)	0 -	0 -	7 (100%)	203
total	17 (8%)			83 (41%)			68 (34%)			28 (14%)			7 (3%)			

<remark> ○ : The exits can be opened successfully D : The exits can't be opened smoothly

X : The exits can't be opened at all

The destruction modes of exits

From the investigation of brick walls and exits , seven destruction modes(fig.9)has been divided. Mode_1(the door collided against the doorsill or extruded upper frame)was the mostly frequent of exits destruction modes from Table 5, there were 112 exits which occupied 73% of totally 154 cases; the following was Mode _2(the side frame deformed by the compression of brick walls)which were 61 exits which occupied 40%. Consequently, the generally sequence of destruction of wood doors were firstly door collided against the upper frame or doorsill, secondly the destroyed brick walls squeezed the frame to deform and close strictly with panel, in the end the locking was stuck , even the axis of hinge was pulled off.

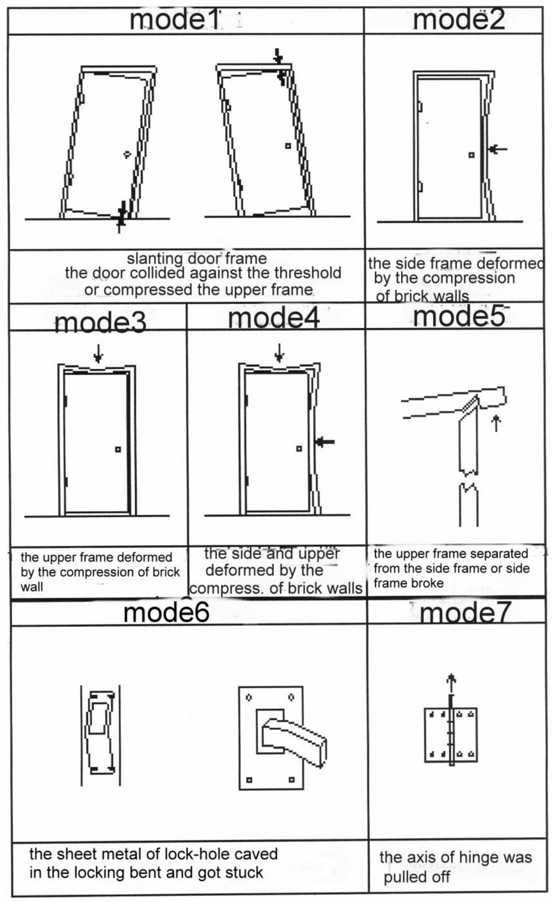

Fig.9. The destruction modes of exits

Table 5.Statistics of exits damaged modes

floor	exits damaged modes（154 samples）						
	1	2	3	4	5	6	7
	the door panel extruded the doorsill or upper frame	the side frame was extruded and deformed by brick walls	the upper frame deformed by the compression of brick walls	the side and upper frame deformed by the compressio n of brick walls	The component of the frame break away	the sheet metal of lock-strike caved in the locking bent and got stuck	the axis of hinge was pulled off
1F	4	10	1	13	-	26	1
2F	38	19	5	12	-	7	1
3F	41	17	9	12	-	7	1
5F	27	14	6	4	-	1	0
6F	2	1	0	0	-	0	0
total	112（73%）	61（40%）	21（14%）	41（27%）	（incomplete information）	41（27%）	3（2%）

3-2 The analysis of earthquake damage of fixed window glass

There were many factors , such as types , thickness , unit area , shape of glass , the construction of fixed window , could influence the damaged behavior of fixed windows. Following are the related analysis :

Type and thickness of the glass

The plan of the indoor court with cafe in the hotel was a polygon. After earthquake , there was only one tempered glass broke and the broken glasses were like pellets. There were 25 pieces of ordinary glass (about half) broke in the vicinity. In the locale , there were still three pieces of glass with 9mm thickness damaged and their dimension were 180cm×210cm. For different from the 3mm ordinary glass , the thicker glass only damaged with diagonal cracks , and they did not have the danger of flied or fell. According to the result , when the tempered glass and thicker glass are squeezed , they can absorb more energy and the modes of damage are not easy to hurt people and better for seismic performance.

