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FEM analysis of masonry-FRP interface

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Summary

The use of numerical methods for the analysis of masonry structures has been extremely limited due to the large number of influence factors. Due to the high complexity of masonry behaviour, the approach towards the numerical simulation of its structural behaviour has led researchers to develop several constitutive models characterized by different levels of complexity.

In order to solve a given structural problem, several idealizations of material behaviour can be established, each of them being necessarily associated with different degrees of complexity. When dealing with masonry structures, the most common idealizations of material behaviour are elastic behaviour, plastic behaviour and non- linear behaviour.

The aim of this paper is formulation of a numerical simulation hypothesis to study the effect of interface model between Fibre Reinforced Polymer (FRP) and masonry. The hypothesis consists in assigning different stiffness values for the mortar joints. These values simulate the degradations which occur in mortar joints. These lead in obtaining a real structural behaviour. The non linear analysis with finite element method will be used in micro-modelling of a strengthened masonry beam with GFRP at the intrados subjected to vertical load acting in the middle span.

KEYWORDS: non linear analysis, FEM, FRP strengthened masonry beam, micro-modelling interface

1. INTRODUCTION

The numerical modelling of masonry structures through the FEM is a very computationally demanding task because of two different aspects: on the one hand the typological characteristics of masonry buildings do not allow us to refer to simplified static schemes, on the other hand the mechanical properties of the material lead to a widely non-linear behaviour whose prediction can be very tricky. The calibration of numerical models depends by complete characterization of the material possible after some experiments.

Masonry structures are made of blocks connected by mortar joints. Due to this intrinsic geometrical complexity, which is obviously reflected in the computational effort needed, it is necessary to assume a properly homogenised material and perform the analyses through the finite element method (FEM), when the global behaviour of an entire structure is investigated. On the contrary, when a single structural element is being studied, the actual distribution of blocks and joints can be accounted for [1]. In the next chapters an analysis of a masonry arch in micro-modelling will be presented.

2. THE DIFFERENT MODELLING APROACHES FOR MASONRY

2.1. Theories and methods for modelling masonry

In order to solve a given structural problem, several idealizations of material behaviour can be established, each of them being necessarily associated with different degrees of complexity. Naturally, different types of constitutive models (i.e. different descriptions of the material behaviour, associated with different idealizations of the geometry, such as two- or three-dimensional description), originate a sequence, or hierarchy, of models, which allow the analysis to include more complex response effects as well as more costly solutions.

When dealing with masonry structures, the most common idealizations of material behaviour are elastic behaviour, plastic behaviour and non- linear behaviour. These different idealizations are schematically represented in Figure 1, where each idealization is represented by a typical general load-displacement diagram [2].

By adopting a non- linear analysis instead of a linear analysis, a more comprehensive insight into the structural response can be obtained, with a higher cost, both in terms of necessary input data and required knowledge of the analyst. In the following, a brief description concerning the three idealizations referred to above is given and the most relevant issues are discussed.

2.2.1. Linear elastic behaviour

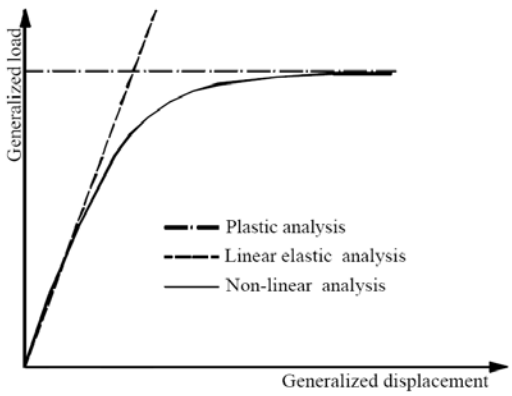

Figure 1. General load-displacement diagrams of a structural analysis.

The linear elastic analysis is the procedure usually followed in structural analysis, where the material is considered to exhibit an infinite linear elastic behaviour, both in compression and tension.

In the case of masonry structures, where joints possess relatively low tensile strength, or even no-tensile strength in the case of dry joints, cracks arise at low stress levels and, therefore, the assumption of elastic behaviour is quite debatable.

In general, linear elastic analyses are not appropriate for ancient constructions [3]. However, in a first stage of analysis, the hypothesis of linear elastic behaviour can be of great help to the analyst. Linear analysis requires little input data, being less demanding, in terms of computer resources and engineering time used, when compared with non-linear methods. Moreover, for materials with tensile strength, linear analysis can provide a reasonable description of the process leading to the crack pattern.

