Structural Analysis of Historical Constructions – Jerzy Jasieńko (ed)
© 2012 DWE, Wrocław, Poland, ISSN 0860-2395, ISBN 978-83-7125-216-7

FRACTURE MECHANICS CHARATERISTICS OF FLEXURAL STRENGTH OF GRANITE STRUCTURAL COMPOENTS REINFORCED BY METAL

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ABSTRACT

This paper investigates the flexural behavior of granite beams reinforced by metal rods. One of stone masonry pagoda of cultural heritages in Korea is planned to be restored after fully disassembly. The stone masonry pagoda was constructed about 1400 years ago. Large numbers of unit granite components are found as being in fractured state. In order to reconstruct the stone masonry pagoda, the damaged granite components are planned to be replaced by new ones or to be reused after reinforcement using metal rods which has been experimentally tested. The reinforcement method is to make holes in fractured sections of granites for metal rods to be inserted for reconnection of separated parts. The metal rods with epoxy are long enough to transfer the bond force between granite and metal rods which is so-called pinning method. To secure the reinforcement method the development length for metal rods and flexural behavior of unit components are experimentally investigated. The ultimate strength after flexural cracking differs by the reinforcement degree of metal rods. The fracture mechanics approach is able to explain why the strength differs from initial to ultimate stages. On the basis of the experimental results and the analysis simple design guide lines for reinforcement method using metal rods is proposed for fractured granite structural components for restoration.

Keywords: *Granite Component, High-Strength Concrete, Reinforcement Method, Flexural Strength, Fracture mechanics*

1. INTRODUCTION

1.1. Reconstruction of Stone Pagoda after Disassembly

The retrofit and strengthening techniques for cultural heritage requires balance between traditional approaches and current technology applications. Retrofit of stone cultural heritage require more durability and high strength requirement than any other material constructions. Majority of stone type of cultural heritage in Korea is granite which had been used to construct pagodas, bridges, and fort walls in Korea. The retrofit and reconstruction for one of largest stone pagoda in Korea has been done since the beginning of the last decade. A stone masonry pagoda of Mireuksajiseoktop (stone pagoda of Mireuksa Temple) designated as one of national treasure of Korea has architecturally and historically significant value because it shows a distinctive architectural form different from any other pagodas built in its neighboring ancient countries in Korea. The pagoda shows how the people in the time of construction developed their techniques of popular wooden frame constructions in that time to the construction of the stone pagoda, which many have believed the first type of stone pagoda in such construction technique.

1.2. Pinning Method

Where conditions of stone include fractured and broken material, an ideal remedial treatment is one in which the broken areas are reinforced by joining broken stone with each other. Treatment options

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include the application of adhesives and grouts, as well mechanical pinning repairs. The insertion of pins through the stone has the ability to distribute forces between the broken components in more controlled manner in order to resist the stresses associated with deterioration and applied loads. While this might appear simple in concept, the mechanics of how the pinning repair functions and how the treated stone will behave are complex. As with any conservation treatment, serious consideration must be given to the proper design and application of the repair, as well as a thorough understanding of the mechanisms causing stone decay and failure.

The concept of inserting rods or pins in stone is similar to anchorage design in reinforced concrete structures in current design code provisions, and similar evaluation methodology has been employed by Modena and Cecchinato (1985) in studying the structural behavior of limestone lintels strengthened with stainless steel bars. In their study rods of 11mm diameter in circular section, both smooth and notched, were embedded in stone samples of 220cm length with cement and cement-acrylic resin mixture. Conducting bending tests, and crack patterns and failure mechanisms of sample suggested calculation of strength could be determined with formulas used for reinforced concrete beams.

Zambas et al. (1986) used tensile reinforcement to reconnect separated parts of architectural elements such as beams, architraves, and lintels during restoration of the Acropolis monuments, and employed reinforced concrete theory to determine the number and size of the bars. The results of the bending tests indicated that the action of the beam occurred in linear elastic manner.

Testing was also conducted with the same type of materials by Vintzileous and Papadopoulos (2001) to explore dowel action of the connection; the purpose being to determine the minimum cover required to ensure that shear failure would occur in a titanium bar and not in the marble. Test results obtained were in accordance with available experimental data regarding the dowel mechanism of steel bars embedded in concrete. There is difference between supplementary injection anchors and reinforced concrete, as pointed by Gigla (1999); bars are not embedded directly to the substrates, so that the bond strength of a rod depends on the injection technology as well as properties of the existing material; and measurement of maximum test force without consideration of displacement offers limited knowledge of load bearing capacity.

