A NUMERICAL STUDY OF MASONRY CRACKS PART II

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ABSTRACT

Brick walls of ceramic without any mortar covering or paint are used extensively in building façades in Spain. One of the most used masonry wall system is based on non-bearing panels partially supported, about two thirds of the brick width, over the edge beams of the structural skeleton. The edge beam is veneered with special thinner bricks to achieve the visual continuity of the façade. A considerable number of these walls show cracking. In a previous work, finite element simulations were performed in order to gain insight on the causes of cracking. A special finite element, based on the strong discontinuity analysis and the cohesive crack theory is used in the numerical simulations. The results agree with the overall cracking patterns observed but if an imposed displacement is applied in the range allowed by the standards, extensive cracking occurs. This implies that the design displacements are not the actual ones. In this work, an elastic study using the principle of superposition is used to determine the effective deflections under service loading. Then these deflections are applied to the structure and the evolution of cracking is studied. This study shows that the masonry panels of the first and last store have the major probability of cracking. Another parametric study is carried out changing the elastic and tensile properties of the masonry. This study shows that although the cracking of the masonry panels starts at different loads for different tensile properties, the crack patterns are similar for a given panel geometry and loading. This numerical study provides a method of design to determine the crack width for different geometries, loadings and fracture properties.

RESUMEN

Las paredes de ladrillo visto de cerámica se utilizan extensivamente en fachadas de edificios en España. Uno de los sistemas más usados de edificación se basa en los paneles apoyados parcialmente, cerca de dos tercios de la anchura del ladrillo, sobre las vigas del borde del esqueleto de la estructural. Las vigas del borde se cubren con ladrillos de tamaño especial para alcanzar la continuidad visual de la fachada. Un número considerable de estas paredes demuestra agrietamiento. En un trabajo anterior, se realizaron simulaciones con elementos finitos para estudiar los problemas de agrietamiento de las fachadas de ladrillo visto. Un elemento finito especial, basado en el análisis de la discontinuidad fuerte y la teoría de la fisura cohesiva se utiliza en las simulaciones numéricas. Los resultados coinciden en general con los patrones de agrietamiento observados, pero si se aplica un desplazamiento impuesto con los valores máximos que permiten las normas, aparecen muchas grietas. Esto implica que los desplazamientos de calculo no son los reales. En este trabajo, se utiliza un estudio elástico basado en el principio de la superposición para determinar las flechas eficaces bajo la carga máxima de servicio. Luego, estas flechas se aplican a las vigas de cada panel por separado y se estudia la evolución del agrietamiento. Este estudio demuestra que los paneles de ladrillo del primero y el ultimo pisos tienen la probabilidad mas alta de agrietarse. Se realiza otro estudio paramétrico cambiando las características elásticas y la resistencia a tracción. Este estudio demuestra que aunque el agrietamiento de los paneles comienza a distintas cargas al cambiar las características de los paneles, los patrones de agrietamiento son similares para una geometría y tipo de carga dados. Este estudio numérico proporciona un método de diseño para controlar la anchura de la grieta para las diversas geometrías, cargas y características de fractura.

KEY WORDS: Durability, Finite Element, Masonry, Cohesive crack.

1. INTRODUCTION

In the last decades, the price of residential flats raised considerably in Spain. One of the consequences was the reduction of the time employed in the building process. One of the most used construction systems for residential buildings is based on a skeleton of reinforced concrete or steel columns with reinforced concrete uni or bidirectional slabs. Masonry walls are used as partitions and the façade is usually constructed partially

