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Flexural behavior of stone slabs strengthened with reinforced mortar

Zi-Xiong Guo [a,b,*], Lan Wang [a,c], Zhen-Ling Chai [a,b], Yong Ye [a,b], Bahram M. Shahrooz [d]

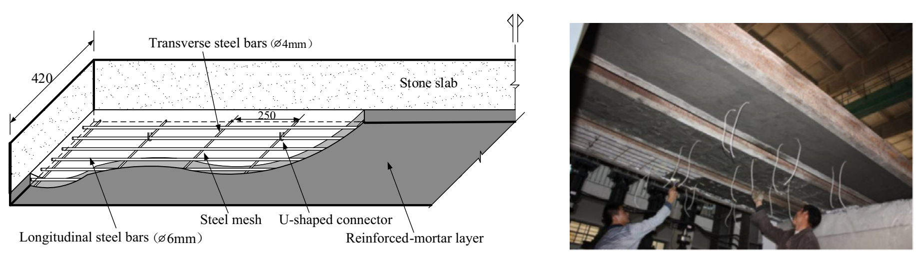
[a] College of Civil Engineering, Huaqiao University, Xiamen 361021, China
[b] Key Laboratory for Structural Engineering and Disaster Prevention of Fujian Province, Xiamen 361021, China
[c] Department of Civil and Architectural Engineering, Liming Vocational University, Quanzhou 362000, China
[d] Department of Civil and Architectural Engineering and Construction Management, University of Cincinnati, 765 Baldwin Hall, Cincinnati, OH 45221-0071, USA

HIGHLIGHTS

- Flexural behavior of stone slabs strengthened with reinforced mortar is studied.
- Effect of different parameters on behavior of strengthened slabs is evaluated.
- A model is proposed to predict the flexural strength of strengthened stone slabs.

GRAPHICAL ABSTRACT

Flexural behavior of stone slabs strengthened with reinforced mortar: experimental study and theoretical analysis.



(a) Configuration (b) Strengthening procedure

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ABSTRACT

This paper describes an experimental and analytical program focused on developing a strengthening technique to enhance the flexural performance of stone slabs. The technique involves the use of reinforced mortar bonded to the soffit of the stone slabs, which can be used for strengthening of stone slabs in existing structures, or manufacturing of composite stone members for new constructions. The experimental program consisted of flexural testing of strengthened stone slabs and an unstrengthened specimen serving as the benchmark. The amount of reinforcement ratio and mortar strength were varied as the test variables. An analytical model was also developed to predict the cracking and ultimate moment of strengthened stone slabs. The unstrengthened specimen failed suddenly in a brittle fashion; however, the strengthened stone slabs experienced a ductile failure mode and developed a higher flexural strength. As expected, the enhanced performance was proportional to the reinforcement ratio, but the strength of mortar affected only the cracking moment. The stone slab and the reinforced mortar layer exhibited good composite action, and no obvious interfacial failure was observed. The analytical model developed could reasonably predict the cracking and ultimate moment of stone slabs strengthened with reinforced mortar.

1. Introduction

Stone masonry structures have been used since ancient times, like pyramids in Egypt, the Parthenon Temple in Greece, and Zhao-zhou Bridge in China. There are stone masonry buildings still

* Corresponding author at: College of Civil Engineering, Huaqiao University, 668 Jimei Avenue, Xiamen 361021, China.

E-mail addresses: guozxcy@hqu.edu.cn (Z.-X. Guo), wang_lany@163.com (L. Wang), dlzlc@hqu.edu.cn (Z.-L. Chai), qzyeyong@126.com (Y. Ye), bahram.shahrooz@uc.edu (B.M. Shahrooz).

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being used in the countryside of many European and Asian countries. In most cases, stone is used as compression elements, such as walls, columns or arches. Meanwhile, stone slabs served as flexural members are commonly adopted in the southeastern costal area of China, as shown in Fig. 1. Generally, the stone slabs have a cross section (width × height) ranging from 300 mm × 100 mm to 500 mm × 150 mm, and a length ranging from 2500 mm to 4000 mm. The stone slabs are laid in parallel on the top of stone beams or walls at both ends. The gap between adjacent stone slabs has a width of 5–15 mm, and is usually filled with cement mortar. The inherent brittleness of stone poses serious concerns regarding the safety of these buildings. Hence, effective strengthening techniques are needed to improve the flexural performance of stone slabs.

