Seismic Assessment and Strengthening Design of Masonry Wall with Arch Opening

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SUMMARY:
In this study, the structural behaviour and the effect of strengthening for historic masonry walls with arch openings under horizontally cyclic loading are investigated by experiment. Results obtained from the three un-strengthened specimens show the initial crack occurred at a drift angle of approximately 2/1000. In addition to the specimen test, a method for evaluating the ultimate load of a brick wall with arch opening has been developed from a simplified model. Comparing the ultimate load evaluated and that obtained from test specimens, the difference is less than 6% for low or medium bearing and less than 9% for high bearing. Furthermore, a strengthening design is also developed for the strengthening method using 2 thin stainless steel straps imbedded into the intrados face of the arch. Finally, seismic assessment and strengthening design of masonry brick wall with arch openings is illustrated with the Li-Xian Building of Former Japanese Infantry 2nd Wing Camp.

Keywords: Historic Building, Brick Masonry Arch, Seismic Assessment, Strengthen, Drift Angle

1. INTRODUCTION

Arch is an important architectural element of masonry historic buildings in Taiwan. Due to the geometric characteristic of arch, the masonry wall with arch opening is easy to get damage during earthquake. Thus for the reservation of historic buildings, properly repairing the earthquake damage and improving the seismic resistant ability of masonry wall with brick arch are worth to be investigated. From four practical strengthening methods in previous study, only 1 strengthening method is compared in this study. 2 thin stainless steel straps (10mm x 1mm) are imbedded into the intrados face of the brick arch. The arch subjected to vertical loads is also compared. The main purpose of this study is to understand the improvement of ultimate strength and seismic performance of historic brick arch strengthened with proposed methods. The results obtained in this study will provide architect useful information for planning and design retrofitting of historic buildings.

2. EXPERIMENTAL PROGRAM

2.1. Wall Specimens

Four arch specimens with thickness 1B were manufactured in Dutch bond (**Figure 1**). In order to simulate the bricks used in most historic buildings in Taiwan, all specimens use bricks with 23x11x6cm in size. The dimension of each of the specimen is 202cm in width and 239cm in height. The cement mortar used is 1:2 (cement: sand).

Table 1 lists the details of the specimens. WU1, WU2 and WU3 are un-reinforced specimens used for comparison the performance of specimens with different vertical loads. Specimens WS1, WR1 and

WR2 are strengthened, 2 thin stainless steel straps are imbedded into the intrados face of the arch. In these two specimens, WR1 and WR2 are strengthened after specimens WU1 and WU2 damaged, and used to compare the performance with un-reinforced specimens. During manufacturing the specimen, the cutting slot is filled with EPOXY mortar.

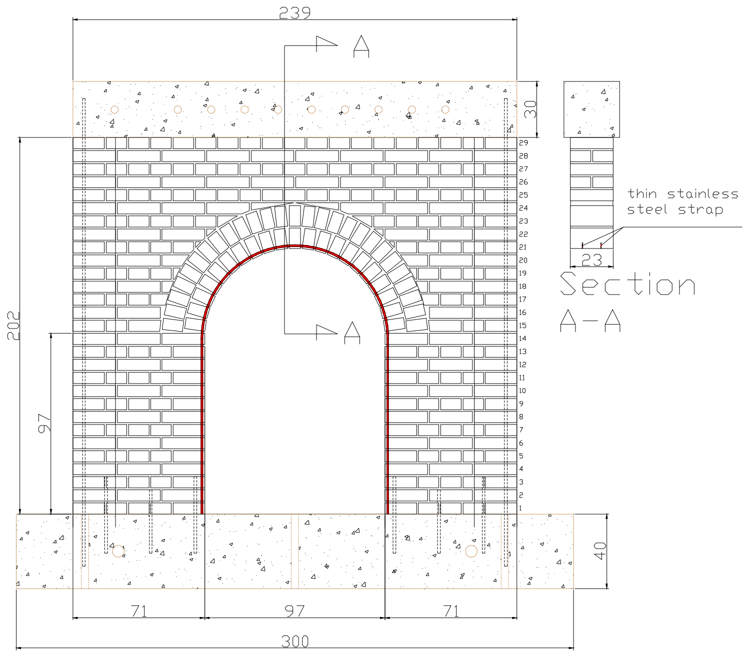

Figure 1. Brick arch specimen, 2 thin stainless steel straps are imbedded into the intrados face of the brick arch (specimens WS1, WR1 and WR2)

