II.02
Assessment of an Experimental Test Setup for Glazed Tiles by Finite Element Simulations

Paulo Cachim¹ and Ana Velosa¹

¹ DECivil & LABEST, University of Aveiro, Portugal, pcachim@ua.pt, avelosa@ua.pt

Abstract The use of glazed tiles in façades is typical of urban 19th Century Portuguese architecture and an identity mark that has been the subject of studies and thesis denoting the fascination of this artistic expression, but also the complexity of the theme, that still lacks a deep study in order to support conservation and restoration interventions. Ceramic tiles cannot be studied without taking into account their architectonic support, to which they give special chromatics and luminosity. Despite the large cultural heritage represented by buildings with ceramic tile façades, conservation and restoration interventions have been made without a consistent basis. Conservation and restoration interventions need solid scientific knowledge of materials used in the old buildings in order to allow for the development of compatible materials and techniques. The characterization of tiles and mortars has been developed and although characterization schemes are currently applied with success in mortars, further development is needed in terms of tiles and of the mortar/tile system. Some of the main problems to be found in ceramic panels are cracking and detachment originated by differential volumetric variations of the different materials (masonry, mortar and tiles) originated by hydrothermal actions. Numeric modelling of these structural systems will allow for the identification of critical areas, that may need intervention and, above all, numerical experiments can be used to test solutions related with the experimental tests. This paper presents numerical simulation for the determination of mechanical behaviour of tiles that includes tension and shear parameters. The results of the numerical model are compared with results of laboratory tests. The model aims at being a tool to evaluate the compatibility of mortars for the re-adherence of ancient tiles.

1 Introduction

Although the use of ceramic glazed tiles in façades is widespread throughout Portugal, having reached its peak in the 19th Century, a considerable number of
buildings need intervention. Detachment, cracking, and loss of tiles are frequently noticeable in these façades, and the lack of a solution to these problems contributes to further degradation [1-2]. In order to establish a solid basis for the conservation of this particular heritage, a scientific approach comprising the study of materials and behaviour of the mortar/tile system is necessary. With the aim of studying the adhesion and shear between the elements present in the system, numerical modelling and laboratory tests were initiated to evaluate these parameters and their effect on the degradation/conservation of these systems.

2 Testing and modelling glazed tiles

The problem of modelling glazed tiles regarding mechanical actions is rather complex. In fact, at least three materials are involved: masonry (or other wall support); mortar (or other material used to bond the tiles to the wall); and the glazed tiles. Besides these materials, there are the interfaces between them: tile/mortar and mortar/brick. Therefore, an adequate modelling of the mechanical behaviour of glazed tiles in façades will imply the knowledge of the properties of three materials and of the bond between them.

Strength properties of bricks and mortars are commonly available or can be determined from standard tests, but there is usually little or no information for tiles. In addition, deformation properties (modulus of elasticity) of the materials are more difficult to obtain. Further difficulties arise when ancient constructions are being restored, because information regarding old materials is even less accessible.

Characterization of the interface behaviour between mortar, tiles, and bricks is difficult and involves several problems. Appropriate tests do exist, such as ASTM C 482 [3] to characterize the bond strength of ceramic tile to Portland cement paste or RILEM MR14 [4] for determination of the bond of renderings by shear tests. Although such tests are not completely adequate for the characterization of the tile/mortar/brick structure, they can be used as a basis for the development of new test.

In this work, a protocol is being developed to assess the tile/mortar/brick structure with a single test. Basically, the test is a double shear test in which two glazed tiles are bonded to one central brick. The whole specimen is then tested under a compressive load (see Fig. 1). The layout of the test is similar to that of RILEM MR14.