supported, about two thirds of the brick width, over the end beams. The good quality and appearance of the ceramic masonry unit used lead to intensive use of this type of exterior walls without mortar cover or paint.
There are no Spanish standards for this construction system. Usually the standards NBE_FL90 [1], NTE-FFL [2] and NTE EFL [3] are used. The first gives instructions about the properties of the mortar and masonry units used in bearing walls and the last two standards provide rules for the structural design of bearing walls. A considerable number of these buildings show cracking in different zones of the façade walls. As a result of the lack of standards, every construction company uses its own experience to prescribe the necessary recommendations to minimize the width and extension of the cracks. There are many possible load patterns that can cause such cracks. The authors developed a special finite element, based on the strong discontinuity approach and the cohesive crack theory, that is very effective in the numerical simulation of cracking in quasi brittle materials such as concrete and masonry. The authors applied such element to the analysis of the cracks appearing in the foregoing masonry walls in order to have a better understanding of the cracking phenomena. Detailed notices about this element can be found in [4, 5, 6]. In previous work [7, 8], the steps taken to incorporate this element in a finite element program and test its efficiency to detect cracked zones was explained. But one of the conclusions of that study was that the deflections allowed by standards, seem to be design values rather than the real or average ones. The program is applied to a typical structure loaded with service imposed deformations to gain a better understanding of the cracking phenomena and to device a method that can be used in the design of this type of façades.

2. STRATEGY OF THE WORK

To study the cracking process of a typical structure, it is essential to determine the maximum real expected displacement it can undergo. So, firstly, an elastic study using the principle of superposition is used to determine the effective beam deflections under service loading. It is shown that the study of seven patterns of loading are required to determine the effective deflections of the structure beams according to the sequence used in the construction. Then these calculated deflections are applied to separate typical panels to study the cracking process. Lastly, a parametrical study applied to the critical panel is done changing the modulus of elasticity and the tensile strength of the masonry wall.

3. CALCULATING REAL DEFLECTIONS

3.1 Procedure of the work.

As mentioned before, an elastic study using the principle of superposition is used. To do this, a series of data have to be assumed for the geometry of the building, the service loads and the sequence of construction. A typical building of four stories is studied. A vertical expansion joint in the masonry wall every two panels is supposed to exist. One common masonry panel geometry, selected by a consulting office for a large number of construction companies in Spain, is used. Figure 1 shows the geometrical details of the studied building while figure 2 shows the loading cases needed for the elastic calculation. A life load of 200kg/m^2, slab own weight of 250kg/m^2 and flooring cover load of 150 kg/m^2 are assumed. Also the weight of the masonry panel is taken as 300 kg/m^2. Room's dimensions are taken as 5.00 X 5.40 meters. The sequence of construction is supposed as follows:

a) constructing all the concrete skeleton,
b) constructing all the masonry panels starting from downstairs floors
c) terminate the finishing process starting from downstairs
d) finally a creep factor of two, that can increase the displacements with time, is supposed.

The column's dimensions are taken as 400 × 400 mm for the ground and first floor. For other floors, dimensions of 300 × 300 mm are supposed.

3.2 Calculation Results

Figure 3 shows the real displacements of the beams in every floor and the shortening of columns supposing that there is no masonry panel in the ground floor. Three groups of curves for each floor can be noticed in this figure; the first group (full line) represents the total displacements of the beams, the second (dashed line) represents the total effective displacements of the beams and the third (doted line) represents the effective deflections. The total instantaneous displacements of the beam are calculated after applying all the expected loads. Factor of two is applied to include the creep effect. The effective displacements of the beams are calculated as the total ones minus the displacement produced till the construction of each masonry panel. The effective deflections are calculated as the total effective ones minus the shortening of the columns.

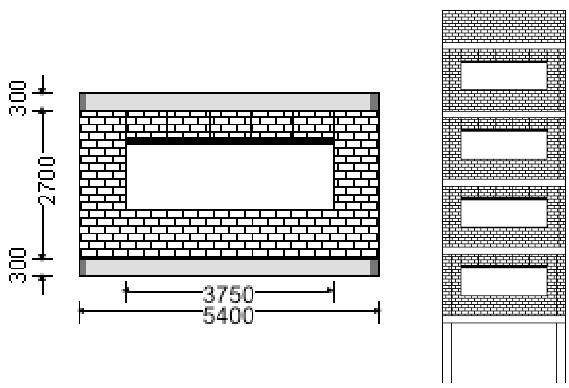

Figure 1: Panel and structure geometries. (all dimensions are in mm.)

