# AN EXPERIMENTAL STUDY OF REPAIR AND STRENGTHENING OF EARTHQUAKE DAMAGED BRICK ARCH

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**ABSTRACT :**

The masonry wall with arch opening often gets damage during earthquake. In this study four strengthening methods for improving the seismic resistant ability of this problem are tested. These methods are developed under the condition that the original form is not changed. In method 1, a thin stainless steel strap is imbedded into the bottom face of the arch. In method 2, nine thin stainless steel straps with various lengths are imbedded into the brick joints horizontally. In method 3, two thin stainless steel straps are imbedded along the semi-circular joints of the arch. In method 4, eight thin stainless Z shape pieces are planted along the horizontal and vertical joints of often found damaged area. Totally, five specimens are manufactured and cyclic horizontal loading is applied. From these tests, the earthquake-resistant performance including damage mode, hysteretic loop, energy absorption and ultimate load are compared and discussed. Furthermore, the strengthening effect of post-earthquake strengthening is discussed for strengthening method 1. According to the test in the four strengthening methods, method 1 obtains a greatest value of ultimate loading and good stiffness however it has to cut a slot through bricks. In method 2 the loading resistance is not so high like method 1, but the original form is not interfered.

**KEYWORDS:** Masonry, Brick Arch, Retrofit, Historic Building, Strengthen

## 1. INTRODUCTION

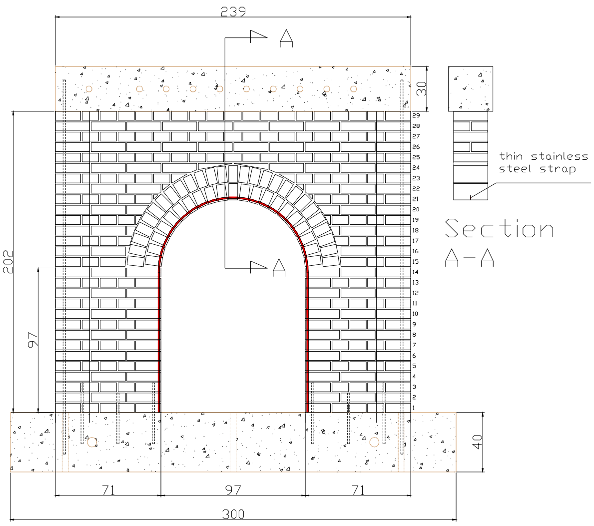
Arch is an important architectural element of masonry historic buildings in Taiwan. Due to the geometric characteristic of arch, the masonry wall with arch opening is easy to get damage during earthquake. Thus for the reservation of historic buildings, properly repairing the earthquake damage and improving the seismic resistant ability of masonry wall with brick arch are worth to be investigated. In this study four practical strengthening methods are tested. These methods are developed under the condition that the original form would not be changed. 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

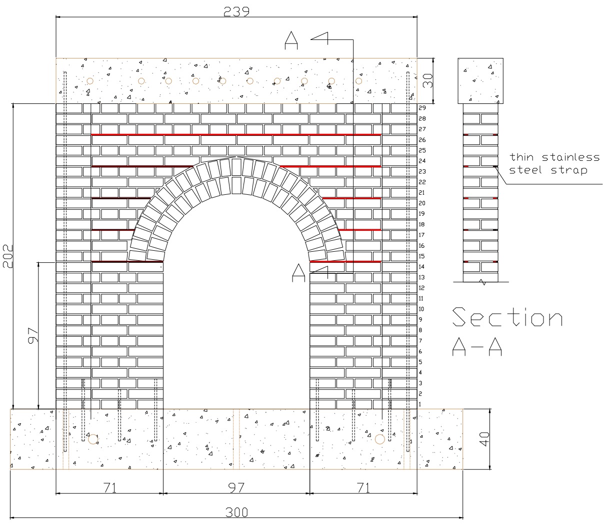
### *2.1. Wall Specimens*

Five 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).