This test is aimed to characterize the type of failure that will occur due to shear actions at the interface of the materials. These actions may be caused by differential movements of the different materials as a result of moisture or temperature, for example, or by direct applied forces. With this layout it will be possible to identify the weakest point of the structure, since failure theoretically can occur in mortar, in the tile/mortar interface, or in the mortar/brick interface.
Because this type of test is not really a shear test, in the sense that shear stresses are not constant in the interface of the materials and that the tiles could bend, a series of numerical simulations has been performed to investigate the importance of the geometry in the performance of the structure. It is expected that the main mechanisms of the test will be identified with the numerical simulations.

The results, in terms of shear stress, $\tau$, can be obtained by dividing the applied force, $F$, by the contact area of the two tiles, $A_t$, as:

$$\tau = \frac{F}{2A_t}. \quad (1)$$

### 3 Experimental results

A small preliminary series of tests was performed to assess the testing apparatus. In these tests, the geometry of the test specimens was as shown in Fig. 1. The mortar used in these preliminary tests had a 1:4 cement to sand ratio and a water content of 20% of the cement weight. Tiles were placed as is usual in Portugal, by first placing a layer of mortar on the brick and on the tile back and then placing them together. The bending strength of mortar, measured in a standard 40 mm x 40 mm x 160 mm prism was 4.31 MPa. Tiles had a size of 150 mm x 150 mm x 5 mm, and the contact area of mortar with the tile was 140 mm x 150 mm. Brick thickness was 70 mm. A photo of the test specimen is shown in Fig. 2. To ensure an adequate contact surface between the tiles and brick with the testing machine plates, a 5 mm neoprene plate was introduced between the machine and the specimen. Tests were performed under displacement control at a rate of 0.01 mm/s.
All specimens broke, as expected, at the tile/mortar interface, indicating that the test setup is appropriate for characterization of that interface. The average force measured was 1.8 kN. The average shear stress as defined by equation (1) was $\tau = 85.7$ kPa. A photo of typical tile and mortar surfaces after the test is shown in Fig. 3.

4 Finite element model

A 2-D finite element model that uses plane and link elements was applied. The software used was SAP2000. Four-node plane finite elements were used to model
glazed ceramic tiles, mortar, and bricks. Linear-elastic behaviour was assumed for these elements. For the interfaces, two-node link elements were employed. These are the only finite elements of the model with non-linear behaviour. Two sets of properties were used for these elements in order to model tile/mortar and mortar/brick interfaces.

The material properties (Young modulus and Poisson coefficient) used for the brick, mortar, and tile are presented in Table 1.

**Table 1 Material properties for finite element calculations**

<table>
<thead>
<tr>
<th>Name</th>
<th>E (N/mm²)</th>
<th>ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>8000</td>
<td>0.30</td>
</tr>
<tr>
<td>Mortar</td>
<td>15000</td>
<td>0.20</td>
</tr>
<tr>
<td>Tile</td>
<td>150000</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Regarding the stiffness of the links, a parametrical study was performed in which the properties of normal and tangential stiffness were changed. Because the links were used to simulate the bond between materials, their stiffness should be high so that a perfect bond between materials could be modelled. On the other hand, if it is too high some numerical errors could occur.

**Table 2 List of numerical simulations**

<table>
<thead>
<tr>
<th>Designation</th>
<th>Mortar thickness (mm)</th>
<th>Type of mesh</th>
<th>Stiffness of spring (kN/m)</th>
<th>Horizontal displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-5-rf</td>
<td>15</td>
<td>Refined</td>
<td>$10^5$</td>
<td>Free</td>
</tr>
<tr>
<td>15-6-rf</td>
<td>15</td>
<td>Refined</td>
<td>$10^6$</td>
<td>Free</td>
</tr>
<tr>
<td>15-7-rf</td>
<td>15</td>
<td>Refined</td>
<td>$10^7$</td>
<td>Free</td>
</tr>
<tr>
<td>15-6-rr</td>
<td>15</td>
<td>Refined</td>
<td>$10^7$</td>
<td>Restrained</td>
</tr>
<tr>
<td>15-6-cf</td>
<td>15</td>
<td>Coarse</td>
<td>$10^6$</td>
<td>Free</td>
</tr>
<tr>
<td>10-6-cf</td>
<td>10</td>
<td>Coarse</td>
<td>$10^6$</td>
<td>Free</td>
</tr>
<tr>
<td>20-6-cf</td>
<td>20</td>
<td>Coarse</td>
<td>$10^6$</td>
<td>Free</td>
</tr>
</tbody>
</table>