Table 1 Tested material properties (*MPa*)

Specimen	L×H×T(cm)	Strengthening method	Equipment Weight (*kN*)	Applied Vertical Load (kN)	Total Vertical Load (kN)
WU1	239×203×23	Without strengthening	12.2	-	12.2
WU2	239×203×23	Without strengthening	12.2	59.0	71.2
WU3	239×203×23	Without strengthening	12.2	87.8	100.0
WS1	239×203×23	2 thin stainless steel straps (10mm x 1mm) are imbedded into the intrados face of the brick arch (Figure 1)	12.2	-	12.2
WR1	239×203×23	2 thin stainless steel straps (10mm x 1mm) are imbedded into the intrados face of the brick arch strengthened post WU1 damaged	12.2	-	12.2
WR2	239×203×23	2 thin stainless steel straps (10mm x 1mm) are imbedded into the intrados face of the brick arch strengthened post WU2 damaged	12.2	59.0	71.2

2.2 Material properties

gives the fundamental properties of the brick arch specimens. All the strengths are tested in lab. The materials are taken at the same time as specimens manufactured.

The value of elastic modulus E_m is between 733MPa to 1534MPa according to the stress strain relationship of brick masonry specimens cut from a wall specimen (Chang, et al. 2010). Because this is obtained from a used wall specimen, for a new specimen the elastic modulus may be greater than 1534MPa. The average flexural strength f_{mb} is 1.77Mpa. To simply the calculation, the material is assumed to be homogeneous. Based on Chen, et al. (2002) the limit elastic modulus E_m is estimated as following:

$$f_m'=0.27f_{bc}^{0.7}f_{mc}^{0.3} \tag{2.1}$$

$$E_m=138f_m' \tag{2.2}$$

where

f_m' is the compression strength of masonry (MPa)
f_{bc} is the compression strength of brick (MPa)
f_{mc} is the compression strength of mortar (MPa)

Take specimen WU1 for example, f_{bc} =57.09MPa, f_{mc} =28.04MPa, f_m'=0.27$f_{bc}^{0.7}f_{mc}^{0.3}$=12.45MPa, E_m=138f_m'=1718MPa. For specimen WS1, f_m'=11.07MPa,and E_m=138f_m'=1528MPa.

Compare the Elastic Modulus of Masonry E_m calculated from Eqn. 2.2 and the flexural test value (733MPa ~1534MPa) of the cut specimens, the calculated Elastic Modulus of Masonry E_m is much close the maximum test value.

Table 2 Tested material properties (MPa)

	Material properties	WU1	WU2	WU3	WS1
1	Compression strength of brick **,** f_{bc}	57.09	52.61	53.83	49.31
2	compression strength of mortar, f_{mc}	28.04	27.76	52.51	26.62
3	Compression strength of Masonry, f_m'	12.45	11.73	14.43	11.07
4	Elastic Modulus of Masonry, E_m	1718	1619	1991	1528

2.3 Test setup

Figure 2 is the test setup designed for this study. The lower RC beam is fixed on the steel base by high strength bolt. The upper RC beam and the steel cap are bolted together with 10 bolts (D= 30mm). The end of the steel cap is connected to the actuator that is attached to the reaction wall. During test, the upper beam transmits the horizontal load to the top plane of the brick arch. The loading was measured by the load cell on the actuator, and the displacement was measured using a displacement transducer.

During test, the arch specimen was subject to an increasing cyclic lateral loads (**Figure 2**) which were controlled by the stroke of the actuator. The test is stopped as the specimen has been seriously damaged. Specimens WU2 and WR2 are simultaneously loaded with cyclic lateral load and a 59.0kN vertical load. Specimen WU3 is simultaneously loaded with cyclic lateral load and a 87.8kN vertical load. The mechanism of the vertical loading system is shown in **Figure 3**. The vertical load is amplified by the action of lever arm and pulleys.

2.4 Experiment Results

The maximum load obtained and its corresponding displacements are listed in Table 3. Based on the test results, we suggest that drift angle 2/1000 could be assigned as the initial damage point, and drift angle 4/1000 to be the ultimate performance point for historic building seismic assessment. In order to compare in later section, we define the load ratio to the Maximum load of WU1 (un-reinforced specimen) as ultimate load ratio 1.0.