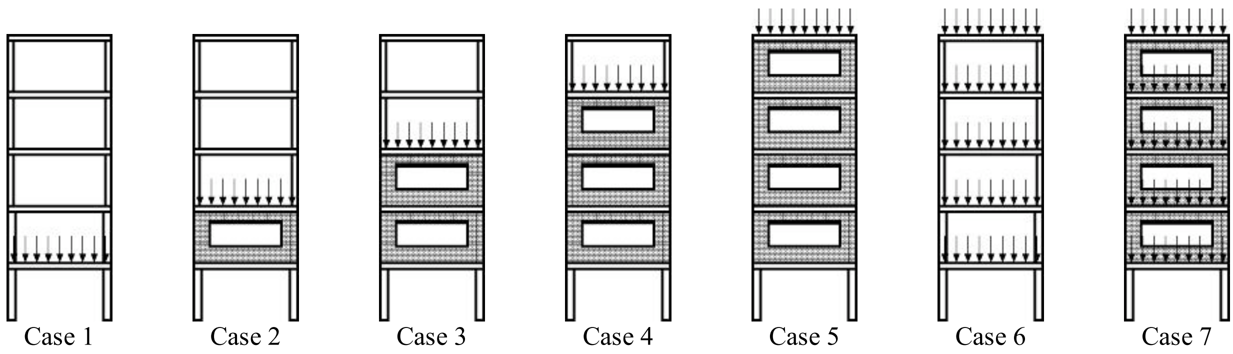

Figure 2: Loading cases required for the calculations.

3.3 Discussion

From this part of the work, it can be noticed that the maximum total displacement occurs in the last floor because it is affected by the column's shortening in all floors while the total maximum deflection occurs in the first floor and dose not exceed 2.4 mm. The maximum shortening of columns occurs in the first floor also with a value of about 1.1 mm. This large value of shortening is of the same order as the beams deflection. The maximum effective deflection, which controls the cracking, occurs in the first floor, with a value less than 1.5 mm.

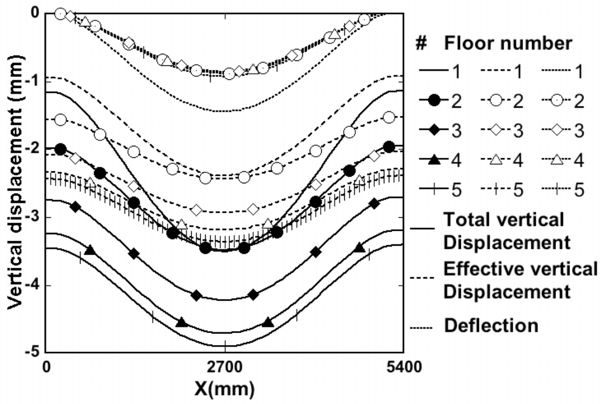

Figure 3: Total and effective displacements and deflections for the beams in all floors.

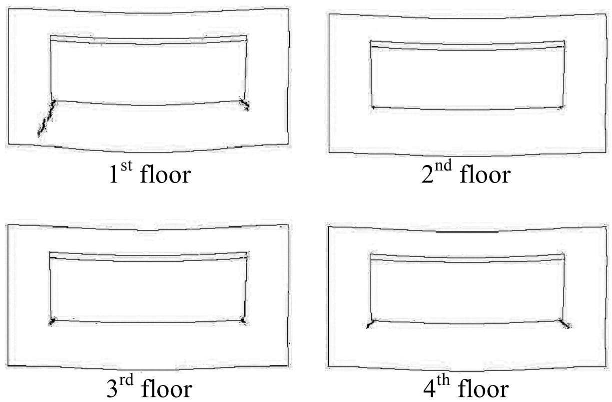

Figure 4: Crack patterns in all floors of the building under service loads.

