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MECHANICAL BEHAVIOUR OF THICK MORTAR JOINTS UNDER COMPRESSION: EXPERIMENTAL AND ANALYTICAL EVALUATION

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1. ABSTRACT

The first results of a research program on the mechanical behaviour of hand-made flat bricks, mortar and masonry with thick mortar joints, used for restorations of Roman and Byzantine monuments in Northern Greece, are presented. Compressive and tensile strength of bricks and mortars are measured and stress-strain curves of bricks using strain gages are plotted. The compressive strength curves of small masonry piers are measured for three values of joint thickness. Finally, the analytical results under compression of twelve masonry piers, covering a wide spectrum of joint thicknesses, modeled by a specific nonlinear F.E. computer code are also presented.

2. INTRODUCTION

The masonry of Roman and Byzantine monuments, in Greece in particular and in all the Mediterranean region in general, is characterized by the flat clay bricks and the thick mortar joints. For the restoration of these monuments there is a need of hand-made flat bricks and mortars compatible with the original ones. There is also a need of studying the mechanical behaviour of masonry with thick mortar joints masoned by using materials of this kind. A lot of work to these directions has been done at the Reinforced Concrete Laboratory of Aristotle University of Thessaloniki [1, 2, 3]. In the present paper the first results of a research program studying the mechanical properties of hand-made bricks, mortars and masonry with thick mortar joints are presented.

Keywords: Byzantine Masonry, Bricks, Mortars. Compressive strength, Deformations

3. EXPERIMENTAL RESEARCH

3.1 Bricks

The 9th Ephorate of Byzantine Antiquities is using, for the restoration works, handmade flat clay bricks manufactured by small local factories in the outskirts of Thessaloniki. Physical characteristics of the bricks: External cracks are visible in some of the bricks. The presence of internal hair cracks was detected in many bricks by ultrasonic tests.

- Dimensions: l x l x t = about 40 x 30 x 5 cm
- Dry specific gravity: 16 KN/m³
- Furnace temperature: 800 - 900 °C

Mechanical characteristics of the bricks: Strong anisotropy was detected in strength and Young Modulus along the directions l and l, by both destructive and ultrasonic tests.

- Compressive strength - deformations: Small cubic specimens (18 pieces, 4x4x4 cm) and two groups of prismatic specimens (2x9=18 pieces, 4x4x12 cm) were cut along the l and l direction from macroscopically uncracked bricks. Four prismatic specimens of each group were instrumented using strain gages on two opposite surfaces of each specimen (fig. 1). The results from the relative tests are summarized in the table below:

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Loading direct.</th>
<th>Compressive strength (MPa) min-max → mean / st. deviation</th>
<th>Young Modulus Initial val. (MPa)</th>
<th>Poisson ratio Initial values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic</td>
<td>Random</td>
<td>f'_c = 10.64±15.84→13.20/s=1.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prismatic</td>
<td>l</td>
<td>f'_c = 6.68±12.22→10.50/s=1.83</td>
<td>E'_c = 3400±8000</td>
<td>ν'_c = 0.08±0.20</td>
</tr>
<tr>
<td>Prismatic</td>
<td>l</td>
<td>f'_c = 5.00±10.63→7.08/s=1.75</td>
<td>E'_c = 2500±6000</td>
<td>ν'_c = 0.12±0.20</td>
</tr>
</tbody>
</table>

The type of failure was characterized by the formation of inclined cracks and crushing at the core of the cubic specimens, while the prismatic ones failed by cracking along the loading direction (fig. 1). The typical stress-strain curves of a prismatic specimen are shown in fig. 2. The significant difference between the deformation on opposite surfaces of the specimen reveals flexure due to eccentricity of the loading.

- Tensile strength: Two triads of prismatic specimens 4x4x20 cm were cut from uncracked bricks, along the l and l direction respectively. The ends of the specimens were glued with epoxy resin into special metallic holders and direct tension was applied. The mean values of tensile strength were found: f'_{bt} = 1.80, f'_{bt} = 1.29 MPa respectively.

![Fig.1 Prismatic brick specimen under compression](image1)

![Fig.2 Stress-strain curves of prismatic brick specimen under compression](image2)
3.2 Mortar

The original mortars of Roman and Byzantine Monuments are composed of lime, pozzolana, crushed bricks, sand and water. The mortars used for restoration always contain some cement so that their strength is increased and the hardening process is accelerated. In the R/C Lab. of Aristotle Univ. of Thessaloniki a great variety of mortar compositions have been developed and tested during the last fifteen years, to support the restoration of many important monuments. The composition and the expected mechanical properties at the age of 28 days of the mortar chosen for the present research program are the following [3] :

- Composition by the weight : Lime/Pozzolana/Cement/Crushed bricks/sand/water = 1.0/0.2/0.8/3.0/3.0/2.1
- Tensile strength (flexure test according to DIN standards) : $f_{mt} = 0.84\text{MPa}$
- Compressive strength (according to DIN standards) : $f_{ncc} = 3.43\text{MPa}$
- Dynamic Young Modulus (ultrasonic tests) : $E_m^d = 4600\text{MPa}$