Dimension and shape of the window unit

According to the reference[3] , the allowable deformation of glass under the same construction were proportional to the height of the window and inverse proportion to the width of the window. In other words , the higher and narrower windows have better seismic performance than the lower and wider ones during earthquake.

$$\triangle = \triangle 1 + \triangle 2 =$$

$$2 \times C1 + 2 \times \frac{H \times C2}{W} = 2 \times C1(1 + \frac{H \times C2}{W \times C1}) \cdots\cdots\cdots(1)$$

$\triangle$:allowable deformation of window glass
$\triangle 1$:the additional deformation of window by glass horizontally sliding
$\triangle 2$:the additional deformation of window by glass rotating
C1 :the side spare space of glass
C2 :the upper and bottom spare space of glass
H :the height of inside frame
W :the width of inside frame

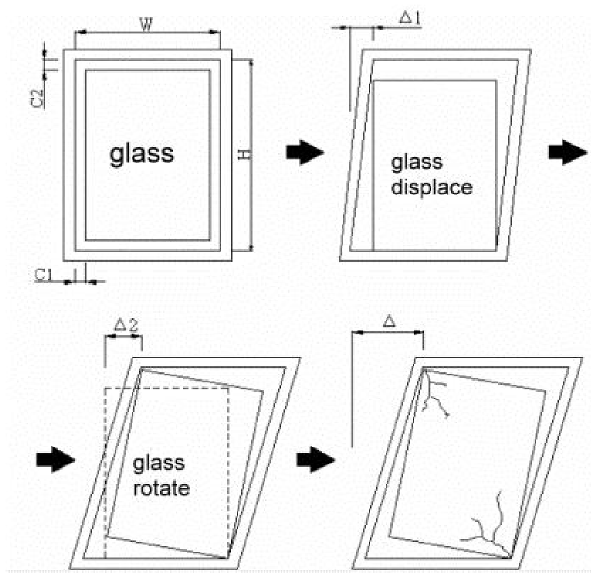

Fig.10. The destruction modes of fixed window glass

On the other side , the height of the view windows around the lobby and restaurant were all 180cm. For the proportion of the form , the width of the middle windows were 90cm and the side windows were 210cm. There were three of all fixed windows damaged in the earthquake and they all had large area(180cm×210cm). So when the height of the windows were the same , the wider ones were easy damaged in the earthquake.

The construction and spare space of window

Fixed windows often used on the doors ,and we found that most of the glass were fixed to the prominent edges of windows by adhesion force of the silicones. A few of the large-area fixed window glass were fixed with aluminum layers and filled the interstices with the silicones. According to the observation , the interval between the glass and window frame was very small. In general , the bottom of the glass was close to the frame and there was 5mm spare space on the top , and among 0mm to 5mm on the sides. So there was limited space for the glass to move and rotate. According to formula[1] , if the value of C1 and C2 (the spare space on the sides or bottom and top) was higher , the allowable displacement of the glass was bigger and the fixed window glass would not damage easily in the earthquake.

IV.CONCLUSION

4-1 The exits (Table 6)

(1) The major reasons that caused the exit damage were that the door panel squeezed the top of door frame or the doorsill , or the cracked brick walls extruded the door frame and led to the deformation of the frame , so that the panel was jammed with the frame and the door could not open . At last , the lock strike was bent and jammed and even the axle of the door hinge was uprooted and damages.
(2) For general lower RC building with brick partition walls , the lower story that the exits obtained higher damage than higher story.
(3) The 0.5B brick wall with exit , the width of cracks due to the earthquake were wider than 2mm or the damage degree of the walls were over ? , all had serious damage in the exits.
(4) The wooden door frame was easy to bend or deform in the earthquake and caused the door jammed. The steel doors did not have the residual deformation easily , but the doors could not easily open by people after being jammed.
(5) If there are lintel of the exit doors , that can prevent the cracked brick walls from directly pressing the top of the door frame to extrude the panel and hinder from fleeing.
(6) The interval between panel and top of the frame or doorsill and between the lock strike and strike hole must have more than 10mm spare space.