The addition of pins or rods placed into stone for conservation purposes can be employed with a variety of materials and techniques. The requirement, scale and application methods are typically determined by the type and characteristics of deterioration. Pins inserted between two pieces of completely fractured stone can be utilized as concealed repair, also known as blind pinning. Hong and Lim (2009) showed the flexural behavior of granite beams reinforced titanium.

1.3. Objective

The objective of this paper is to use the fracture mechanics approach to investigate the flexural strength of granite beam reinforced by metal rods. The behavior of the granite beams and slabs reinforced by pinning methods which have been experimentally studied by Hong (2009). For the estimation of the ultimate strength of reinforced concrete beams without web reinforcement Carpinteri (1981) presented a fracture mechanic model for the collapse of reinforced concrete beams considering

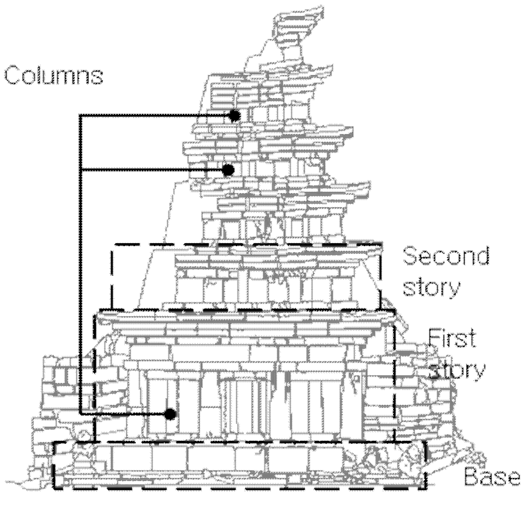


Fig. 1 Stone Pagoda Mireuksa for Restoration Construction

four different failure modes. After reaching the plastic moment of reinforced concrete beams in bending, the reinforcement ratio is critical factor whether the behavior is stable or unstable according to his study. The different location of reinforcing rods on fractured section is one of main variables. Also it will be discussed whether or not the theory of reinforced concrete structures may be applied to the granite reinforced by steel rods.

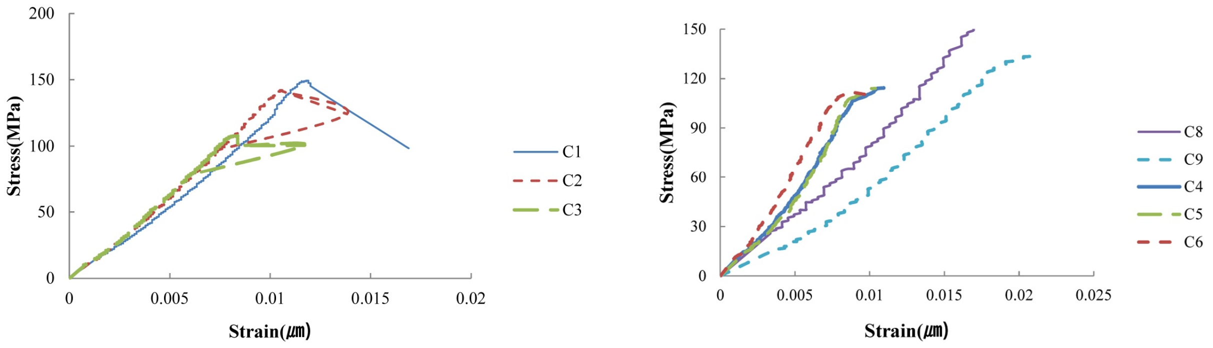
This study investigates applicability of the fracture mechanics model developed by Bazant (1988) to the interpretation of the behavior of granite flexural members reinforced by metal rods becuse the behavior of high-strength concrete beams and granite beams show similar patterns. The main differences between his model and our experimental specimens are the high strength of granite and multi-layer of reinforcement in the section of the beams. The primary objective of this study is to provide the reinforcement scheme in sections for fractured granite using metal rods with epoxy bonding.

2. EXPERIMENTAL PROGRAM

In order to propose the reliable reinforcement method for retrofit of fractured granite stones, a series of experimental programs were prepared. The test programs include the material tests for mechanical properties of granite and metal rods. The compressive and tensile strengths with fracture parameters for granite were measured.