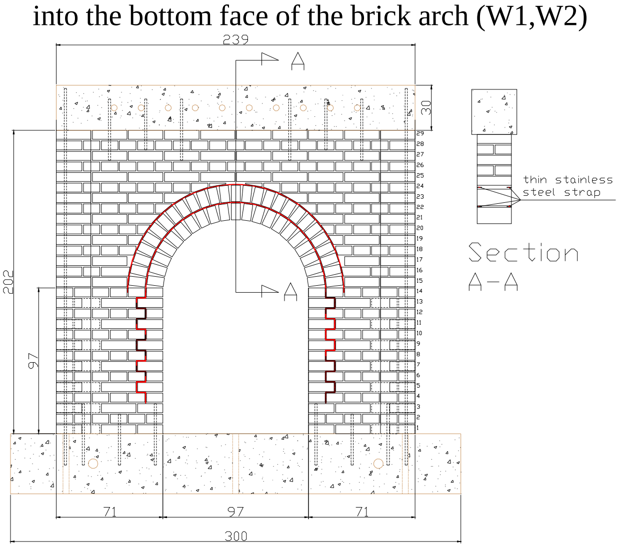
Table 1 lists the details of the specimens. W0 is an un-reinforced specimen used for comparison the performance of strengthened specimens. Specimen W1 and W2 are strengthened by method 1 (Figure 1(a)), a thin stainless steel strap is imbedded into the bottom face of the arch. In these two specimens, W1 will be strengthened after damaged, and used to compare the performance with W2 which is strengthened prior to damage. Specimen W3 is strengthened by method 2, nine thin stainless steel straps (20x1mm) with various lengths are imbedded into the brick joints horizontally at each side (Figure 1b). Specimen W4 is strengthened by method 3, 2 thin stainless steel straps (10x1mm) are imbedded along the semi-circular joints of the arch at each side (Figure 1c). W5, the final specimen in Table 1, is strengthened by Method 4, eight thin stainless Z shape pieces (10x1mm) are planted along the horizontal and vertical joints of easy damaged area at each side(figure 1d). This is under the observation that horizontal joints are easy to be cut than the other method. During manufacturing the specimen, the cutting slot is filled with EPOXY mortar.



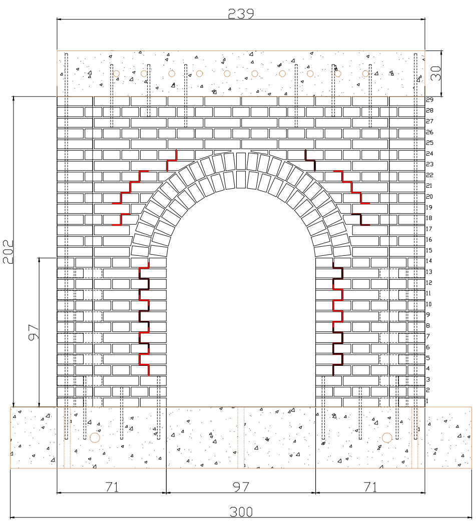

(a) Method 1: a thin stainless steel strap is imbedded into the bottom face of the brick arch (W1,W2)




(b) Method 2: nine thin stainless steel straps are imbedded into the brick joints horizontally(W3)




(c) Method 3: 2 thin stainless steel straps are imbedded along the semi-circular joints of the arch (W4)




(d) Method 4: eight Z shape stainless straps are planted along the horizontal and vertical joints of easy damaged area (W5)

Figure 1 Brick arch specimens

Table 1 Details of the brick arch specimens

| Specimen | Strengthening method | Remark |
|---|---|---|
| W0 | | Un-reinforced specimen |
| W1 (Bottom face slot) | Method 1: a thin stainless steel strap (10mm x 1mm) is imbedded into the bottom face of the brick arch (Figure 2a) | strengthened post W0 damaged |
| W2 (Bottom face slot) | Method 1: a thin stainless steel strap (10mm x 1mm) will be imbedded into the bottom face of the brick arch (Figure 2a) | Strengthening prior to damage |
| W3 (Horizontal joints) | Method 2: nine thin stainless steel straps (20mm x 1mm) with various lengths are imbedded into the brick joints horizontally (Figure 2b) | Strengthening prior to damage |
| W4 (Semi-circular joints) | Method 3: 2 thin stainless steel straps (10mm x 1mm) are imbedded along the semi-circular joints of the arch (Figure 2c) | Strengthening prior to damage |
| W5 (Z shape) | Method 4: eight Z shape stainless straps (10mm x 1mm) are planted along the horizontal and vertical joints of easy damaged area (Figure 2d) | Strengthening prior to damage |

### *2.2. Material properties*

Table 3.1 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.

