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Flexural and Shear Strength of Granite Reinforced by Metal Rods

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Abstract This paper investigates feasibility of reinforcement method for fractured granite of slab type and beam members used as components of old stone masonry pagodas. Investigation of the effect of reinforcement to flexural and shear strength is performed using the concept for the high strength concrete since the mechanical properties of granite are similar to properties of high strength of concrete. In this experimental program two types of notched specimens are intended for failures with shear and flexural cracks. Intended fractured specimens are reinforced by metal rods, so called pinning method. The rods are inserted in holes and bonded with inorganic cement. The metal rods are supposed to transfer forces by tensile resistance in flexure and dowel action in shear. Increase in shear and flexural capacities and ductile behavior after sudden yielding of the metal rods are observed. The final failure cracks in reinforced specimens occurred different from interfaces along the original cracks. Locations of metal rods, their numbers, and construction of anchored rod are main variables to be examined for guidelines for reinforcement methods.

Keywords: Granite, high-strength concrete, reinforcement method, pinning method, shear and flexural strength

Introduction

Background Stone pagodas have been the symbol of Buda since Buda had spread out over Asian countries. Most of Asian countries have preserved many pagodas in temples. Korea developed Buda architectural buildings including sculptures influenced by Chinese style Buda art, and thereby they transferred the culture to Japan since 4th century. Among the heritage Korean temples keep many stone pagodas meanwhile Japan preserves many wood pagodas.

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 form different from 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. Unfortunately, the pagoda in the study had been devastated considerably and it is known that it was repaired several times. Most recently, it was strengthened with a concrete backing in 1914.

Since the late twentieth century, Korean government has begun an intensive repair project for this pagoda considering conservation and preservation aspects as well (NRICH 2005). The structural behaviour of structures whose architectural style is a traditional wooden frame and built by the dry construction method of stone masonry structures has not been investigated in engineering approaches yet. The first phase of repair project is to dismantle the pagoda. The work of dismantlement shows many of components in the fractured state.

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

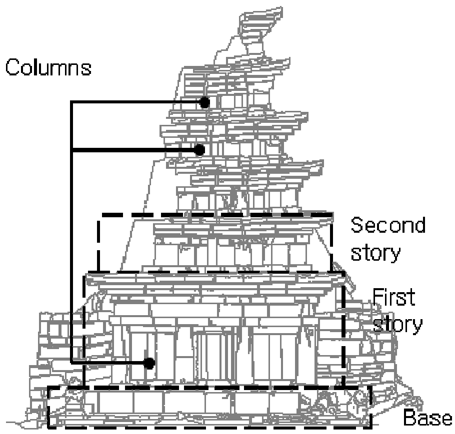


Figure 1: Stone pagoda for reconstruction

This paper is to investigate flexural and shear capacity of granite beams and slabs reinforced by pinning methods which have been studied in the previous research. 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.

Properties of Materials

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 area. Since the properties of granite depend on the location, we need to perform material test. The average compressive strength is about 94 MPa.

Metals Material for the rods for reinforcement in this study is chosen as stainless steel. As other option, the chemical, physical and mechanical properties of titanium make it one of the most appealing choices for mechanical pinning reinforcement even if its cost is high.

Table 1: Compressive strength of granite

Specimen	*Strain* (mm/mm)	*Stress* (Mpa)	*Elastic Modulus* (Mpa)
Granite-1	0.00906	108.8	12008.8
Granite-2	0.01118	89.7	8023.3
Granite-3	0.01560	82.0	5256.4
Average	0.01195	93.5	7826.5

Flexural and Shear Strength Experiments

In order to investigate the efficiency of pinning for failed components of large scale two stage experimental programs were prepared. In the first phase experimental program bending failure and shear failure of undamaged components were intended.

Table2: Test Specimens

Specimen	*Loading type*	*Dimension* $L\times W\times H$(mm)	*Reinforcement*	*Location of pins*
B1			3 steel rods	Center (2), top (1)
B2			3 steel rods	Center (2), top (1)
B3		1500×800×350	3 steel rods	Top (1), bottom(2)
B4			3 steel rods	center(1), bottom(2)
B5	Flexure		3 steel rods	center(1), top (2)
B6		1500×700×500	3 steel rods +Steel plate	top(1), bottom(2), Top(plate), bottom(plate)
B7		1000×800×250	3 steel rods +Steel plate	Top (plate), center(2), bottom(1)
B8		1500×800×350	Epoxy	Epoxy
S1	Shear	1500×800×350	3 steel rods	center(1), bottom(2)
S2			3 steel rods	center(1), bottom(2)
C1			No	
C2	Compression	1000×700×700	8 steel rods	Parallel
C3			8 steel rods	Zigzag

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. 2and 3. 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. 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.