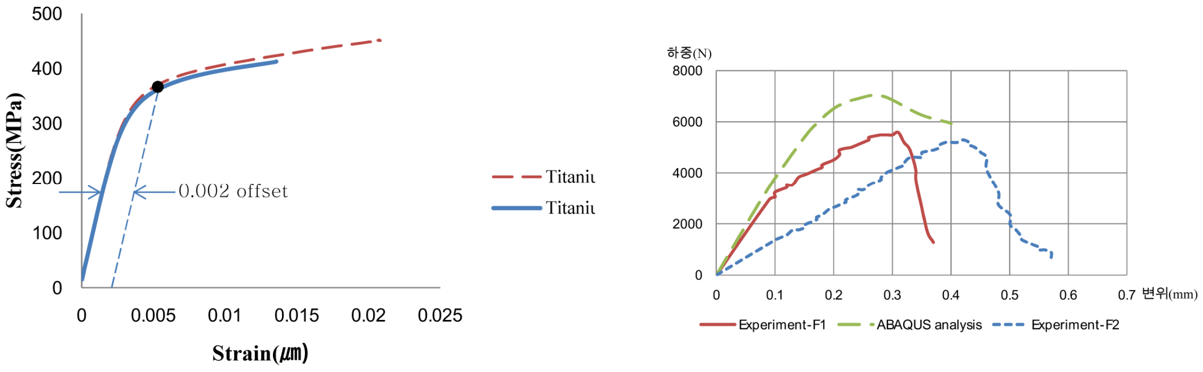
2.1. Material Testing

Granite: Most pagoda in Korea have beam made of granite since granite is abundant in many area. The granite for the pagoda was prepared from the mountain in the neighboring area of the location of the pagoda. Since the properties of granite depend on the location, we need to perform material test. The average compressive strength is about 94 MPa.



(a) Compressive strain-stress curve of granite cylinder

(b) Compression test of granite cube



(c) Tensile strain-stress curve of titanium

(d) Tensile stress-strain curve of titanium

Fig. 2 Stress-strain curves for granite and metal rods

Metal: Material for the rods for reinforcement in this study is chosen as titanium which is one of the most appealing choices for mechanical pinning reinforcement even if its cost is high. The average tensile strength of titanium was to estimate the development length and the theoretical ultimate strength of beams in this study.

Table 1 Compressive strength of granite

Specimen	Ultimate load (kN)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
C1	950.57	149.42	130.06
C2	903.37	142.00	
C3	685.60	107.77	
C4	285.79	114.31	127.80
C5	285.84	114.00	
C6	275.84	110.34	
C7	284.95	113.98	
C8	451.25	180.50	
C9	334.15	133.66	

Table 2 Tensile strength of titanium

Specimen	Ultimate load (kN)	Yield Strength (MPa)	Tensile Strength (MPa)
Titanium-1	93.88	367.97	446.93
Titanium-2	91.95	358.83	457.34

2.2. Pull-out Test for Development Length

Bond strength between granite and titanium rods with expoxy should be provided for satisfactory behavior of reinforced components after retrofitting. Nie specimens of 150 × 150 × 300 are prepared with varying size of titanium rods. Two ifferent failure modes are observed depending on the embedment length: the yiedling of rods and splitting failure of granites. Two patterns of splitting cracks of sinlge center line and radial patterns show brittle behavior after the peak point because of short embement length.

2.3. Fracture Toughness

To estimate the stress intensity factor of the typical granite beams five beams of three different sizes are tested. The results of the three point load beam testswith 100 mm vertical notch with well known formula are used to estimate the stress intensity factor.

$$\sigma = \frac{6M}{b^2}\left(M = \frac{Ps}{4}\right)$$

$$K_I = \sigma\sqrt{\pi a}\,F(a/b)$$

where for *s/b=4*,

$$F(a/b) = \frac{1}{\sqrt{\pi}}\cdot\frac{1.99 - a/b(1-a/b)\left(2.15 - 3.93a/b + 2.7(a/b)^2\right)}{(1+2a/b)(1-a/b)^{3/2}}$$