2.2.2 Plastic behaviour

Plastic analysis, or limit analysis, is concerned with the evaluation of the maximum load that a structure can sustain (limit load). The assumption of plastic behaviour implies that, on one hand, the maximum load is obtained at failure and, on the other hand, the material should possess a ductile behaviour. Apparently, this last requirement seems to be unrealizable since the plastic deformations may exceed the ductility of the masonry. However, the limited ductility în compression does not play a relevant role as collapses, except in the case of columns, are generally related to the low tensile strength [3]. Thus, the assumption of a zero tensile strength renders the method of plastic analysis as adequate for the analysis of masonry structures.

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The limit analysis theory is an analytical approach aiming to determine the value of the limit multiplier (LM) to be applied to a given load case in order to cause the failure of a structure, considering a rigid-perfectly plastic behaviour. It was initially developed to study the plastic behaviour of steel structures. The application to masonry structures has been initiated by Drucker and Kooharian. [4], [5], [6].

To be helpful in the framework of masonry structures, the limit analysis theory is based on three fundamental assumptions:

- the compressive strength of the constitutive material is supposed to be infinite. In the reality, the commonly used building materials are strong enough to avoid the occurrence of crushing as failure mode.
- the tensile strength of the constitutive material is supposed to be zero. In the reality, the commonly used building materials present some (limited) tensile strength but the joints between the blocks constitute weak planes: the global tensile strength is then based on the negligible value of mortar bond.
- the sliding between blocks along an interface is supposed to be impossible. In the reality, such sliding appears sometimes but seldom observed: the joint inclination is usually correctly chosen with regard to the orientation of the resultant force.

2.2.3 Non-linear behaviour

Non-linear analysis is the most powerful method of analysis, the only one able to trace the complete structural response of a structure from the elastic range, through cracking and crushing, up to failure. The existence of mortar or dry joints, generally the weakest link in a masonry assemblage and characterized by a marked non- linear behaviour, induces a nonlinear response on masonry structures, even for moderate loads, e.g. serviceability loads. Therefore, non-linear behaviour, being the most complete method of numerical analysis, appears as the most adequate approach to be used in numerical simulations of masonry structures. Its use depends on which objectives are required from the analysis. If the sought information can be attained using a simpler method, which turns out to be less expensive or more in agreement with the expertise of the analyst, then its use is advised.

Several non-linear constitutive models have been developed for the analysis of masonry structures. The most popular theories used to formulate consistent constitutive models are plasticity and continuum damage mechanics, generally based on a phenomenological approach, i.e. the constitutive model is directly based on the observed features from experimental tests.

The first approach addressed here is the theory of plasticity. The first scientific work concerning plasticity goes back to Tresca's memoir in 1864 on the maximum shear stress criterion, [9]. Basically, the plasticity theory attempts to replicate the dislocations of the material, being the plastic material behaviour characterized by the occurrence of permanent deformations. Initially developed for ductile materials, nowadays plasticity is extensively used for other materials such as soils, concrete and masonry. A number of non-linear models based on the plasticity theory aiming at the study of masonry structures have been developed in recent years, both for continuum and discontinuum approaches [10], [11], [12], [13], [14].

3. FEM ANALYSIS OF A STRENGTHENED MASONRY BEAM

3.1 Model parameters

The model proposed to be analyzed is composed by common brick 240x115x60mm and 10 mm mortar joint. The section outcome has 115 x 240 mm. The span of the beam is 600 mm. The constitutive model is presented in figure 2. The program used to calculate the model was ANSYS WORKBENCH Multiphysics. Brick and mortar was considered solids and their properties are defined in table 1. A vertical load in the middle of the span was applied. Both supports are hinged.

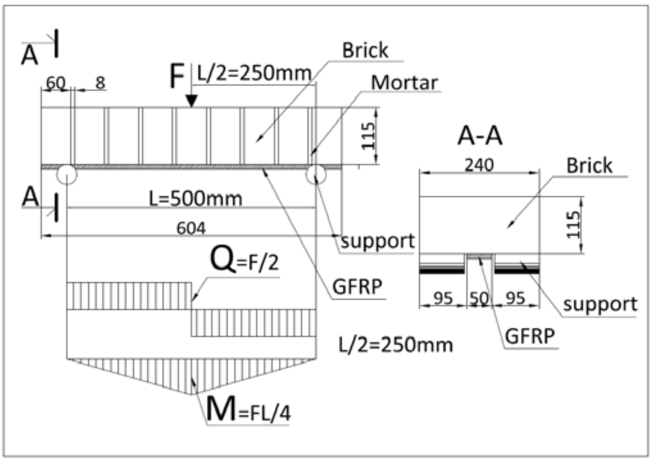

Figure 2. Loading schema of the model analyzed

3.2 Material parameters

All structural material properties were considered linear elastic. Different values of Young's Modulus were given to mortar between 10000 MPa and 1000 MPa.