Table 2 Tested material properties

| Property | Strength(MPa) |
|---|---|
| Compressive strength of brick | 54.47 |
| Compressive strength of mortar | 31.84 |
| Shear strength of interface between brick and mortar | 0.98 |
| Tensile strength of interface between brick and mortar | 0.50 |

### *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 3) which were controlled by the stroke of the actuator. The test is stopped as the specimen has been seriously damaged.

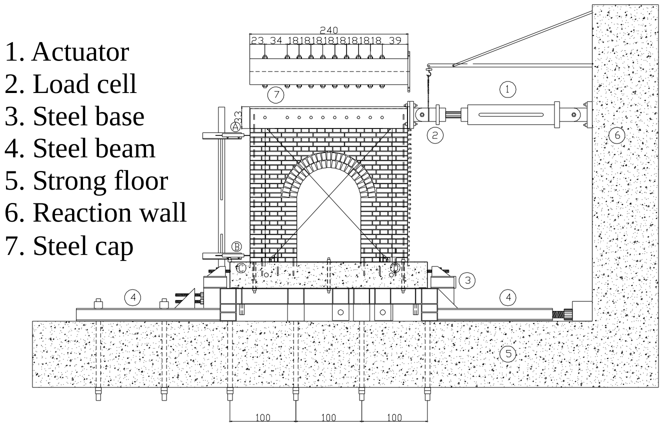



Figure 2 Test setup

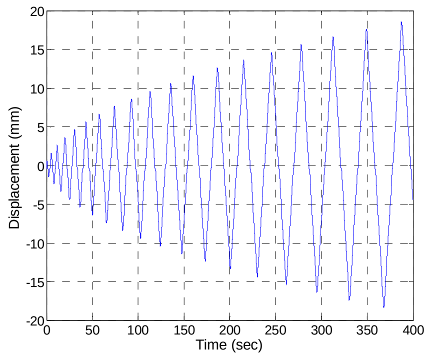



Figure 3 The input stoke of the actuator

## 3. EXPERIMENT RESULTS AND DISCUSSION

Figure 4 through Figure 9 show the loading-displacement relationship and the damage mode as well as crack sequence developed in the wall specimens. The maximum load obtained and its corresponding displacements are listed in Table 3. In order to compare in later section, we define the Maximum load and its corresponding displacement of W0 (un-reinforced specimen) as 100%. The hysteretic loops close to ultimate load are chosen to compare their stiffness variation and energy dissipation (Figure 10).

### *3.1. Comparison of damage mode and ultimate load*

For un-reinforced specimen (W0), the first crack occurs at the upper right, as actuator push the specimen from right to left. Similarly, the second crack develop at upper left, as actuator pull back. After these two diagonal cracks become larger, cracks happen at the bottom due to over-turn moment (Figure 4). The ultimate load is 131.5 kN, its corresponding displacement is 13.3mm.

After damage, the specimen was strengthened by Method 1 and designated as specimen W1. As shown in Figure 5, under the same controlled loading as W0 the second crack occurs at the lower left is different from the mode of un-reinforced specimen W0. Because of this change of damage mode, the maximum load and the corresponding displacement become greater, and the hysteretic loop contain a greater area too. Only specimen W1 has a greater corresponding displacement than W0 (131% in forward and 141% in backward), this is because it is a post damage specimen, some small cracks decrease the stiffness, but the straps yields to get a better ductility.

The test of W2 (strengthened pre-damage by method 1) is shown in Figure 6. The first 2 cracks occur at the spandrel, and the crack is nearly horizontal. This position is near the welded point of the stainless steel strap. The stiffness of this specimen is greater than that of W0 and W1, but the corresponding displacement only 74% in forward and 79% in backward. Specimen W3 has a similar damage mode as W0, but the crack position is upper than W0. The first 2 cracks become horizontal after breaking through the arch (Figure 7).

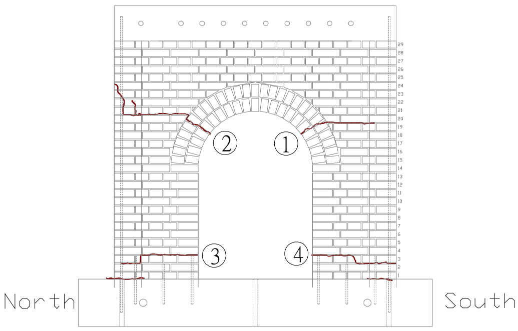
The test of specimen W4 has a completely different damage mode with others. The spandrel of the specimen damaged first, thus if this method is used, the spandrel also need to be strengthened. Due to this damage mode, although the stiffness becomes greater, the ultimate load did not increase visually (Figure 8). The test of specimen W5 also show the first 2 cracks occur at the upper part of the specimen. The cracks develop through the joints without Z shape strap (Figure 9). Furthermore, comparing the test of W3 and W4 with W0, we find that method 3 and method 4 do not visibly improve the ultimate load.