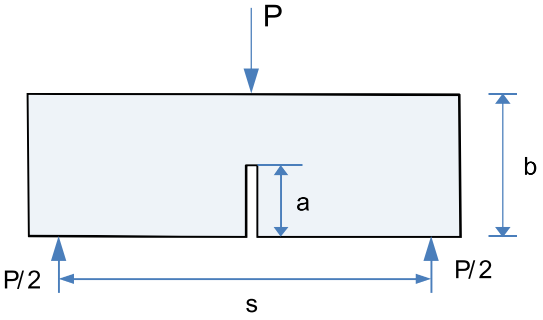


Fig. 3 Granite beam specimen for fracture test

2.4. Flexural and shear strength experiments

In order to investigate the efficiency of pinning method for failed components of large scale the experimental programs for beam specimens were prepared. The main variables of the test programs for beams were the reinforcement layout in section and reinforcement ratio. The minimum reinforcement ratio for stable behavior of granite reinforced by metal rods is one of important parameter among engineers who design the reinforcement schemes for retrofit of stones using pinning method. Table shows the locations of metal rods in sections and reinforcement area.

Table 3 Beam test specimen

Specimen	Size(mm) B × H × L	Reinforcement Layout in Secion	Titanium Dimension for Reinfrocement		
			Total Length (mm)	Nominal Diameter (mm)	Sec. Area (mm^2)
B1	400×300×800	Undamaged Ref Beam	-	-	-
B2		Undamaged Ref Beam	-	-	-
B3		Epoxy only	-	-	-
B4		Bottom (2)	300	16	402.1
B5		Cen(2) Bot(3)	200	8	251.3
B6		Cen(1) Bot(2)	350	22	1140.4
B7		Cen(2) Bot(3)	200	12	565.5
B8		Cen(1) Bot(2)	300	16	603.2
B9		Top(1) Bot(2)	300	16	603.2
B10		Cen(2) Bot(2)	200	12	452.4
B11		Top(2) Bot(2)	200	12	452.4
B12		Cen(2)	200	16	402.1
B13		Cen(2)	400	8	100.5
B14		Cen(2)	300	8	100.5
B15		Cen(2)	200	8	100.5
B16		Cen(2)	100	8	100.5
B17		Bot(3)	300	16	603.2
B18		Cen(2) Bot(2)	300	20	1256.6
B19		Cen(2) Bot(3)	350	22	1900.7
B20		Cen(2) Bot(2)	400	24	1809.6

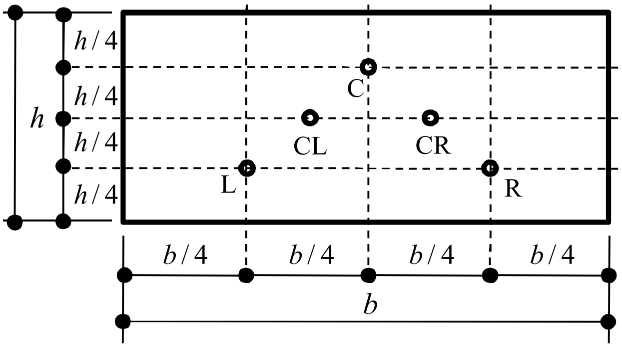


Fig. 4 Reinforcement layout in section

To supplement and add the data set of the previous reserch by the author almost same reinforcement configuration were planned. The three layers of reinforcement were located at the distance at 1/4 from the bottom face, the middle of the section and the distance at 1/4 from the top face. These locations allow us to make insertion holes for metal rods at enough distance from surfaces without cover fracture during retrofit work in field. The bottom reinforcement is supposed to resist bending moment right after tensile crack. The role of the reinforcement in the center of the section and in compression is to provide stabile behavior after the peak load.

In this study rods can be inserted into fractured structural elements such as slabs and lintels. The technique involves drilling holes, usually of equal length, into each fragment, injecting an adhesive or grout into holes, and then inserting rigid pins into each fragment. The locations of holes are shown in Fig. 4 and 5. The bending resistance is expected to increase in the case of two rods below the center lines. In addition, the surfaces of the fragments are usually coated with adhesive before they joined together.

