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RETROFITTING OF HISTORIC STONE MASONRY BUILDINGS IN EGYPT : AN EXPERIMENTAL STUDY

by

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ABSTRACT

One of the very early type of masonry materials used in construction is natural stone. Sedimentary rocks such as limestone were used in building construction in Egypt during the 12th to 15th century period Multiwythe masonry walls made of two stone masonry outer wythes with a wide cavity filled with pieces of stone and low quality mortar was the common type of wall construction in this period. Unsatisfactory seismic performance of these buildings has been observed in past earthquakes. specially during the most recent earthquake of October 12th, 1992. There is an urgent need to restore and repair this type of walls. In this paper, a review of previous experimental work carried out to study wall behavior, in-situ evaluation. nondestructive evaluation, repair and retrofit of stone masonry is presented. Review of literature reveals that further research is needed to provide a better understanding of the behavioral characteristics of multiwythe stone masonry walls and to develop repair and retrofitting methodologies. An overview and objectives of an ongoing cooperative research program between Drexel University and Helwan University on multiwythe stone masonry walls are also presented.

INTRODUCTION

Stone masonry walls are considered the most commonly used structural elements in historic buildings. Although stone masonry walls are considered one of the oldest type of construction, little is known about their unique behavior. Unsatisfactory seismic performance of this type of walls has been observed, specially in recent earthquakes around the world. This is attributed to its limited tensile and shear strengths. Stone masonry walls are very stiff and brittle elements with low resistance to seismic action [Drysdale et al. 1993].

Mortar used in this type of walls is typically lime-based mortar. Bond and tensile strength of this type of mortar is very low, and the bed joints offer limited tensile and shear strengths. This is a key factor for the observed unsatisfactory seismic performance.

Field survey conducted on stone masonry walls in Egyptian historic buildings constructed during the Mamluk period, (12th to 15th century) revealed that they have suffered significant deterioration and damage during the October 12th 1992 earthquake in Cairo. In addition, deterioration caused by environment and differential settlement has been observed. Research work is needed to study wall behavior, and to develop repair and retrofitting techniques for this type of construction. This will help in restoration of these buildings, which are considered as a commonwealth.

Walls used in constructing these buildings are the so-called three-leaf (multiwythe) stone masonry (i.e. two stone masonry "face" walls with a gap between them filled with low quality mortar and small pieces of stone). Limestone was used in constructing this type of walls and the mortar used consisted of hydrated lime, fine sand, stone powder and flying ash. Restoring this type of walls is one of the most difficult aspects and could not be accomplished unless enough information about their behavior and the engineering properties of their constituents is provided. Nondestructive testing and in-situ evaluations are useful in providing this information. Studying bond stresses and load transfer between the wythes of these walls are of significant importance in understanding their behavioral characteristics.

In this paper, a brief review of previous work is presented. Also, some important issues regarding behavior, in-situ evaluation, repair and retrofitting of unreinforced masonry are discussed. Based on literature review, research areas pertaining to this type of buildings are identified. Recently, a cooperative research program between Drexel University and Helwan University has been initiated to address research needs in this area. The objectives and scope of the program, which is currently conducted at the Masonry Research Laboratory at Drexel University, are presented.

IN-SITU EVALUATION OF MECHANICAL PROPERTIES OF HISTORIC MASONRY WALLS

Evaluation and in-situ investigation of actual mechanical characteristics and structural behavior of masonry elements are typically made using core drilling for extracting materials for visual inspection and in some cases for chemical analysis. Bore hole vedio surveys can be used for detecting internal voids. Mechanical characteristics of the stone masonry walls were analyzed using the flat-jack testing technique. Fig. 1 [Gelmi et al. 1993]. Flat jack was used as in-situ nondestructive technique to evaluate the compression stress and the deformabilty of masonry walls [Romuldo 1996. Carputi &Martino 1994]. A review of some potential techniques for in-situ evaluation of masonry properties [De Vekey 1991] showed that the flat-jack could measure stress to within 5% but was less reliable for elasticity strength determination. Destructive shear tests were performed on masonry walls belonging to an existing three-story building in Florence [Angotti et al. 1991] in which the vertical structure consists of mixed stones and brick units. Test specimens were isolated from the rest of walls to form panels with dimensions in accordance with the optimal dimensions indicated by Sheppard (1985). A study was made for evaluating the actual improvement achieved in the mechanical characteristics of the masonry as a result of injecting it with consolidating material [Betto et al. 1996]. Evaluation was made using flat-jack, sonic and ultrasonic tests. Core boring was also done to verify how well the gabs had filled by the injection.