### 3.2. Comparison of hysteretic loop

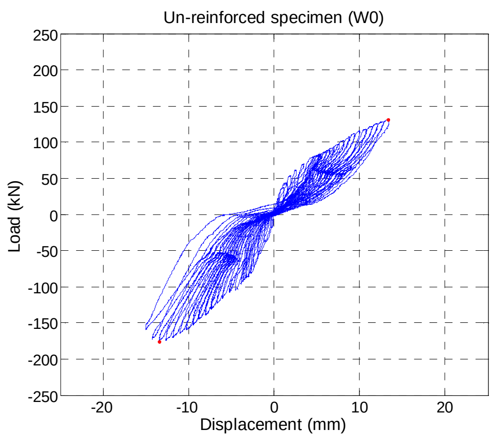
As shown in Figure 10, un-reinforced specimen W0 got a relative narrow loop than that of the other specimens. W1 (method 1, post damage) have a greatest energy dissipation than the others. For the conservation of historic building, method 1 will limited to arch with finish mortar, because it has to cut a slot through bottom surface of the arch. For the case of without finish mortar, it will appear the interference of the arch form.

### 3.3. Comparison of strengthening post and prior to the earthquake damage

Practically, due to weak strength of materials, historic buildings frequently need to be retrofitted after earthquake. The post damage strengthening performance is quite important for designers. Comparing Figure 5 and 6, the damage mode of W1 is quite different from that of W2. The post damage specimen W1 is damaged more seriously than W2. Although the specimen strengthened prior to damage has a larger ultimate load in forward loading, the corresponding displacement is small, relatively. In fact, the specimen strengthened post damage still present a good seismic performance in this study.

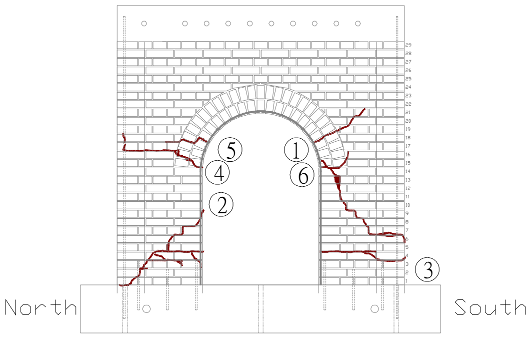



(a) Damage mode

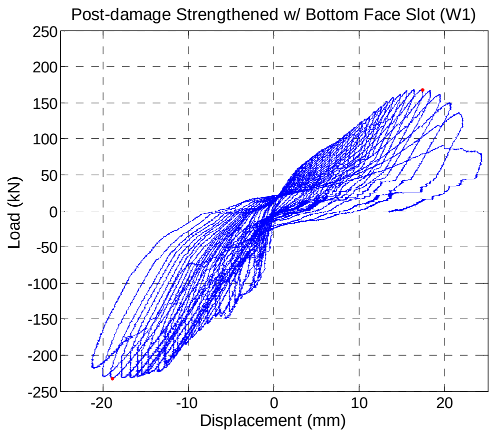



(b) Loading-displacement hysteretic loop

Figure 4 Test result of un-reinforced specimen (W0)