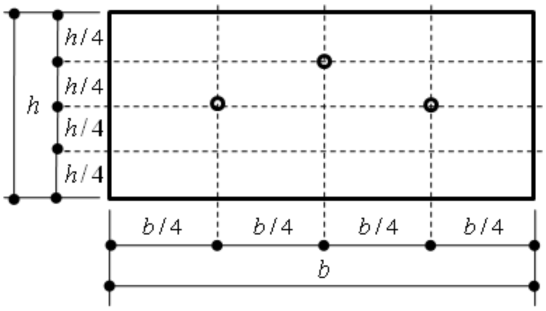
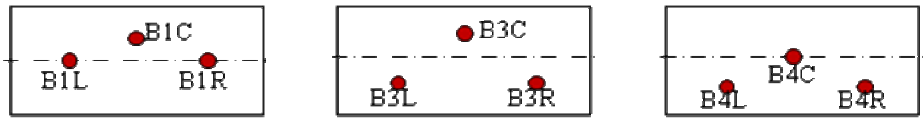
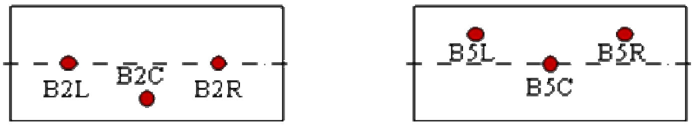


Figure 2: Typical location of reinforcing rods in section



(a) Arrangement of two bottom reinforcing rods



(b) Arrangement of two top reinforcing rods

Figure 3: Patterns of rod placement in section

Test Results

The investigation of the test results gives us three different flexural behaviors of granite beams reinforced by two bottom metal rods as shown Fig 4. Specimen BR1 shows high strength of brittleness while specimen BR3 shows ductile behavior. Specimen BR4 increases additional strength after large deflection. These three distinctive behaviors depend on the stress state in the top reinforcing rods. The tensile stress in the top reinforcing rod indicates small depth of neutral axis inducing a brittle failure while the compression stress state exhibits ductile behavior. The tensile stress in the top rods is developed when the vertical crack occurs along the fractured line which has been joined by epoxy. The specimen BR1 experienced the vertical crack along the same crack line and then failed in a brittle manner. The degree of ductile behavior of specimens BR3 and BR4 depends on the distance between top and bottom reinforcing rods in the fractures sections. The specimen BR3 of the largest arm length between the top and bottom reinforcing rods shows the largest ductility.

The specimens of one bottom rod BR2 and BR5 show tri-linear behavior as shown in Fig. 5. The placement of the bottom rod in lower half section of specimen BR2 results higer elastic stiffness and strength. The maximum deflections of these specimens are smaller than those of specimens having two bottom rods.

Shear strengths of specimens reinforced by rods increase and the degree of their ductility depend on the location of the final crack. When the final cracks occurred at the maximum bending moment, the ductility increased. However, the ductility was limited where the final crack followed the fractured line as shown in specimen SR2 as shown in Fig. 7.