In order to test the mechanical properties of the mortar, six prismatic samples 4x4x16xcm were taken for every one of the six masonry piers constructed. The results from the 36 samples are as follows :

- $f_{mt} = 0.75 \pm 1.75\text{MPa}$, mean value : $1.23\text{MPa}$, standard deviation : $s = 0.31\text{MPa}$
- $f_{ncc} = 3.56 \pm 4.45\text{MPa}$, mean value : $3.96\text{MPa}$, standard deviation : $s = 0.80\text{MPa}$

3.3 Masonry Piers

In the first part of the research project presented here, six masonry piers 90x45x18cm were constructed, divided into three couples of twin piers. The only parameter was the bed joint thickness taking the values of 20, 35 and 55mm, while the brick height and the thickness of the vertical joints were 50 and 30mm correspondingly for all the piers. The piers were constructed horizontally in wooden mould. The bricks were fixed at the proper places into the mould using small nails (fig.3). Then mortar was poured to fill the joints. This method can ensure the complete filling of the joints and has the advantage of correct geometry. On the other hand it has the disadvantage of bad cohesion between mortar and bricks due to shrinkage of the mortar and the absence of the gravity pressure.

Fig.3 Wooden mould for masonry piers with the bricks fixed at their positions

Fig.4 Instrumentation of masonry specimen
This could affect seriously the shear strength but has negligible influence on compression strength. The piers were tested under compression in vertical position. A force controlled testing machine having a capacity of 1000KN was used.

**Instrumentation - monitoring:** Five displacement sensors (LVDT) were mounted on each pier. Two of them were fixed longitudinally and horizontally on each side of the pier, while the fifth sensor measured the thickness deformation ($\varepsilon_t$) in the center of the pier (fig. 4). A load cell was used for the monitoring of the compressive force. To collect and store the data, a portable computer SANYO LT16, connected to an A/D card having 16 input channels was used. To reduce the "noise" a regulating condenser was connected to every input channel. In spite of this, "gravity functions" were used in order to smoothing the resulting stress-strain curves.

**Experimental results:** The compressive strength ($f_{wc}$), the initial value of Young Modulus ($E_{wo}$) and the longitudinal deformation at failure ($\varepsilon'_{wu}$) for the six piers are shown in the following table:

<table>
<thead>
<tr>
<th>Specimen</th>
<th>W20</th>
<th>W35</th>
<th>W55</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>Mean</td>
</tr>
<tr>
<td>$f_{wc}$ (MPa)</td>
<td>6.752</td>
<td>6.281</td>
<td>6.517</td>
</tr>
<tr>
<td>$E_{wo}$ (MPa)</td>
<td>65.80</td>
<td>62.30</td>
<td>64.05</td>
</tr>
<tr>
<td>$\varepsilon'_{wu}$ (%)</td>
<td>2.60</td>
<td>2.10</td>
<td>2.35</td>
</tr>
</tbody>
</table>

The stress-strain curves ($\sigma - \varepsilon_t$, $\varepsilon_h$, $\varepsilon_t$) for the piers W20B, W35B and W55A are shown in fig.5, 6 and 7. The mean values of the LVDT’s on each of the opposite sides of the pier were used for the ($\sigma-\varepsilon_t$) and ($\sigma-\varepsilon_h$) curves. About $\varepsilon_t$ it must be pointed out that it represents the local transversal deformation at the point of measurement. The stress-volumetric strain curve ($\sigma-\varepsilon_v$, $\varepsilon_v = \varepsilon_t + \varepsilon_h - \varepsilon_t$) is also plotted for each pier. The following remarks can be made:

- The compressive strength of masonry, as it was expected, decreases for increasing joint thickness.
- The Young Modulus follows the same rule but for the thinner joint it is greater than $E_{bo}$, while for the thicker joint it is smaller than $E_{mo}$. These inconsistencies could be attributed to many reasons such as higher $E_{bo}$ along the thickness of the bricks ($E_{bo}$ was measured along the two other directions of the bricks), higher $E_{mo}$ due to the confinement of the mortar between brick layers, hair cracks due to mortar shrinkage, imperfect measurements etc.
- The ultimate deformations and the nonlinearity of ($\sigma-\varepsilon_t$) curve increase rapidly with the joint thickness.
- The shape of ($\sigma-\varepsilon_t$) curves is the typical one for brittle materials showing high dilatancy near failure and apparent instant values of Poisson ratio much greater than 0.5.
- Type of failure: Short vertical hair cracks are observed at the main sides of the piers under a compressive stress $\sigma_{cr} \approx (0.50=0.65)f_{wc}$. Suddenly a major vertical crack is formatted $\sigma^m_{cr} \approx(0.75=0.85)f_{wc}$, the crack is widened rapidly and the pier fails. The major crack appears either on the main sides of the specimen (pier W35B:fig. 9) or on the one or both the lateral sides of the specimen causing the splitting of the pier out of its plane (piers W20B and W55A:fig. 8,10).
4. ANALYTICAL RESEARCH