4. STUDING THE CRACKING PHENOMENON

4.1 Procedure of the study

After calculating the effective displacements with the forgoing elastic study, these displacements are applied separately to each panel and a nonlinear calculation is carried out to study the cracking process. Since a vertical expansion joint in the masonry wall every two panels are assumed, only one panel is analysed applying the imposed displacement calculated in section 3.

There are large number of analytical papers [9,10,11] use the homogenization technique to give relations between the strength of the masonry unit and mortar with the overall strength of the wall. The same concept was investigated experimentally [12,13] for concrete blocks. As the masonry wall is a non-homogeneous material, several works investigate the strength of the masonry wall at varying directions with the bed joint [14]. From all mentioned papers, it can be concluded that an equivalent homogeneous material can be used for masonry walls. The equivalent strength depends on the strength of the unit and mortar as well as on the direction of the loading with respect to the bed joint where the strength changes by about 20 % [14]. So, as a first approximation, homogenous isotropic material is assumed for the masonry wall with modulus of elasticity of 3 GPa, fracture energy of 100 N/m and tensile strength of 1.0 MPa.

4.2 Results

Figure 4 shows the crack patterns for each floor after exposing the structure to the maximum service loads. As it can be noted from the figure, the cracks occur in the same position in all the floors (in the window corners). The first floor suffers the largest cracks followed by the last floor. The intermediate floors hardly suffer cracks.

5. THE PARAMETRIC STUDY

5.1 Studied cases

As shown in section 4, the first floor is the floor that suffers the maximum cracking, so in the parametric study this floor is considered. Various values of the modulus of elasticity and tensile strength are used to study the effect of using different mortars and masonry unit qualities in the cracking phenomenon. Although there is much information about these values in the literature, their values span a large range. On the other hand, there is a lack of information about the overall fracture properties. In two Spanish investigation [15, 16] using different masonry units, the modulus of elasticity for the wall E ranged from 22 to 38 GPa, the tensile strength f_t from 1.5 to 5.8 MPa and the fracture energy G_F from 45 to 75 N/m. it is necessary to emphasize that both researches used small masonry units cut from the original ones. As the material properties are affected considerably by the type of masonry unit, the mortar quality and the method of construction and since our object in this part is studying the effect of changing the properties (not studying the crack pattern for special values), estimated values are used for the characteristics. In this study, three values for the modulus of elasticity are considered as well as for the tensile strength. The value of the fracture energy was kept constant. Table 1 shows the combination of properties that have been considered.

Table 1: The tensile strength and modulus of elasticity values for all studied cases.

		E (GPa)		
		2	**3**	**4**
f_t (MPa)	**0.5**	Case 1	Case 2	Case 3
	1.0	Case 4	Case 5	Case 6
	1.5	Case 7	Case 8	Case 9

5.2 Results

Figures 5 and 6 show the crack patterns for all the nine cases for two different displacements. It can be noticed that there are some cases for which the patterns of cracks are almost the same. The value of (1000 f_t/E) is calculated for each case and it is found that the cases with the same value show almost the same crack pattern. It may also be noted that cracks at the bottom corners of the window always occur, and that for some cases (top row), a horizontal bottom crack also occurs and becomes dominant as shown next.

It can be shown from dimensional analysis and cohesive crack properties that the maximum crack width for a given displacement level must follow an equation of the form:

$$w_{max} = G_F/f_t \, \Phi(u\, f_t/G_F,\ h/\ell_{ch},\ h/\ell)$$

Where $\ell_{ch} = E\, G_F/f_t^2$, u is the (imposed) displacement at the centre of the beam and h and ℓ are the panel height and length respectively.

In Figure 7 the evolution of the maximum crack width at each deflection step is plotted as a curve of ($w_{max}f_t/G_F$) versus (uf_t/G_F) for each value of h/ℓ_{ch} corresponding to the cases defined in Table 1.

Two families of curves are clearly visible. The first family has been drawn with open symbols in Figure 7; it correspond to cases with values of $h/\ell_{ch} > 6$ for which the dominant crack is always the crack at one of the bottom window corners. For this family, it is shown that the crack initiation (first point close to abscissa zero) depends on h/ℓ_{ch}, but then the crack width grows rapidly with increasing u and approaches a proportionality line (dash-dot line) for which, roughly, $w_{max} \approx 0.53u$.