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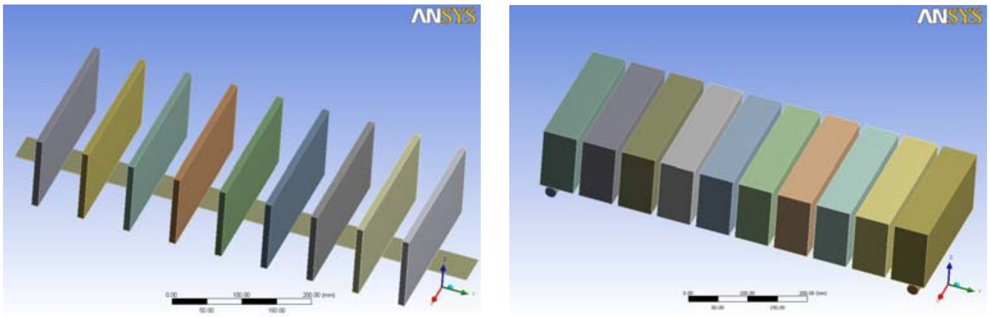
Table 1. Model materials properties

Material	Young's modulus (MPa)	Poisson's ratio	Density (kg/m³)	Tensile ultimate strength (MPa)	Compressive ultimate strength (MPa)
GFRP	77000	0.28	2600	1500	-
Brick	18000	0.20	1900	-	20
Mortar 1	10000	0.18	2100	-	8
Mortar 2	9000	0.18	2100	-	8
Mortar 3	8000	0.18	2100	-	8
Mortar 4	7000	0.18	2100	-	8
Mortar 5	6000	0.18	2100	-	8
Mortar 6	5000	0.18	2100	-	8
Mortar 7	4000	0.18	2100	-	8
Mortar 8	3000	0.18	2100	-	8
Mortar 9	2000	0.18	2100	-	8
Mortar 10	1000	0.18	2100	-	8
Mortar 11	500	0.18	2100	-	8

3.3 Model geometry and mesh definition

All mortar joint and all brick was defined by solid element which was sketch in Autocad. The sketch was exported with an Acis extension file so that make possible import in ANSYS Design Modeler. After the file was imported material properties was assigned to each solid, and an appropriate mesh method was choose. The model has 25 solid parts, 18687 finite elements and 99554 nodes. These steps are illustrated in figure 3.



(a) (b)

Figure 3. Geometrical models of a) – mortar joints and GFRP strip; b) – bricks

The force applied had 60 kN and was kept constant at each step of E modulus. The duration of each analysis was approximately 20 minutes. After each analysis the material properties of mortar was changed.

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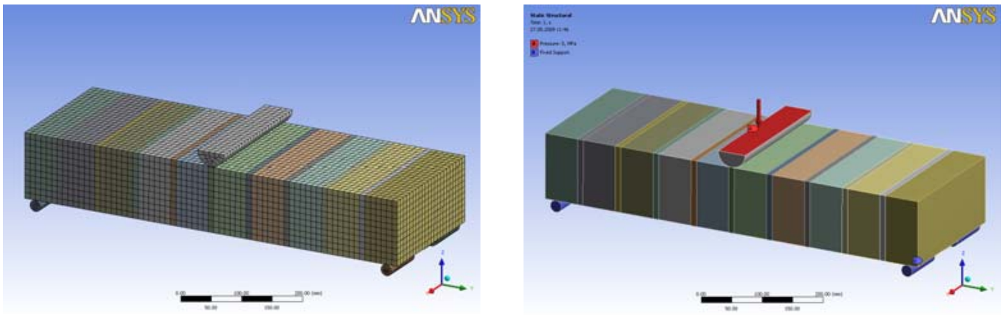
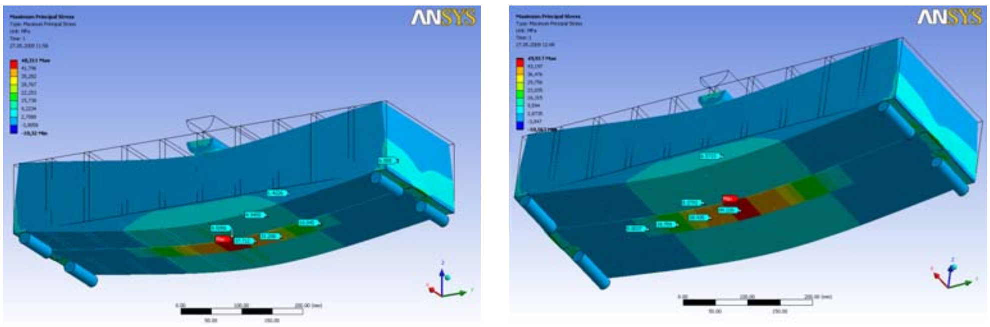