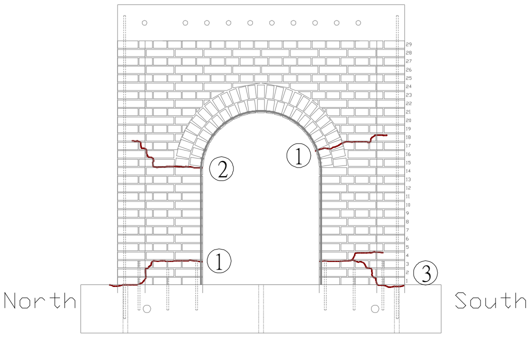



(a) Damage mode

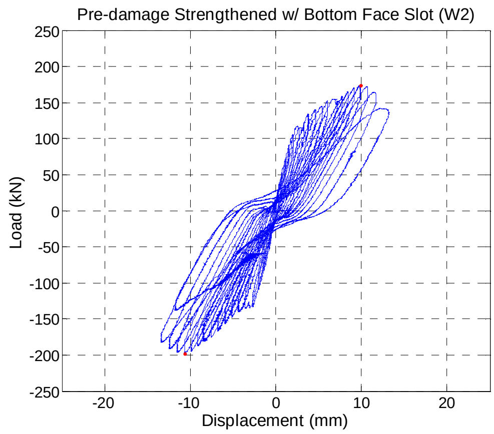



(b) Loading-displacement hysteretic loop

Figure 5 Test result of post-damage strengthened w/ bottom face slot (W1)

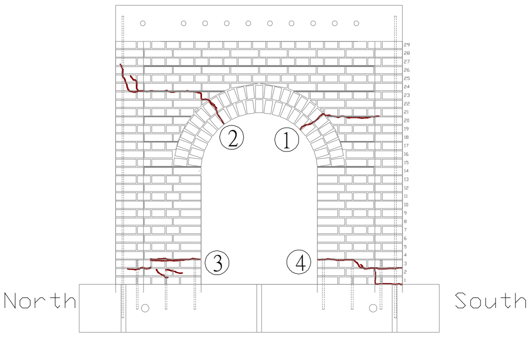



(a) Damage mode

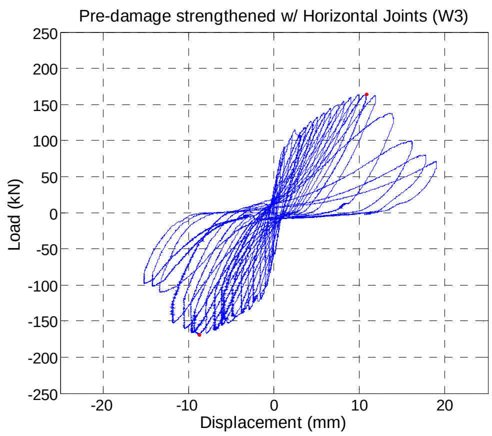



(b) Loading-displacement hysteretic loop

Figure 6 Test result of pre-damage w/ Bottom face slot(W2)

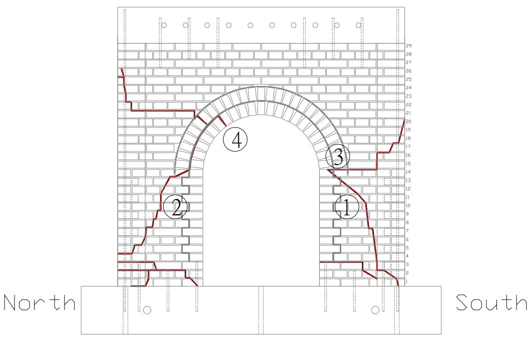



(a) Damage mode

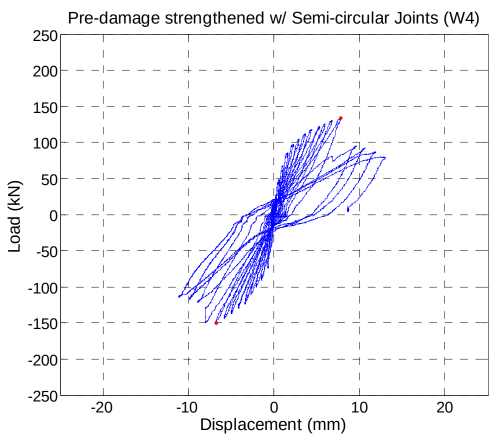



(b) Loading-displacement hysteretic loop

Figure 7 Test result of pre-damage w/ horizontal joints (W3)