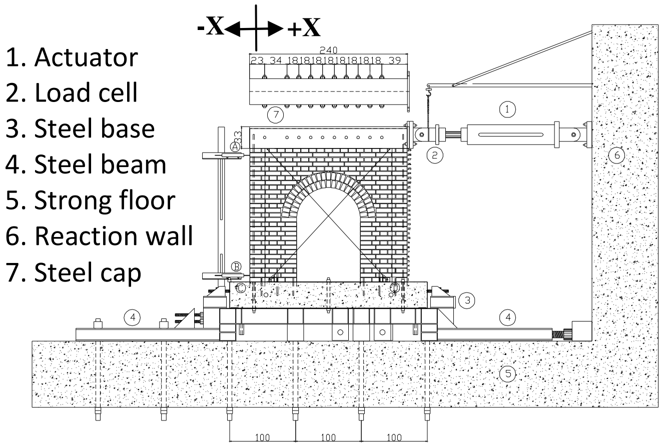

Figure 2. Test setup

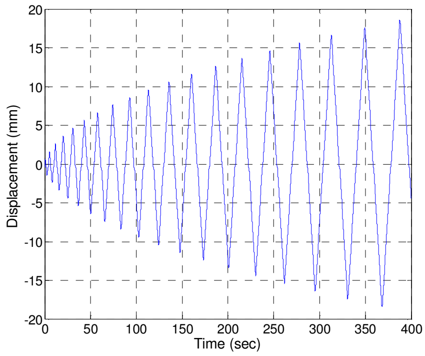

Figure 3. The input stoke of the actuator

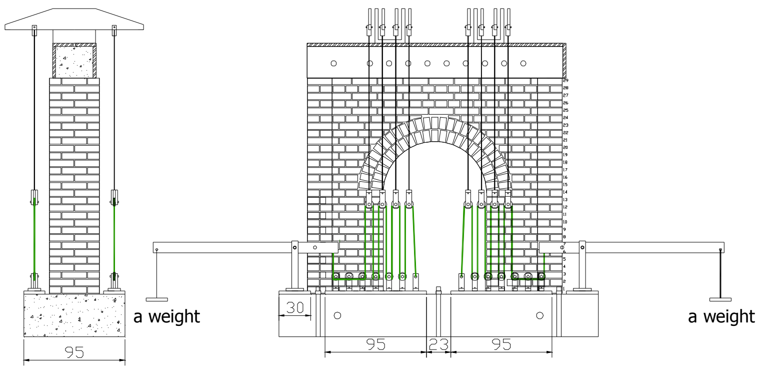

Figure 4. The mechanism of the vertical loading system (unit:cm)

Table 3. Tested results

Loading Direction		Forward (-X)			Backward (+X)		
Specimen	Loading Cycle	Drift Angle	Loading (kN)	Ultimate Load Ratio	Drift Angle	Loading (kN)	Ultimate Load Ratio
Un-reinforced WU1	11	-2.20/1000	-105.4	0.60	2.13/1000	83.9	0.64
	14	-3.13/1000	-123.1	0.70	2.73/1000	92.8	0.71
	23	-6.24/1000	-175.8	1.00	5.53/1000	128.6	0.98
Un-reinforced WU2 w/ 59.0kN vertical load	8	-3.01/1000	-166.5	0.95	3.38/1000	122.2	0.93
	13	-4.29/1000	-185.6	1.06	4.33/1000	132.0	**1.00**
	17	-5.90/1000	-204.3	1.16	6.16/1000	146.3	1.11
Un-reinforced WU3 w/ 87.8kN vertical load	9	-2.40/1000	-190.2	1.08	2.45/1000	168.4	1.31
	10	-2.88/1000	-197.4	1.12	2.79/1000	176.5	1.37
	13	-4.66/1000	-209.9	1.19	3.68/1000	184.7	1.40
Post damage Strengthened WR1	12	-2.91/1000	-147.0	0.84	3.59/1000	101.9	0.77
	21	-5.77/1000	-223.3	1.27	6.39/1000	161.3	1.23
	24	-6.86/1000	-229.7	1.31	7.73/1000	168.3	1.28
Post damage Strengthened WR2 w/ 59.0kN vertical load	9	-2.66/1000	-115.6	0.66	2.94/1000	110.4	0.84
	14	-4.52/1000	-152.7	0.87	4.76/1000	146.8	1.12
	21	-6.68/1000	-185.7	1.06	8.40/1000	181.6	1.36

3. ESTIMATE OF ULTIMATE LOAD

The brick arch simplified as frame model, and take linear elastic structural analysis. Taking the specimen of this study as an example, refer to the experimental results, assume the initial crack section E start a 45° crack to spandrel then change to be developed horizontally as shown in Figure 5. In the limit performance state, the crack almost completely throughout the specimen, so assume that the arch stress equal to the flexural strength of the masonry, the corresponding horizontal force is the horizontal ultimate load P_u.