4-2 Fixed window (Table7)

(1) The movable windows have spare space on track and the window frame have greater allowable deformation. For the reason , there are fewer movable windows damaged except for collapsed or seriously damaged building. The main earthquake damage is that the fixed window frame extrudes glass and causes the glass crush.
(2) When the fixed windows have the same height , the larger-area glass will easily damage in the earthquake. The glass with the same area has greater height-width ratio, in other words , the higher and narrower windows have better seismic performance than the lower and wider ones during earthquake.
(3) The general glass with 3mm thickness are easy to crack , and people will stab or slash with the

incisive piece of glass. The glass which are thicker than 9mm have better they can absorb more energy and the modes of damage will not cause many incisive pieces to hurt people easily.

(4) The tempered glass is stiffer than general glass and better for seismic performance. When the tempered glass crushes in the earthquake , the fragments are like pellets and will not hurt people and hinder from fleeing.

(5) When the glass extrude in the earthquake , the elastic gasket between the glass and window frame can assure the glass that has enough sliding and rotated space.

(6) The dimension of the glass has to smaller than the inside frame of the windows. During the fixed process , we can fix the glass in the middle of the window frame with elastic gasket. There must be more than 5mm spare space for absorbing the deformation between the glass and frame and avoiding the glass damage from the frame extruding quickly.

As the earthquake damage experience and conclusion showing , if we can bring the concept of the earthquake resistance into the design and construction , it will must reduce the damage and increase the probability of fleeing in the earthquake.

Table.6 the comparison between damaged and undamaged exit doors

Item		Influence factors		damaged	undamaged	remarks
A	Walls	1	Crack's width	>2.0mm	<2.0mm	1/2B brick wall
		2	Damage degree	>III	<III	1/2B brick wall
B	Materials	3	Frame	wooden	steel	Wooden door deforms easily
		4	Panel	steel	wooden	Wooden door easily forces to demolish for fleeing
	Constructions	5	Windowsill effect	Yes	No	Windowsill extrude the frame and the lock-strike hole damage
		6	Lintel	No	Yes	Avoid the damage from the compression of brick wall
D	Spare Space	7	Spare space in panel	<10mm	>10mm	Between panel and top or bottom of the frame
		8	Spare space in lock-strike	<10mm	>10mm	Between lock-strike and top or bottom of the lock-hole
E	Others	9	residual deformation	>5/1000	<5/1000	residual deformation of the frame and the door is unable to open
		10	Story	Low story	High story	In the same building
		11	Bolt of door	lock	unlock	Bolt-type lock-strike jam easily

Table.7 The comparison between damaged and undamaged fixed windows.

Items		Influencing factors		damaged	undamaged	remark.
I	Window shape	1	Window style	Fixed windows	Movable windows	More space for deforming in Movable windows
		2	Size and shape	Large area , short and wide in shape	Small area , thin and long in shape	-
II	Materials	3	Glass type	Ordinary glass	Tempered glass	Tempered glass is not apt to shatter, and the pieces are not easy to hurt people.
		4	Glass thickness	<5mm	>5mm	Thick glass is stronger, and the pieces are not apt to shoot around
III	Construction	5	Glass construction	No spacer, fixed by Silicon	Elastic spacer , fixed by layer and Silicon	-
		6	Surrounding remaining spare space	no	>5mm	The larger the area of glass is, the bigger the remaining spare space is.

REFERENCES

1. Building Disaster Prevention , No.245 , 1998,6 The Japan Building Disaster Prevention Association.
2. Hisashi OHIRA and Makoto TSUJIMOTO , “Case Study on Apartment Entrance Doors Damaged by the Hyogoken-Nanbu Earthquake” , Conference paper No.21049 , 1996,9 , JASA , Japan.
3. Ja-Shian Chang , Chia-Chi Chen ,”Performance-Base Design Criteria Based on the Earthquake Damage of Emergency Doors and Window Glass” 2000,10 , (NSC88-2625-Z-006-007), National Science Council , Taiwan .
4. Chia-Chi Chen , Ja-Shian Chang , “The Earthquake Damage of Exit and Fixed Window Glass” , 2002,10 , (NSC-90-2625-Z-165-001) , National Science Council , Taiwan .
5. Tzung-Hsien Woo , “Performance-Based Design Criteria Based on the Earthquake Damage of Emergency Doors and Window Glass” Master Thesis , 2001,01,National Cheng-Kung University , Tainan , Taiwan.