Table 4 Beam test result

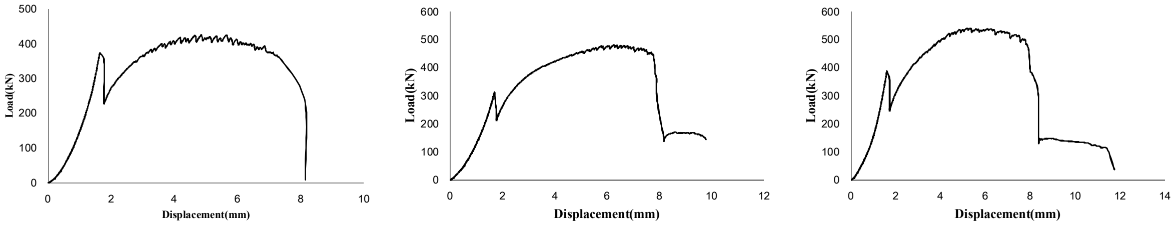
Specimen	Fracture Failure of Granite Load (kN)	Center Displacement At Fracture (mm)	Ultimate load At Yielding of Metal Rod (kN)	Center Displacement at Yielding (mm)	Failure Mode
B1	364.50	1.58	-	-	-
B2	393.90	1.97	-	-	-
B3	260.97	1.74	-	-	-
B4	374.40	1.64	426.10	4.86	Fr
B5	325.36	1.69	281.30	4.93	B
B6	370.42	1.65	556.70	3.46	S
B7	313.50	1.7	482.00	6.28	Fr
B8	390.00	1.6	541.20	5.34	Fr
B9	351.30	1.69	428.80	4.22	S
B10	382.90	1.7	297.30	4.92	B
B11	389.10	1.22	166.20	4.90	B
B12	328.10	1.08	221.60	4.67	B
B13	267.90	0.704	76.40	2.29	B
B14	314.40	0.97	55.00	2.11	B
B15	288.10	1.02	74.10	2.47	B
B16	301.00	1.08	60.30	2.74	B
B17	396.90	1.78	475.20	3.95	S
B18	372.80	1.49	541.60	3.13	S
B19	381.22	1.58	642.78	2.82	S
B20	319.87	1.62	644.25	3.09	S

Supplemental reinforcement from internal connections is employed in cases where tension stresses occur which the stone cannot withstand, and the repair can be used both as local reinforcement of single elements and as global remedial action for the structure. The tensile resistant bars or rods, usually small diameter stainless threaded rods, are grouted into position using a suitable cement or resinous grout, an appropriate coverage of which helps to ensure corrosion resistance of the bars.

3. TEST RESULTS

3.1. Failure Modes

The global behaviour and local strain distribution were observed to indentify the effects of main parameters for the experimental program. The test results showed three distinct failure modes after the peak load governed by the fracture failure of granite. The ductile and brittle failure modes depend on the reinforcement ratio as shown in the following load-deflection curves. Also the additional load increment were made possible by the degree of reinforcement above some point.

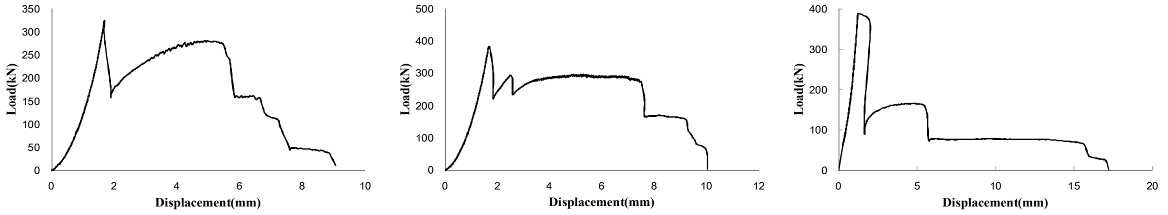


(a) B4 (b) B7 (c) B8

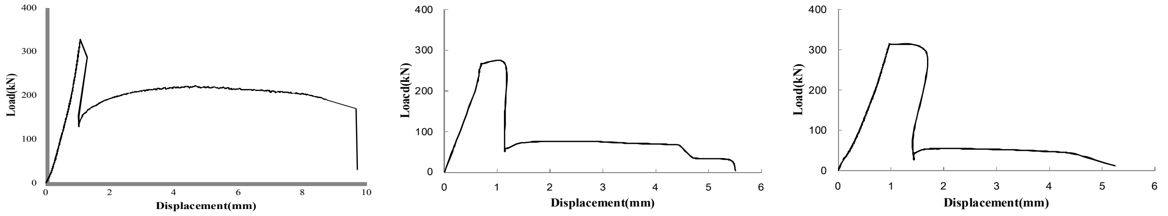
Fig. 5 Ductile behavior of moderate reinforced beam

Three specimens of B4, B7, and B8 showed the additional load increment after the fracture and ductile failure mode up to some points. Most specimens in brittle failure modes have single layer of reinforcement except low reinforcement ratio.