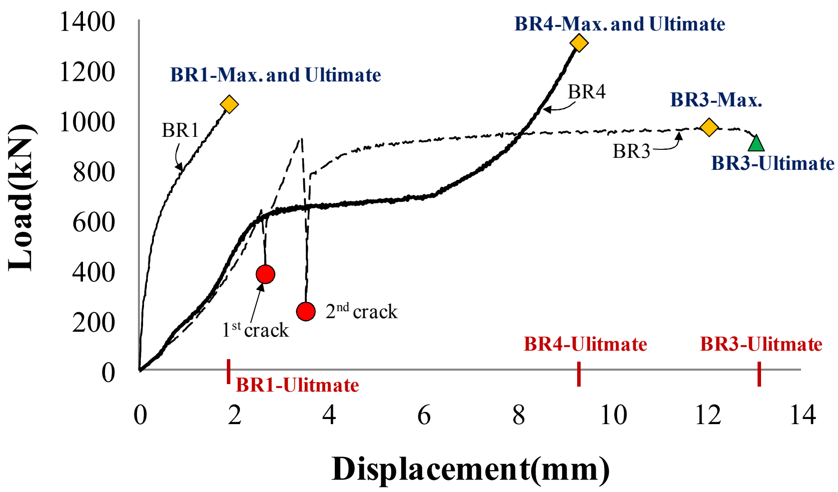


Figure 4: Deflection-load curves of specimens of two bottom rods

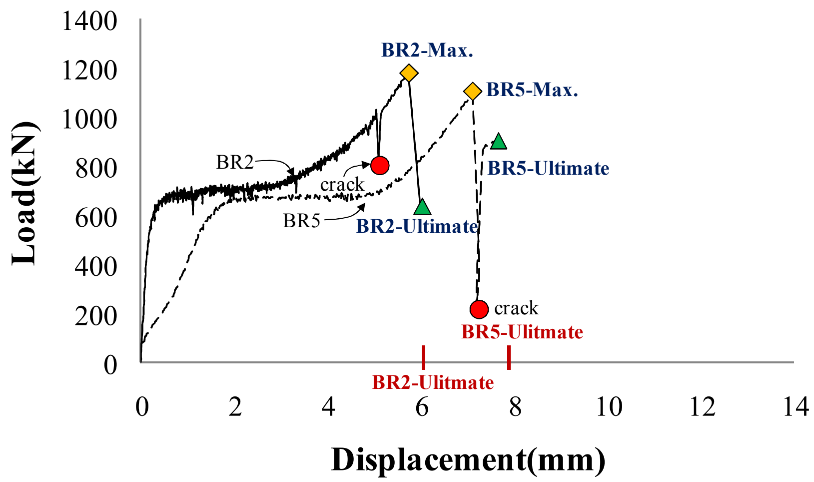


Figure 5: Tri-linear curves of deflection vs. load of specimens of one bottom rod

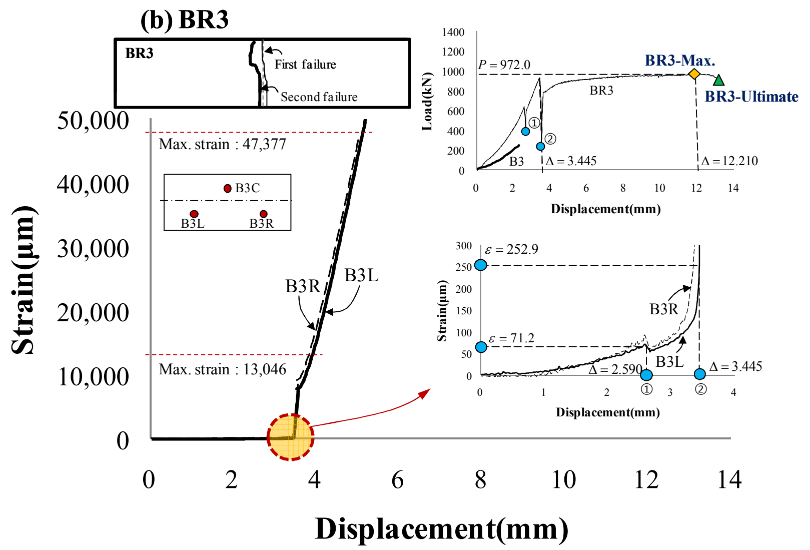


Figure 6: Bi-linear curve for BR3 specimen

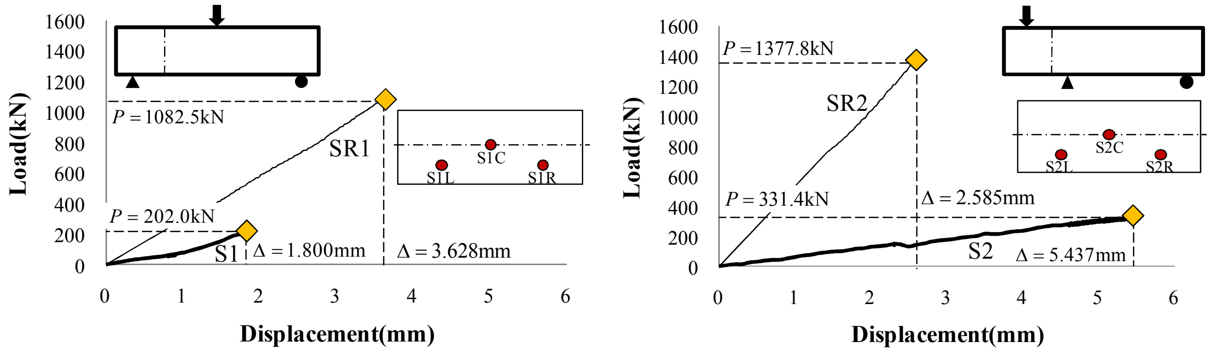


Figure 7: Load-deflection curve of shear tests

Conclusion

We performed the test program for flexural and shear strength of granite members and those with reinforcement by metal rods. The remedial treatment follows the well known pinning methods. Two phases of the test results give us design guidelines for remedial treatment for fractures granite of cultural heritage. Based on the study the following concluding remarks are can drawn:

1) The elastic and brittle behavior of granite in compression needs fracture mechanics for analysis of undamaged components. Application of the method for the high-strength concrete to the granite components should be modified for reliable estimation of strength and reinforcement design.

2) The flexural behavior of granite reinforced implies that the location of reinforcing rods determine strength and ductility. More ductile behavior is expected as the distance between top and bottom rods increases.

3) When the strong tensile resistance along fractured surface by epoxy induces new cracks, ductile behavior can be expected.

Acknowledgement

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