The simplified frame model is shown in Figure 6. The section properties of the members are

The moment of inertia of member b, $I_b = \dfrac{23*59.5^3}{12} = 403{,}736\ cm^4$

The section area of member c, $A_c = 48*23+23*47 = 2185\ cm^2$

The neutral axis of member c, $y_c = \dfrac{47*23*59.5+23*48*24}{2185} = 41.56\ cm$

The moment of inertia of member c,

$$I_c = \frac{47*23^3}{12} + 47*23*(59.5-41.56)^2 + \frac{23*48^3}{12} + 23*48*(41.56-24)^2 = 947{,}957\ cm^4$$

Height of the frame, $h = 173.25\ cm$

Length of the frame, $l = 180.12\ cm$

$k = I_b / I_c * h / l = 0.4097$

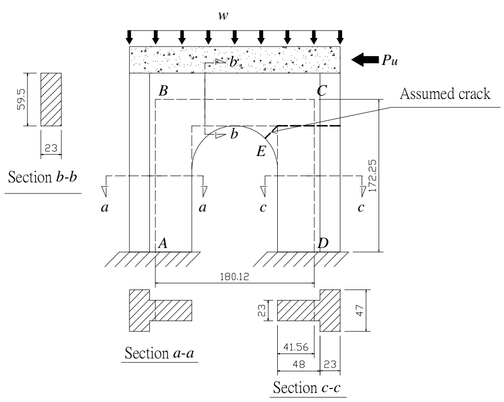

Figure 5. Assumed initial crack position of brick arch specimen (unit:cm)

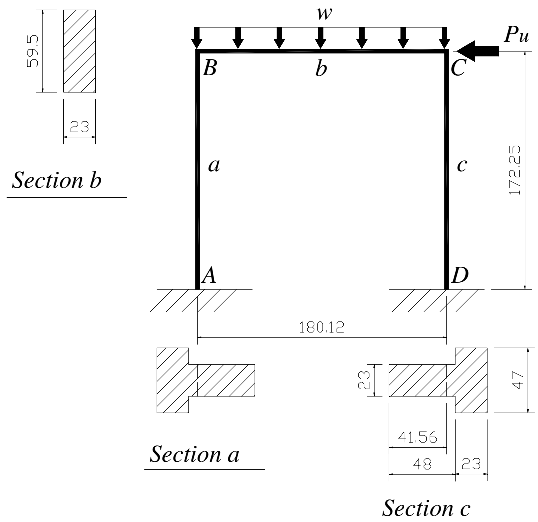

Figure 6. Analysis model for brick arch specimen (unit:cm)

The bending moment M_c, horizontal internal force H_c and vertical internal force V_c of joint C as shown in **Figure 7** could be derived by elastic analysis:

$$M_c = \frac{P_u h}{2}\frac{3k}{(1+6k)} - \frac{wl^2}{6(2+k)} \tag{3.1}$$

$$H_c = -\frac{P_u}{2} + \frac{wl^2}{4h(2+k)} \tag{3.2}$$

$$V_c = \frac{3P_u hk}{l(1+6k)} - \frac{wl}{2} \tag{3.3}$$

From Eqn. 3.1 to Eqn. 3.3, the distributed vertical load w should consider the self weight of member *BC* in **Figure 7**. Consider the actual corner of the brick arch having a bigger section, and observe the damage mode and development of specimen, the crack position is simplified as shown in Figure 5. The corresponding load could be estimated.