In the Reinforced Concrete Laboratory of Aristotle University of Thessaloniki a specific F.E. micromodel has been developed, for the in-plane nonlinear analysis of unreinforced masonry under monotonic loading until failure (Computer code “MAFEA” : MAsory Finite Element Analysis) [4]. It must be pointed out that the computer program, despite its 2D character, calculates and takes rationally into account the out-of-plane principal stresses that developed in bricks and mortar joints under in-plane loading of the masonry. The model is capable of predicting cracking, crushing or out-of-plane splitting of bricks and mortar, as well as sliding or unsticking at the joints and finally the propagation of damages until failure. Using this powerful F.E. program an enlargement of the experimental findings has been attempted. At first three F.E. models (M20, M35, M55), identical with the experimentally tested masonry piers, were created and analyzed until failure in order to verificate the analytical model. The necessary inputs for the MAFEA computer code, apart from the geometry of the masonry models, are the mechanical properties of bricks, mortars and joints given in the following table. Most of them are determined by the experimental research already mentioned.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Dimensions</th>
<th>$f_b$(MPa)</th>
<th>$f_l$(MPa)</th>
<th>$E_d$(MPa)</th>
<th>$v_o$</th>
<th>$\varepsilon_u$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bricks</td>
<td>28x18x5cm</td>
<td>$f_{bc}=9.00$</td>
<td>$f_{bl}=1.55$</td>
<td>6000</td>
<td>0.15</td>
<td>3.25</td>
</tr>
<tr>
<td>Mortar</td>
<td>$t_{bed}=1.0+7.5$</td>
<td>$f_{me}=3.00^A$</td>
<td>$f_{mt}=0.70^B$</td>
<td>3000$^C$</td>
<td>0.20$^D$</td>
<td>3.25$^D$</td>
</tr>
<tr>
<td>Joints</td>
<td>$t_{ver}=3.0cm$</td>
<td>Shear, Tensile strength: $f_{st}=0.30^D$, $f_{tt}=0.15^D$ Mpa</td>
<td>Friction coefficient: $\mu=0.75^D$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^A$: Prismatic strength converted from the cubic strength
$^B$: Direct tension strength converted from the flexural strength
$^C$: $E_{sm}$ under static loading converted from the dynamic Young Modulus $E_{d,mo}^d$
$^D$: From the relative literature

The strength of the models was in very good agreement with the respective experimental ones (fig. 11) taking into account the wide scattering of the material properties. To enlarge the experimental results nine masonry models, with bed joint thickness varying from 1.0 to 7.5cm and the material properties of the table above, have been created and analyzed until failure. Figure 11 shows the compressive strength of masonry models ($f_{mc}$) versus joint thickness to brick height ratio ($t_m / t_b$). It is clear that $f_{mc}$ decreases with increasing joint thickness tending asymptotically to the lower limit equal to $f_{me}$ and to the upper limit equal to $f_{bc}$, for very thick and very thin joint thickness respectively.

The damages of the masonry pier models begin with unstickings at the vertical joints under a compressive stress $\sigma_{cr} \approx (0.60+0.70)f_{mc}$. For higher loading the unstickings spread and propagate vertically cutting the bricks above and below the vertical joints. Failure occurs in a rather brittle manner with crushing of bed joints and cracking or out of plane splitting of bricks. The out of plane splitting appears mainly for thin joints (fig. 12 A,B=M10 model) while major vertical cracks through bricks and joints appear mainly for thick joints (fig. 12 C,D=M60 model).

5. CONCLUSIONS

It is well known that joint thickness is one of the governing parameters for the compressive strength of masonry. This is also proved to be valid for Byzantine or
Fig. 5  Stress-strain curves of masonry specimen W20B

Fig. 6  Stress-strain curves of masonry specimen W35B

Fig. 7  Stress-strain curves of masonry specimen W55A

Fig. 8  Masonry specimen W20B at failure

Fig. 9  Masonry specimen W35B at failure

Fig. 10  Masonry specimen W55A at failure
Roman masonry with flat bricks and relatively weak mortar. The very thick joints of this type of masonry cause a low compressive strength (despite the relatively strong bricks), nonlinear behaviour and high ultimate deformations. This deformability could be very useful under foundation settlements which are very frequent to heavy monumental buildings. Computer code MAFEA is capable of predicting the behaviour of masonry and could be very useful to enlarge and enrich the expensive experimental research.

6. ACKNOWLEDGMENTS

The authors wish to thank 9th Ephorate of Byzantine and Post-Byzantine Antiquities for the generous offering of the materials for the research program.

7. REFERENCES


Fig. 12 Damage patterns of masonry models just before and after failure: A, B: Pier model M10, C, D: Pier model M60
Fig. 12 Damage patterns of masonry models just before and after failure: A, B: Pier model M10, C, D: Pier model M60.