To investigate the effect of the size of the finite elements in the performance of the model, two finite element meshes were used where the maximum size of the shell elements is 0.125 and 0.250 mm. The finite element meshes used are shown in Fig. 3. Because the friction between the tile and the load plate could be important, a simulation considering the tile-restrained horizontal movement was also analysed. Different thicknesses for the mortar layer were also investigated (10 mm, 15 mm, and 20 mm), though 15 mm is the standard thickness. The different configurations used for numerical tests are shown in Table 2.
5 Results of the numerical analysis

In this section, a comparison of different models is performed to show the advantages and disadvantages of each test configuration. The results presented were obtained for the average load of 1.8 kN.

In Fig. 5 and Fig. 6 the normal and tangential stresses at tile/mortar and mortar/brick interfaces for different stiffness of the interface elements are plotted. Regarding normal stresses at the tile/mortar interface (see Fig. 5), it is evident that a peak tensile stress occurs near the bottom of the mortar. This peak tensile stress occurs approximately at the same location as the maximum tangential stress. This combination of stresses seems to indicate that failure at the tile/mortar interface occurs due to a combination of shear and tensile stresses. It also can be observed from the figures that the shear stress is not constant along the interface, indicating that the average stress defined in equation (1) is in fact only a conventional shear stress failure. The mortar/brick stresses observed in Fig. 6 indicate that if failure occurs at this interface it will start at the top of the brick, due also to a combination of shear and tension. The failure observed in the experimental tests indicates that the mortar/brick interface was stronger than tile/mortar interface.
Fig. 5 Normal (left) and tangential (right) stresses at tile/mortar interface for comparison of link stiffness effect.

Fig. 6 Normal (left) and tangential (right) stresses at mortar/brick interface for comparison of link stiffness effect.

Fig. 7 Normal (left) and tangential (right) stresses at tile/mortar interface for comparison of horizontal restraint effect.

In Fig. 7 the effect of the horizontal restraining in the tile/mortar interface stresses is shown. It can be seen that for a small perturbation at the bottom of mortar, the stress distribution along the interface is very similar.
The effects of the mesh size and mortar thickness in the tile/mortar interface stresses are shown in Fig. 8. Regarding the effect of mortar thickness, it is apparent that small variations in thickness cause no significant changes. However, it was observed that the size of elements used in the finite element mesh may have some influence in the calculation of the stresses, indicating that further analysis and comparison with experimental tests should be performed in order to obtain adequate meshes.

6 Conclusions

In this study a layout for the assessment of the behaviour of ceramic glazed tiles in façades has been investigated. Both experimental and numerical tests have been performed. The results and conclusions presented here represent only preliminary investigations on the subject. Nevertheless, some conclusions and guidelines for the continuation of the study can be drawn:

- Despite the fact that the failure modes obtained were in agreement with what was expected, it was not possible to conclude whether failure occurs by tangential or normal stresses in the tile/mortar interface. In fact, according to numerical results it is most likely that failure occurs by a combination of tangential and normal stresses.
- The numerical model adequately simulates the tests and is an important tool for the assessment of the experimental setup, given valuable indications regarding the points that must be taken under consideration.

Despite all the limitations and additional research work necessary to use this type of test, it seems that it can be used for the characterization of the behaviour of glazed ceramic tiles in façades.
7 Acknowledgements

Funding provided by the Portuguese Foundation for Science and Technology to the Research Units LABEST and GeoBioTec and to the Project PTDC/ECM/101000/2008 – AZULEJAR – Conservation of glazed ceramic tile façades is gratefully acknowledged.

8 References