(a) (b)

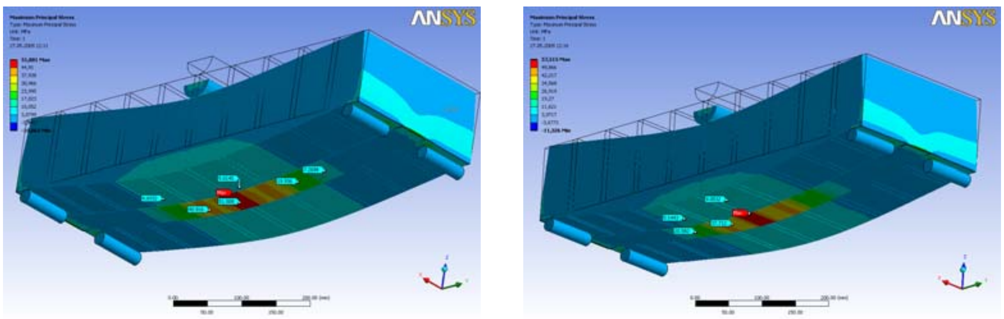
Figure 4. Structural environment analysis: a) –brick type mesh definition; b) – loading schema

3.4 Analysis results



(a) (b)

Figure 5. Maximum principal stress: a) – Mortar 1; b) –Mortar 2



(a) (b)

Figure 6. Maximum principal stress: a) – Mortar 3; b) –Mortar 5

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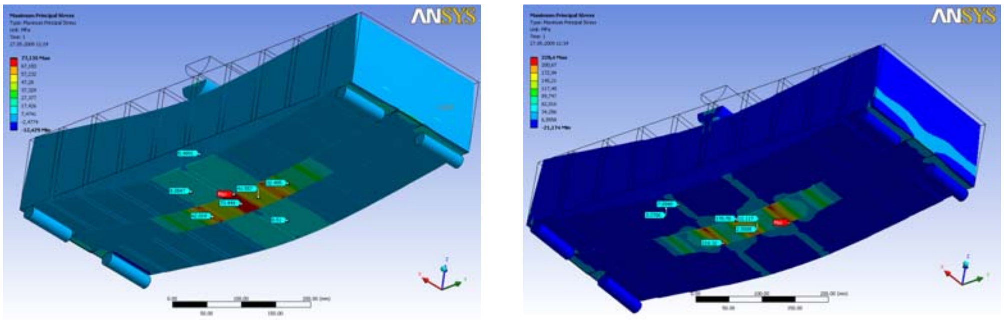
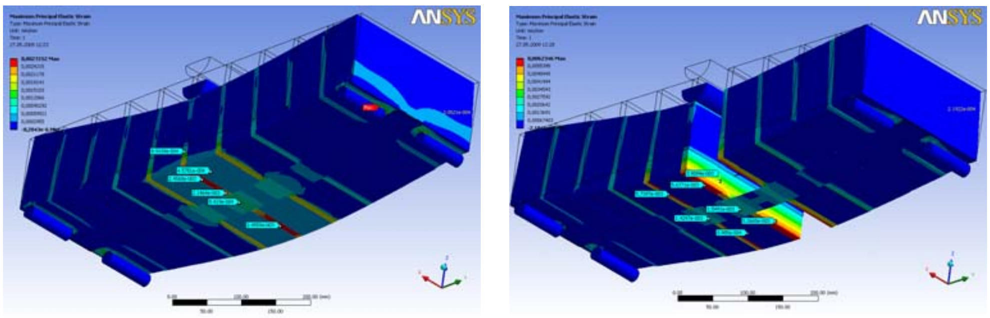