The cross section area A_E= 47*23+23*68.09 = 2647.07 cm^2

The neutral axis of the section $y_E = \dfrac{47*23*79.59+23*68.09*34.05}{2647.07}$ = 52.64 cm

The moment of inertia $I_E = \dfrac{47*23^3}{12} + 47*23*(79.59-52.64)^2 + \dfrac{23*68.09^3}{12} + 23*68.09*(52.64-34.05)^2$
= 1,979,351 cm^4

The maximum flexural tensile stress for section E as crack initially

$$f_E = \frac{M_c y_E}{I_E} + \frac{V_c/\sqrt{2} - H_c/\sqrt{2}}{A_E} = F_b \tag{3.4}$$

Substitute Eqn. 3.1 into Eqn. 3.3 M_c , H_c, V_c into Eqn. 3.4, may derive the ultimate load P_u of the specimen cracked

$$P_u = \frac{F_b + wl\left(\frac{l}{6(2+k)}\frac{y_E}{I_E} + \frac{1}{2\sqrt{2}A_E} + \frac{l}{4h(2+k)\sqrt{2}A_E}\right)}{h\frac{3k}{1+6k}\left(\frac{y_E}{2I_E} + \frac{1}{l\sqrt{2}A_E}\right) + \frac{1}{2\sqrt{2}A_E}} \tag{3.5}$$

The comparison of estimated and experimental horizontal ultimate load of specimen WU1, WU2 and WU3 is shown in **Table 3**. The error is small than 9%, and it is conservative for practical application. As the vertical load increases, the error increases, this simplified model for seismic assessment is a conservative method for vertical load.

Table 3 Comparison of ultimate load

Specimen	l *(cm)*	h *(cm)*	k	Vertical Load *(kN)*	Distributed Load, w *(N/cm)*	Estimated Ultimate *Load,* P_u (kN)	Experimental Ultimate Load (kN)	Error (%)
WU1	180.12	173.25	0.4097	12.2	78.06	175.4	175.8	-0.23%
WU2	180.12	173.25	0.4097	71.2	273.68	192.9	204.3	-5.58%
WU3	180.12	173.25	0.4097	100.0	393.96	201.4	219.5	-8.25%

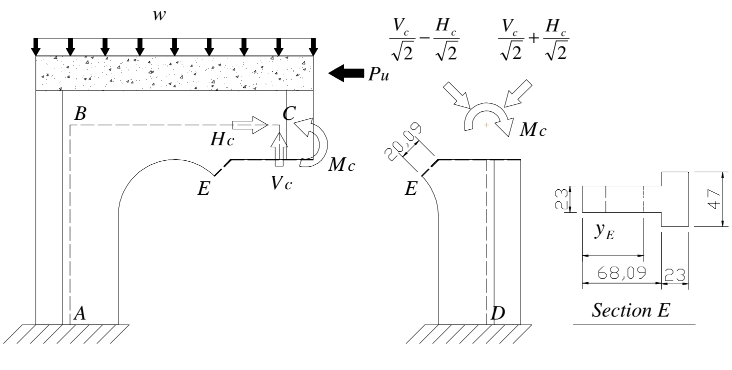

Figure 7. Free body on joint C of brick arch specimen

4. STRENGTHENING STRENGTH OF MASONRY ARCH

According to the previous study, in general, using stainless steel strap for strengthening has shown the improvement of earthquake-resistance. The performance and comparison for different strengthening method are concluded as follows:

Assume the strain of stainless steel ε_S is consistent with the bonded brick arch strain ε_m.

$$\varepsilon_S=\varepsilon_m=F_b/E_{mb} \tag{4.1}$$

Assume the cross section area A_S, and calculate the tensile force at the crack section

$$T_S=E_S*\varepsilon_S*A_S \tag{4.2}$$

where

F_b is the flexural strength, and E_m is the limit elastic modulus of brick masonry.

E_S is the elastic modulus of stainless steel. For $\varepsilon_S>\varepsilon_y$, ε_S must be replaced by ε_y

$$T_S=E_S*\varepsilon_y*A_S \tag{4.3}$$

Assess the horizontal ultimate load P_u of the brick arch before strengthening, then estimate based on previous method. Analyze the required horizontal ultimate load P_{req}, *if* $P_{req}\leqq P_u$, the brick arch need not strengthen; while $P_{req}>P_u$, the brick arch need to be strengthened.

Using 2 thin stainless steel straps (10mm x 1mm) imbedded into the intrados face of the brick arch, the flat stainless strips will supply a tensile force T_S at the crack (**Figure 8**), due to the effect of this tensile force, the ultimate strength of the masonry arch will increase ΔP_u. The strengthening design process is as follows:

Transfer T_S to an equivalent moment M_S

$$M_S=Ts*j_d \tag{4.4}$$

Where j_d is the distance of the centroid of stainless strip to the compression center of brick arch (**Figure 8**c). Conservatively assumed as

$$j_d=d-d_c/3 \tag{4.5}$$

where

d is the distance of the centroid of stainless strip to the edge of the section

d_c is the distance of the neutral axis to the edge of the section.