The second family, which has been drawn with full symbols in Figure 7, corresponds to cases with values of $h/\ell_{ch} < 4$. In this case, the initially dominant crack is, as for the previous family, one at the bottom window corner. However, at a certain deflection, the horizontal crack at the bottom of the panel suddenly opens and becomes dominant; this is seen as a jump in the curves in Figure 7. After the horizontal bottom crack becomes dominant, the maximum crack opening becomes again roughly proportional to the central deflection of the beam, with $w_{max} \approx 0.8u$.

5.1 Design method for the crack width control

The procedure used in this research can be used as a calculation method to control the crack width depending on the geometry of the structure, the expected maximum deflection and the qualities of the mortar and masonry panel units used.
The method can be summarized in the following steps:

a. Given the geometry of the structure and the construction method, carry out an elastic study (as one in section 3) to determine the maximum effective displacement (central deflection) of the beams.
b. Carry out a parametric study analogous to that in Section 5.
c. Plot the results in a graph similar to that in Figure 7 and select the best combination of material parameters to keep the crack opening within the requested limits.

6. CONCLUSIONS:

From the foregoing results, the following conclusions can be drawn:

a. Beam deflections allowed by standards are upper-bound design values, much larger than actual (average) deflections.
b. Shortening of columns are of the same order as the beam deflections under service loads.
c. When there is no masonry panel in the ground floor, panels of the first and last floors suffer the maximum cracking under vertical loads.
d. The maximum real deflection of beams is in the order of 1.9 mm while the maximum effective one, which controls the cracking of the masonry panels, is in the order of 1.3 mm (about span/3800).