One nondestructive method for measuring in-situ shear strength of a wall that has become common in California over the last decade is the in-plane-shear test [Abrams & Epperson 1989] which is also known by the names, "Shove test" or "Push test". The test is very simple, its procedure involves removing a single brick so that a hydraulic jack can be inserted in its place and apply load to the adjacent brick, see Fig. 2. The head joint is removed on the opposite side of the adjacent brick so that the loaded brick can slide once the shear stress across the brick-mortar interface exceeds the ultimate strength. This test is suitable for only single wythe walls.

Nasser and Ghosh (1992) presented a study of the efficiency of the pin-penetration method to evaluate the strength of masonry mortar. They concluded that for properly hardened mortar, the pin penetration tester can be used to evaluate its strength in the joints of masonry structures, and that its penetration in mortar varied inversely with the strength of the mortar. This test can be used to check the quality of the mortar joints and to locate flaws.

Nondestructive testing should be a part of all repair programs, and can be used to identify subsurface cracks and voids before repair, as a means of verifying grout penetration during injection, and as quality control technique following repair. Methods which use stress wave transmission (such as ultrasonic pulse velocity, mechanical pulse transmission, and pulse-Echo technique) have proven to be quite useful for location and characterization of sub-surface cracks and voids [Kingsley et al. 1987, Atkinson et al. 1991, Rossi 1990]. Reasonable correlation between compressive strength and vertical ultimate pulse velocity is shown in Fig. 3.

MATERIAL PROPERTIES OF HISTORIC STONE MASONRY

The conservation and maintenance of historic buildings require knowledge about the constituents materials of mortar and stone and about the mechanical properties of stone masonry subjected to various loading.

Mortar: Historic mortars were typically lime-based, that is lime constituted the major part of all the binder. Also, hydraulic lime was used in many cases to provide hydraulic feature to the mortar. Mineralogical analysis carried out on mortar samples obtained from the collapsed Civic Tower of Pavia, Italy [Baronio & Binda 1992] indicated that the binder to aggregate ratio of the mortar varied between 1 : 3 and 1 : 5 with lime putty as the main part of the binder. The binder to aggregate ratio of historic mortars ranges from 1 : 0.4 to 1 : 5 with the majority of the ratios being in the 1 : 3 range [Suter & Song 1995]. Chemical analysis made on historic mortar taken from Alkanisa Almoalaka and Hessn Babelion constructed during Mamluk period in Cairo revealed that proportions by weight of mortar used are hydrated lime 1 : aggregate (fine sand) 2.17 : fly ash 0.167 : water 1, with a binder to aggregate ratio of 1 : 2.17.

The compressive strengths of mortars obtained from in-situ tests on old stone walls were in the range of 3.0 and 3.5 MPa [Sheppard 1985] while that for original mortars was found to be in the range of 0.1 and 3.5 MPa. The compressive strength obtained from small mortar joint samples is significantly higher than that from equivalent laboratory-prepared specimens [Suter & Song 1995].

Test results reported by many researchers indicate that the ratio between tensile and compressive strengths of historic mortars can be much higher than that of modern mortars. For historic lime-based mortars, an average value of 36% was found for the ratio of tensile to compressive strengths [Suter & Song 1995].

Building stone: Rocks used in buildings and monuments are called stones. The commonly used building stones are limestone, sandstone, marble, slate and shale. Limestone and sandstone are the most commonly used building stones. Compressive strength, density, modules of rupture and modules of elasticity are the major properties of building stones. For most types of stones, the compressive strength is directly proportional to the density when the strength is below 100 MPa. Hewitt (1964) obtained an average compressive strength of 134 MPa and reported an average tensile strength of 15.4 MPa for limestone from quarries in the Province of Ontario, Canada. Compressive strength tests carried out on stone samples obtained from multiwythe stone masonry walls of Alkanisa Almoalaka and Hessn Babelion constructed during Mamluk period in Cairo revealed a low stone compressive strength in the range of 14 to 16 MPa.