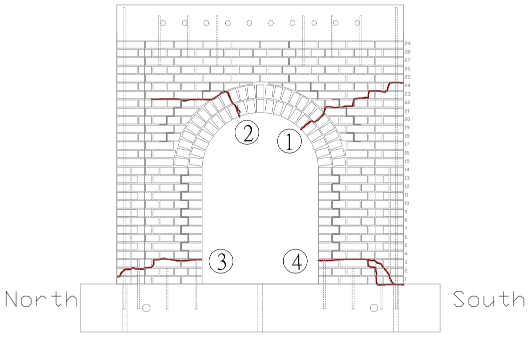



(a) Damage mode

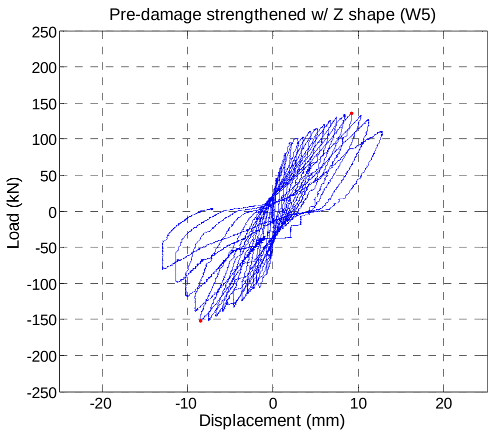



(b) Loading-displacement hysteretic loop

Figure 8 Test result of pre-damage w/ semi-circular joints (W4)




(a) Damage mode




(b) Loading-Displacement Hysteretic Loop

Figure 9 Test result of pre-damage w/ Z shape (W05)

Table 3 Tested results

| Loading Direction | | Forward | | Backward | |
|---|---|---|---|---|---|
| Specimen | | Ultimate Loading (kN) | Corresponding Displacement (mm) | Ultimate Loading (kN) | Corresponding Displacement (mm) |
| Un-reinforced | W0 | 131.5 (100%) | 13.3 (100%) | -175.8 (100%) | -13.4 (100%) |
| Post damage | W1 | 168.3 (128%) | 17.4 (131%) | -231.8 (132%) | -18.9 (141%) |
| Prior to damage | W2 | 173.5 (132%) | 9.9 (74%) | -198.0 (113%) | -10.6 (79%) |
| | W3 | 164.6 (125%) | 10.8 (81%) | -169.0 (96%) | -8.8 (66%) |
| | W4 | 133.7 (102%) | 7.7 (58%) | -149.2 (85%) | -6.8 (51%) |
| | W5 | 136.1 (103%) | 9.2 (69%) | -151.9 (86%) | -8.5 (63%) |

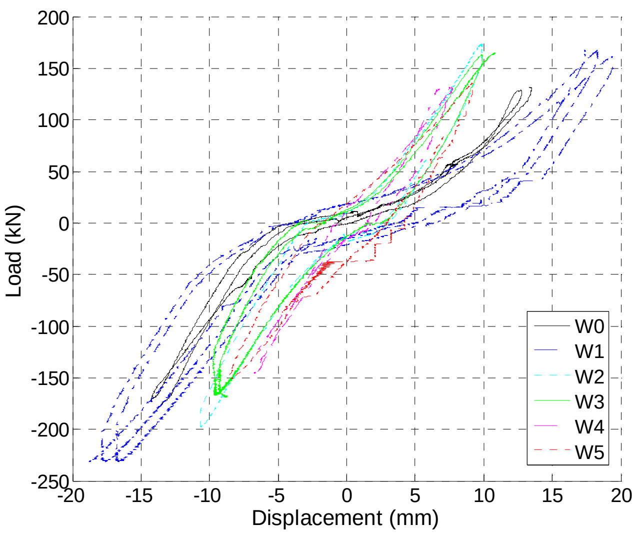



Figure 10 Loading-Displacement Hysteretic Loop of all specimen

## 4. CONCLUSIONS

According to the test of five designed brick arch specimens, 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:

1. The Damage mode of un-reinforced specimen is (1) diagonal tension crack above the arch spandrel (2) horizontal crack at the bottom. Hysteretic loop of un-reinforced specimen is quite narrow than others.
2. The brick arch strengthened with a thin stainless steel strap imbedded into the bottom face after damage can obtain an increase of 28% for ultimate load, and has better energy dissipation. The pre damage specimen using the same method got a largest ultimate load, the strengthen effect is 32%, but method 2 has its limitation in practical application.
3. Method 2 has an increase of 25% (W3), and its energy dissipation is also quite well. As the arch without any finish in the surface, method 2 is the most suitable in this case than method 1.
4. The effect of reinforcement using Z shape pieces planted along the brick joints or thin stainless steel straps imbedded along the semi-circular joints of the arch is not noticeable, because the crack occurs in the portion without reinforcement.
5. According to the test, strengthening before earthquake damage has larger ultimate strength than that obtained after damage, however, post damage strengthening still can improve the ultimate strength of brick arch.
6. In the tested four strengthening methods, for upgrading the ability of horizontal load resistant, method 1 and method 2 will be suggested.

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