The incremental ultimate load ΔP_u could be derived from Eqn. 3.1

$$\Delta P_u=\frac{2}{h}\frac{(1+6k)}{3k}[M_S+\frac{wl^2}{6(2+k)}] \tag{4.6}$$

Add horizontal ultimate load P_u and ΔP_u to be P_u', and compare P_u' with P_{req}, if P_u' smaller than P_{req} then enlarge A_S until $P_u'=P_u+\Delta P_u\geqq P_{req}$.

Taking specimen WS1 as an example, the limit elastic modulus of masonry

$$E_m=138f_m'=138*0.27f_{bc}^{0.7}f_{mc}^{0.3}=1528MPa$$

Use 2-10mm*1mm flat stainless strips with 2mm diameter holes to increase the bond of the slot, the section area A_S=(10-2)*1*2=16 mm^2. The modulus of stainless steel E_s=193GPa.

The maximum strain of masonry $\varepsilon_m = F_t/E_m$=0.00116 > yield strain of stainless steel ε_y=0.00106，and $T_S = E_S*\varepsilon_y*A_S = F_y*A_S$=205*16=3280$N$.

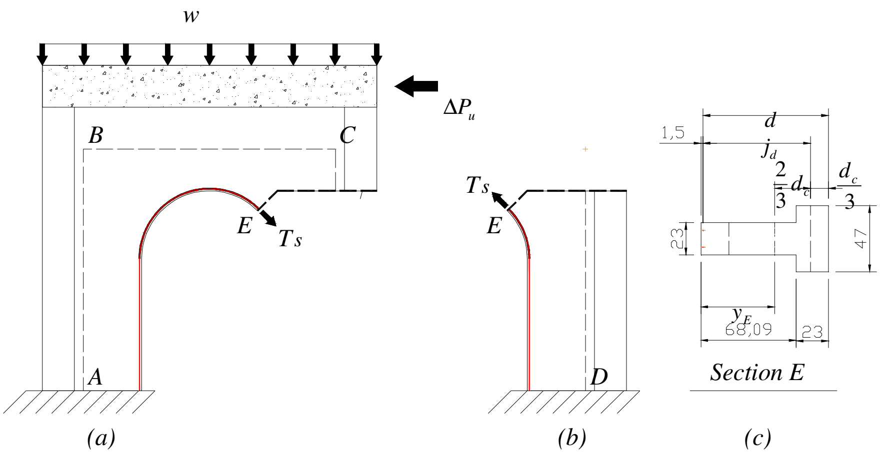

Figure 8. Free body on joint C of brick arch specimen

Table 4 is the calculated results of ΔP_u, P_u' and ultimate Load Ratio. The estimated strengthened horizontal ultimate strength P_u'=188.6kN, this value is smaller than the experimental ultimate load 198kN of WS1 (4.75%). This underestimated value is due to the fact that the neutral axis may move toward compression area after initial crack, and j_d may larger than the assumed value. Besides, the curved shape effect of the stainless strips is not calculated.

Compare the reinforced P_u' and P_{req}, and check the cross section area. Suppose the required ultimate load ratio R_u of specimenWU1 is 1.15

$$P_{req}=175.4kN*1.15=201.7kN$$

then the stainless section should be enlarged to16mm(width)*$1.5mm$(thickness) as shown in **Table 4**.

Table 4 Comparison of reinforcement

Reinforcement (W*T*number)	j_d (cm)	M_S (kN-cm)	ΔP_u (kN)	P_u (kN)	P_u' (kN)	Ultimate Load Ratio R_u
10mm*1mm*2	77.03	252.7	13.2	175.4	188.6	1.08
16mm*1.5mm*2	77.03	663.2	26.5	175.4	201.9	1.15

4. STRENGTHENING DESIGN

Taking the southern 2F brick arch of Li-Xian Building as an example, assess the horizontal ultimate load of the 2F semicircle brick arch. Choose one unit of the Li-Xian Building 2F arches (**Figure 9**). Refer to the investigation report (Hsu, et al. 2008), the shear stress of this wall F_{ve}=1.933kgf/cm^2，ξ=2.07.