For low reinforcement ratio the load decreased after the fracture failure. The degradation of the strength after the fracture was significant in case of B11, B13, B14, B15, and B16. The lower strength of beams after peak load sustained by the tensile strength of the metal rods. The third group of the test results showed the strength increase after fracture but brittle failure modes. These specimens had over reinforcement ratio compared with the other two groups. The critical crack terminated at the end of the metal rods in diagonal crack pattern. The reinforcement in the second layer showed the elastic stage in compression at ultimate because of the prohibition of crack propagation along the centre lines.



(a) B5 (b) B10 (c) B11



(d) B12 (e) B13 (f) B14

Fig. 6 Brittle behavior of under-reinforced beams

3.2. Local Behaviour

To determine the failure modes the strain states in metal and granite were measured. Upon the fracture failure of granite the stress in the titanium rods at the bottom reached the yielding point. The titanium bars in the center and the top layers were observed to be in compression until the bottom bars showed large deformation due to opening of crack. The ductile behavior of beams of double layers of reinforcement was made possible by successive tensile resistance after crack propagation.

4. ANALYSIS AND DISCUSSION

4.1. Failure Mode Identification

The failure mode identification by the experiemental observation is possible by the reinforcement ratio and the reinforcement layout in section. However, the theoertical approach to interpret the behavior is necessary. The brittle number proposed by Carpinteri (1981) was caculated to classify the failure modes. The brittle number formula involves the stress intensity factors, aspect ratio, rupture modulus and reinforcement aera. The brittle numers greater than 0.12 showed the ductile failure modes except B9 which has lower reinforcement ratio.Even though the specimen B11 has moderate reinforcment ratio, the brittle failure mode occured by the reinforcement layout.

4.2. Load-Deflection Curve

The typical load-deflection curve can be characterized by the diagram shown in Fig. 8. It is necessary to identify the three critical points from the theoretical point of view. The fracture failure at point A can be expected by the tensile rupture failure because of inactiveness of titanium rods.

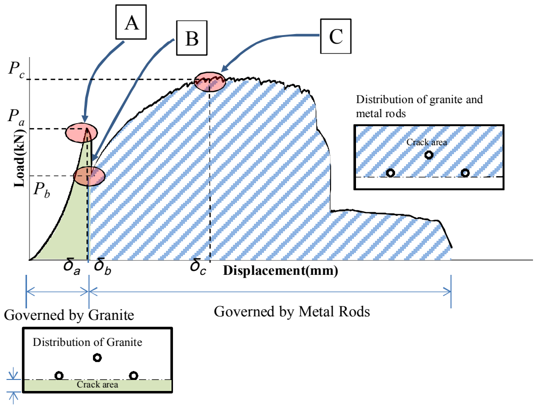


Fig. 8 Reinforcement layout in section

The resistance at point B is the difference between the rupture strength and the flexural strength by the yield strength of the metal rods. In case of the ductile failure modes the ultimate strength at point C can be expressed by the following equations

$$K_I = \frac{1}{b^{3/2}t} Y_M(\xi)\left[M - F_P\left(\frac{b}{2}-h\right)\right] - \frac{1}{b^{1/2}t} Y_F(\xi) F_P, \quad for\ M \geq M_P$$

$$M_F = \frac{K_I b^{3/2} t}{Y_M(\xi)} + \frac{F_P b}{Y_M(\xi)}\left[Y_F(\xi) + Y_M(\xi)\left(\frac{1}{2}-\frac{h}{b}\right)\right]$$

Specimen	Experiment load (kN)	Theory load (kN)	Margin (%)
B4	426.11	427.23	0.26
B7	481.96	501.44	4.04
B8	541.16	544.68	0.65

5. CONCLUSIONS

This study investigates the application of the facture mechanics approach to estimate ultimate strength of granite flexural members reinforced by metal rods. The behavior of reinforced granite beams after the rupture failure depends on the reinforcement ratio and reinforcement layouts. The double reinforcement layouts tended to show ductile failure modes for the degree of reinforcement above some value. The brittle number proposed by Carpinteri is rational to identify the failure modes for given reinforcement ratio.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support by National Research Institute of Cultural Heritage for this study under Reconstruction of Mireuksajiseoktap from year 2009 to year 2010.

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