Mechanical properties of stone masonry walls: Walls in historic buildings often consist of more than one wythe with possibly different materials such as stone, brick and rubble making up the wythes. As a rule, these stone walls are usually very thick and the stresses in the wall are low. On the other hand, the strength of these walls can be very low due to the presence of weak mortar, the method of construction and the deteriorated state of the walls. Old masonry construction are at times characterized by a high degree of deformability and considerable inelastic deformations.

Beolchini (1992) carried out compression tests on stone masonry specimens which were obtained from an eighteenth century building; the average compressive strength was 1.12 MPa, with a strain of 0.013 corresponding to the maximum stress. Chiosterini and Vignoli (1994) reported in-situ compression test results of old stone masonry walls as 3.21 MPa.

Suter and Keller (1990) determined bond strength for five types of mortar and three types of historic masonry units including limestone using bond wrench. The test results revealed that the bond strength was significantly influenced by the type of unit. An average flexural bond strength for lime stone prisms of 0.70 MPa was reported.

Shear strength of stone masonry was determined using in-situ destructive shear tests [Sheppard 1985, Angotti et al. 1991]. Test results revealed an average shear strength of 0.17 MPa.

BEHAVIOR OF HISTORIC MASONRY WALLS

When dealing with the preservation or restoration of historic buildings, the question of how to assess the residual strength of the existing masonry frequently arises. In order to evaluate the residual structural capacity, response to structural loading must be understood. Detailed knowledge of the structural behavior only permits a static check: but together with testing of the building material, it allows the safety level of the structure to be assessed. Historic masonry was commonly built using multiwythe walls consisting in general of two outer skins and a more or less heterogeneous infill: the total thickness being not less than 500 mm. This method of building is around 4000 years old and exists in a variety of forms. Therefore, a detailed understanding of the behavior of these structures is essential in order to reduce any intervention for the purpose of strengthening or repair to a minimum.

Diagonal tensile tests [Fig. 4] were carried out on a series of multiwythe stone masonry wallettes [Vintzileou & Tassios 1995]. It was observed that, even after the opening of vertical cracks, the wallettes were able to sustain constant stress up to a total opening crack as large as 10 mm. This might be attributed to the fact that even after a vertical crack separate the wallette into two halves, each individual half is able to sustain compressive stresses almost as high as the compressive strength of the whole wallette.

Peak and residual shear strengths are well represented by the Mohr-Columb failure criterion. This was concluded from tests carried out by Kingsley et al. (1987) to examine horizontal bed joint shear failure mode and shear load-displacement behavior for unreinforced brick masonry during static and cyclic loading. Similar tests were carried out by Binda et al. (1995) using servo-controlled direct shear apparatus. It was concluded that the servo-controlled direct shear apparatus is an excellent device to investigate the shear strength and deformation behavior of masonry bed joints.

Egermann (1991) investigated the bearing capacity of multiwythe masonry as a basis for efficient repair and re-design work. Factors influencing load capacity was also investigated and summarized in three groups: geometry of units, structure and materials. Multi-material model and silo model were used as mechanical model to describe the load bearing capacity of the wallettes. He concluded that, for multiwythe masonry specimens vertical load can be distributed according to the stiffness of outer and inner layers. The lateral deformation of the infill created a constant horizontal loading of the outer shells, which assumed a belly-shape. The stress in the elements can be determined by the extended Hook's law (multi-material model). The collapse of the specimen was caused by a bending failure of one or both outer shells.

REPAIR AND RETROFITTING OF HISTORIC MASONRY WALLS

Grouting by using cement or polymer-based grouts is one of the most commonly used techniques in repair and strengthening of both modern and old structures [Vintzileou & Tassios 1995]. In the case of structures belonging to the architectural heritage, the use of polymers-based grouts should be as restricted as possible, both because of the incompatibility with the old materials and because of their possibly sensitive in-time behavior. Cement based grouts are made of materials of well-known characteristics and are more compatible with materials used to build old masonry structures. They have however, the disadvantage of possible efflorescence and of low penetrability into narrow cracks or voids less than 2-3 mm wide. The effect of injecting cement-based grout (as a repair technique) in multiwythe stone masonry walls in monuments and buildings belonging to urban nuclei was studied [Vintzileou & Tassios 1995]. Wallettes shown in Fig. 5 were tested under axial compression. Two alternative mix proportions for the grout were used. Grout made of normal portland-type cement was of high penetrability (fine cracks, 0.2 mm wide, were filled) achieved by the addition of both ultrafine material (silica fume) and superplasticiser. The compressive strengths of the two types of grouts used were 13 and 30 MPa. It was concluded that strengthening of wallettes by injecting cement-based grouts is very efficient: it increased the compressive strength of wallettes by 50% to 200% in comparison of the initial strength.