Base shear stress of this wall F_{ve}/ξ=1.933/2.07=0.934 kgf/cm^2

The shear of brick column =0.934*50*109*9.81/1000=49.9 kN

Equivalent horizontal external load = 2*49.9=99.8 *kN*

Figure 10 shows the details of the column, based on the dimension of the arch and column section, the ultimate load P_u could be estimated. **Table 5** lists the results, brick arch ultimate load P_u=77.2kN <99.8kN (equivalent horizontal external load). The assessment result of Li-Xian Building southern 2F brick arch shows that the arches need to be strengthened under seismic code load.

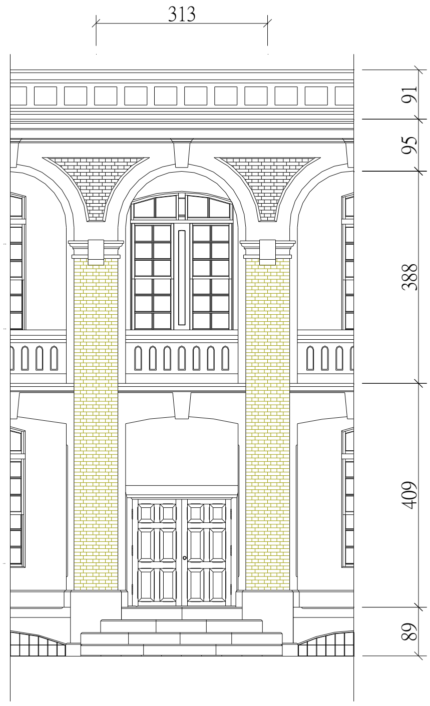

Figure 9. The element size of Li-Xian Building

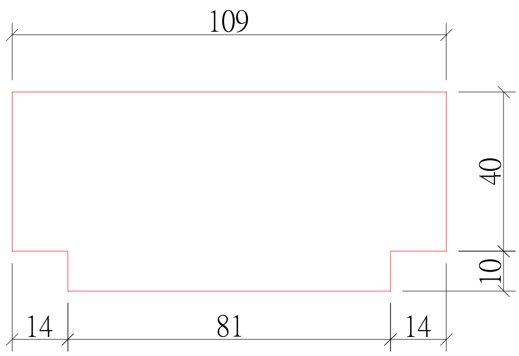

Figure 10. The section of the brick column of Li-Xian Building

Table 5 Estimated horizontal ultimate load of Li-Xian Building unit brick arch

I_b (cm^4)	A_c (cm^2)	y_c (cm)	I_c (cm^4)	l (cm)	h (cm)	k	Vertical Distributed Load w (*N/cm*)	Estimated horizontal ultimate load P_u (kN)
3,572,396	5,450	25	1,135,417	313	483	4.8552	751.45	77.2

Taking the southern 2F brick arch of Li-Xian Building for example, the strengthening design is as follows:

Using 3-16*mm**1.5*mm* flat stainless strips with 2*mm* diameter hole to increase the bonding of the slot, the cross area, A_S=(16-2)*1.5*3=63 mm^2.

Table 6 is the calculated results of the increment ultimate load ΔP_u *and* The strengthened horizontal ultimate strength P_u'. The strengthened horizontal ultimate strength P_u'=101.1*kN*>*98.8kN,* shows that the arches will not damage seriously after strengthening under seismic code load.

Table 6 the strengthening design of Li-Xian Building

Reinforcement (W*T*number)	j_d (*cm*)	M_S (*kN-cm*)	ΔP_u (*kN*)	P_u (*kN*)	P_u' (*kN*)
16mm*1.5mm*3	77.03	994.8	23.9	77.2	101.1

6. CONCLUSIONS

According to the test of designed brick arch specimens, in general, using flat stainless steel strips for strengthening has shown the improvement of earthquake-resistance. Through the study, the following results can be used as the reference of the repair assessment applications for the historical buildings:

1. Based on the test results, we suggest that drift angle 2/1000 could be assigned as the initial damage point, and drift angle 4/1000 to be the ultimate performance point for historic building seismic assessment.

2. Comparing the ultimate load evaluated by the simplified method and that obtained from test specimens, the difference is less than 6% for low or medium bearing and less than 9% for high bearing.

3. The strengthened strength evaluated by this simplified method may be undervalued.

4. The results obtained in this study will provide architect useful information for planning and design retrofitting of historic buildings.

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