In recent years, various strengthening techniques for stone beams and slabs have been reported [1–4]. These techniques include: (a) steel angles used in combination with polyethylene terephthalate plastic (PET) belts [1]; and (b) prestressed and non-prestressed near surface mounted (NSM) carbon fiber reinforced polymer (CFRP) reinforcing bars [2–4], which are installed in shallow grooves in the tension zone of the stone members. The strengthening method using steel angles was found to marginally increase the flexural capacity and somewhat enhance the ductility of the strengthened beams. The use of nonprestressed NSM CFRP bars had little effect on the cracking load capacity of stone beams [2]. On the other hand, the strengthening method using prestressed NSM CFRP bars appreciably enhanced the performance of strengthened specimens: crack formation was delayed; deflection at failure became larger, particularly for higher levels of prestressing force; and the flexural strength was enhanced [3,4]. However, potential safety issues associated with cutting groves and prestressing CFRP materials coupled with the high cost of CFRP bars pose challenges to this strengthening technique. Hence, the method described in this paper is an attempt to remedy these concerns.

The technique of ferrocement laminates has been used to improve the flexural performance of concrete members for several decades [5–8]. Ferrocement laminate consists of different layers of wire mesh embedded in cement mortar [5]. Past studies on reinforced concrete (RC) beams [9–13] and slabs [14] strengthened using ferrocement laminates have demonstrated an increase in flexural strength and stiffness as well as delayed cracking. The interfacial bond between the ferrocement laminates and the RC matrix is a key design factor. Shear connectors and epoxy adhesive have been the primary techniques for achieving composite action between the ferrocement laminate and the RC members [11–13]. For cases with sufficient composite action, the increase in the flexural capacity is dependent on the reinforcement ratio of ferrocement laminates. No research on the performance of stone slabs strengthened with ferrocement laminates has been reported so far. Wang et al. [15] studied the interfacial bonding properties between stone and two types of modified mortar: (1) commercial polymer-modified cement mortar, and (2) Hydroxy Propyl Methyl Cellulose (HPMC)-modified cement mortar. The experimental results showed that the interfacial bonding strength of the specimens with both HPMC-modified mortar and polymer-modified mortar was higher than that of RC members with conventional mortar. Hence, modified mortars could provide the interface resistance needed for strengthening stone elements. Traditional ferrocement laminates for strengthening RC members use wire mesh with small diameter bars as reinforcement. However, such reinforcement would not be sufficient for granitic stones because their compressive and tensile strength is larger than concrete. The method adopted for the reported research using steel bars as reinforcement is referred to as “reinforced mortar”.

Five stone slabs strengthened with reinforced mortar and one bare stone slab were tested to investigate the flexural behavior of stone slabs strengthened with the proposed method. An analytical model was developed to calculate the flexural strength of the strengthened stone slabs.

2. Experimental program

2.1. Test specimens and parameters

Five strengthened stone slabs and one bare stone slab were tested under monotonic four-point bending. The test variables were the reinforcement ratio and the mortar strength. The specimen designation and test parameters are provided in Table 1. Specimen S0 was the bare slab and served as the control specimen. Specimens Sm30s4, Sm30s5, and Sm30s7 were strengthened with four, five, and seven Φ6-mm longitudinal deformed bars, respectively. The mortar used in the above mentioned three specimens was HPMC-modified cement mortar with design strength of 30 MPa. Specimens Sm25s5 and Sm40s5 were reinforced with five Φ6-mm longitudinal bars. HPMC-modified cement mortar with design strength of 25 MPa was used in Sm25s5, and Sm40s5 utilized polymer-modified mortar having design strength of 40 MPa. The transverse reinforcement for all the specimens consisted of Φ4-mm plain bars welded to the longitudinal bars at a spacing of 250 mm.

A schematic of the specimen geometry and reinforcement details is shown in Fig. 2. The slab specimens were designed to be full-scale, with all the three dimensions being close to those of actual stone slabs used in stone building structures. All the stone slabs had rough surfaces, and the soffit was not treated prior to the application of reinforced mortar. Considering the roughness of the slab surfaces, the dimensions of the stone slabs were determined using the average values measured at different locations. The stone slabs had an average length of 3200 mm, and were approximately 420 mm wide by 140 mm deep. The thickness of the reinforced mortar layer was 30 mm on average, and the reinforcement was situated at the mid-height of the mortar layer.

Fig. 1. Stone masonry building in the southeastern area of China.