The seismic resistance of stone masonry walls strengthened with grout injection was experimentally investigated by subjecting specimens to a combination of constant vertical and cyclic acting lateral load [Rossi 1990]. Although the compressive strength of different grout mixes varied from 7 to 32 MPa, the analysis of test results showed no significant difference in the behavior of specimens subjected to seismic loads. The test results indicated the possibility of further reduction or substitution of cement in the grout with other adequate materials.

Biggs (1993) found out that reanchoring is a convenient and efficient for retrofitting historic masonry structures. Different systems of reanchoring were used: mechanical screw type tie, adhesive tie, adhesive screen type and adhesive injected type ties.

NEEDED RESEARCH

Literature review has revealed that the behavior, repair and restoration of historic multiwythe stone masonry walls have not been fully investigated. The interface bond between the different wythes of the walls is important for composite action. It has been also shown that there is a need for accurate models to predict wall stiffness and strength. There is also a need to study different methods for repair and retrofitting of this type of walls for the purpose of restoration. Therefore, a research program has been initiated at Drexel University to study the behavior and to develop repair and retrofitting techniques for multiwythe (three-leaf) stone masonry walls.

JOINT RESEARCH PROGRAM

A joint research program between Drexel University in Philadelphia and Helwan University in Cairo was initiated in 1997 to study the behavior of multiwythe stone masonry walls typical in Egyptian Historic buildings during the Mamluk period. The objectives of the program is to develop effective retrofitting techniques to improve seismic resistance. Phase I of this program, which was conducted in Egypt, focused on field survey of a number of buildings constructed during Mamluk period. Phase II includes testing full scale multiwythe stone masonry wall elements similar to those used in constructing original buildings under out-of-plane and in-plane loading. The test matrix of this phase is shown in Table 1. The objectives of the test program are:

1. studying the behavior of multiwythe historic masonry walls under axial compression, diagonal tension and splitting tension loading;
2. Studying the interface bond between the masonry outershells and infill;
3. studying the efficiency of different retrofitting techniques in improving the behavior of this type of walls;
4. developing a mathematical model capable of simulating the behavior of this type of walls.
5. developing an effective retrofitting methodology for historic buildings in Egypt

This phase is currently in progress at the Masonry Research Laboratory of Drexel University in Philadelphia.

SUMMARY AND CONCLUSIONS

A literature review of historic stone masonry has been presented in this paper. Different aspects regarding in-situ evaluation, behavior, repair and retrofitting, restoration, and analysis of historic masonry walls are discussed. The review indicates that behavior, repair and retrofit, and restoration of historic masonry walls have not been fully investigated. The review also reveals the need for refined models to predict multiwythe wall behavior stiffness and strength. A research program at Drexel University has been initiated to address these issues. The scope of the experimental phase of this program is presented in this paper.

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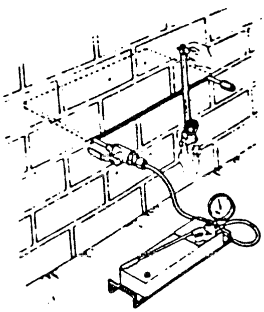


Fig. 1 Deformability Test With Flat-Jack [Gelmi et al. 1993]

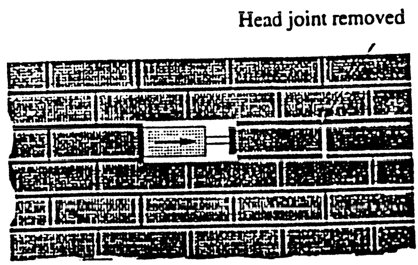


Fig. 2 Shove Test [De Vekey 1991]