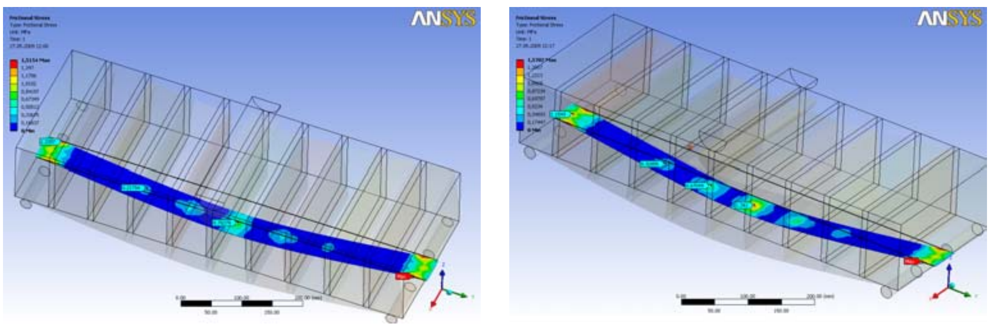
(a) (b)

Figure 7. Maximum principal stress: a) – Mortar 8; b) –Mortar 11



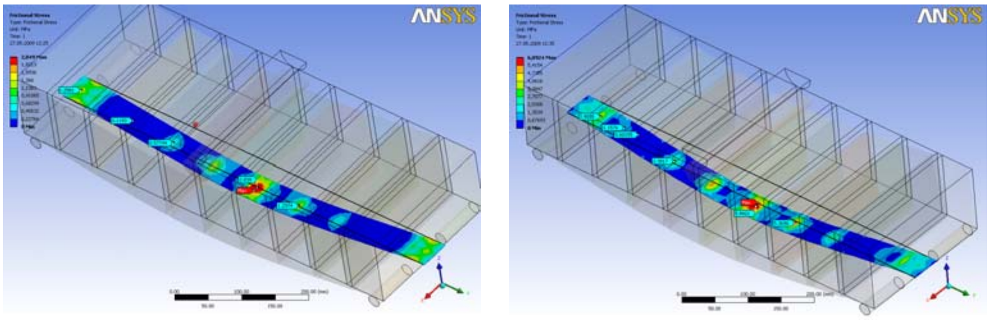
(a) (b)

Figure 8. Maximum principal elastic strain: a) – Mortar 8; b) Mortar 10



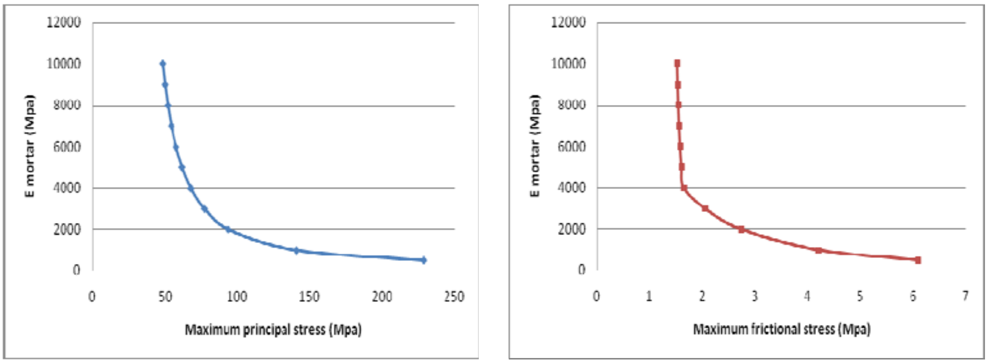
(a) (b)

Figure 9. Frictional stress on the GFRP strip side: a) – Mortar 1; b) – Mortar 5



(a) (b)

Figure 10. Frictional stress on the GFRP strip side: a) – Mortar 8; b) – Mortar 11



(a) (b)

Figure 10. Relation between stiffness and stress: a) – E modulus vs. Maximum principal stress 8; b) – E modulus vs. Maximum frictional stress

3. CONCLUSIONS

The presented results of this research are encouraging but they are only preliminary. The problem of interface (contact) between brick and mortar is very important. To have better results in a micro modelling structural analysis with FEM is necessary to introduce more conditions between elements e.g friction coefficients, shear strength, and others. It is necessary that this kind of analysis to be developed and compared with experimental programs. Another type of analysis could be done if the joint mortars are considered in model as an interface between bricks. The finite element method constitutes an efficient tool to investigate specific behaviours of FRP strengthened masonry elements.

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The modification of mortar stiffness is an acceptable approximation of real behaviour of these materials because in reality degradation of mortar is the first step in failure of masonry specimen. After mortar joints failure, tensile stresses appear in bricks so the results are damage of masonry. The composite strips has capacity to assume tensile stress if they pull together so the overall capacity of the strengthened masonry is improved. In model analysis presented the results are approaching by real behaviour of these strengthened elements.

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