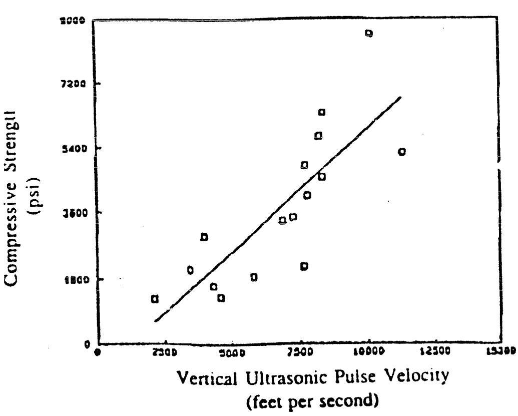


Fig. 3 Correlation Between Ultrasonic Pulse Velocity With Masonry Prism Compressive Strength [Atkinson et al. 1995]

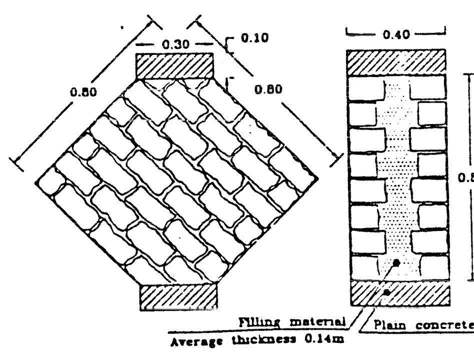


Fig. 4 Specimen for The Diagonal Tensile Test [Vintzileou et al. 1995]

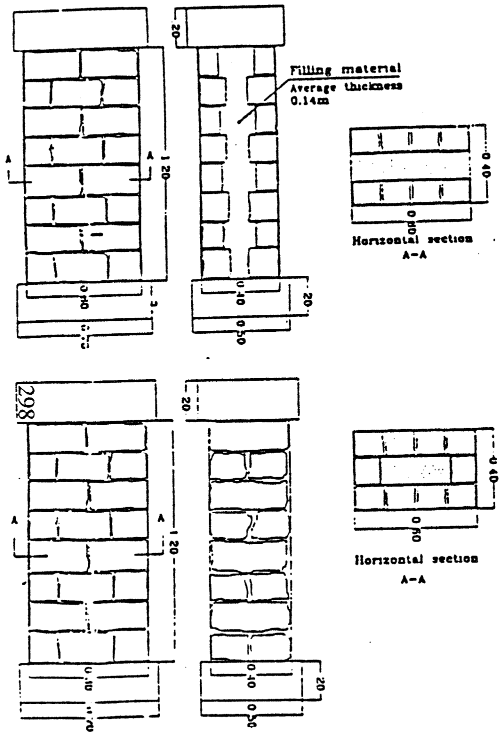
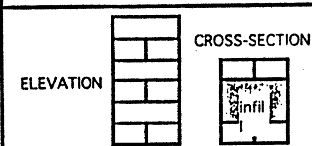
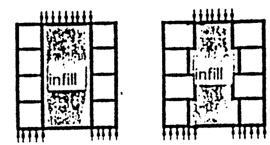


Fig. 5 Geometry and Dimensions of Walletts [Vintzileou 1995]

Table 1 Test Program at Drexel University

Type of Test	Spec-imen shape	Parameters: Interface type (a) P	R	I	Infill type (b) W	S	Retrofitting techniques (c) T1	T2	T3
Axial compression		×			×	×		-	
			×		×	×		-	
Shear test to measure interface bond		×			×	×		-	
			×		×	×			
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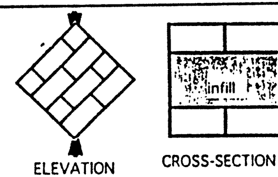
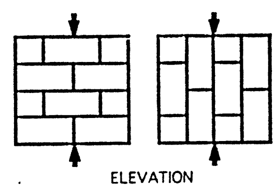
		×			×		×		
		×			×			×	
		×			×				×
Diagonal tension		×			×	×		-	
			×		×	×		-	
Splitting tension – Tension parallel to bed joints		×			×	×		-	
			×		×	×		-	
– Tension Normal to bed joints		×			×	×		-	
			×		×	×		-	

(a) P= plain (smooth) iterface, R= rough inetrface and I= interlocked interface
(b) W= weak infill S= strong infill
(c) T1= retrofitting using grout injection, T2= retrofirring using anchring systems