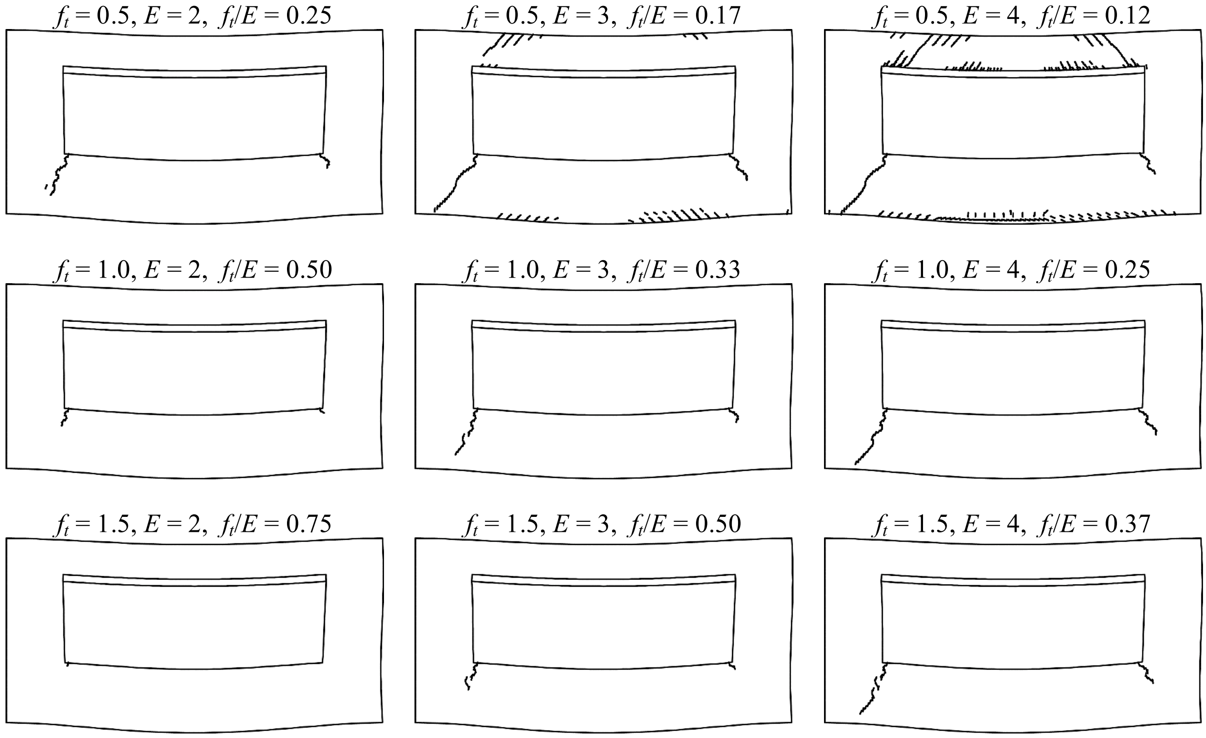

Figure 5: Crack patterns for all the nine cases for an applied imposed vertical displacement equal to the excepted one under service loads, equal to1.45 mm. (f_t in MPa and E in GPa)

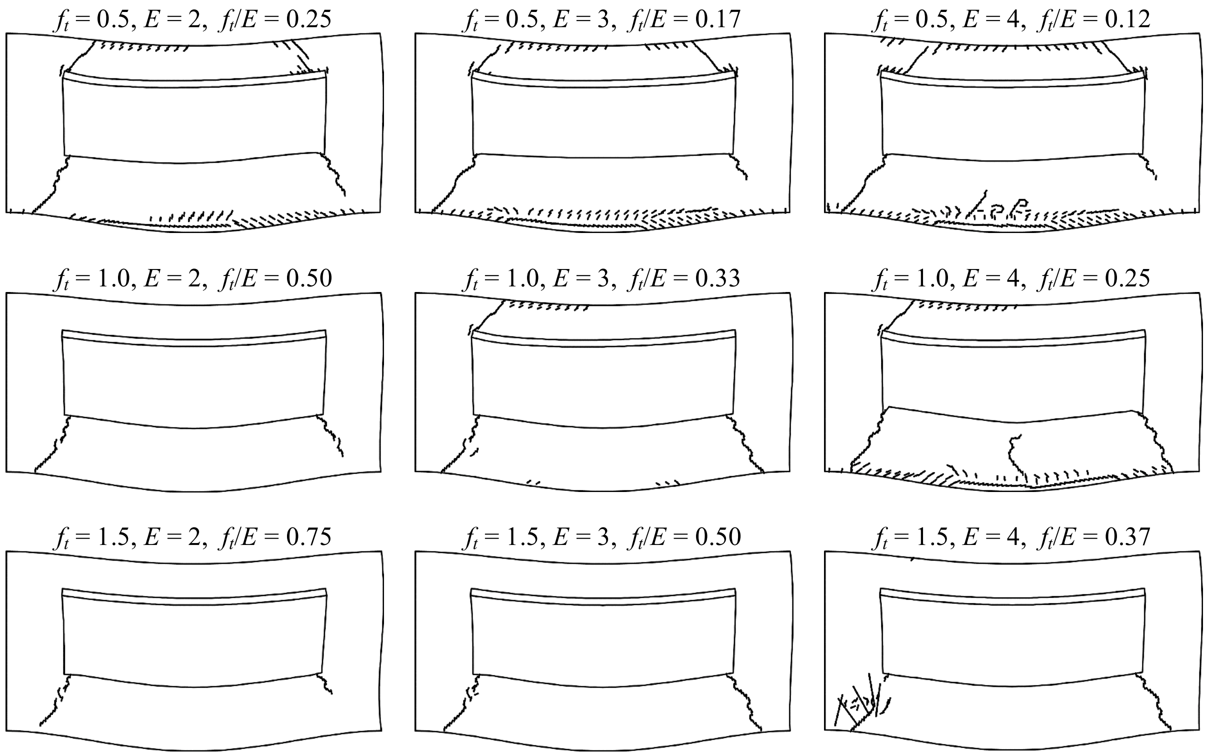

Figure 6: Crack patterns for all the nine cases for an applied imposed vertical displacement equal to the double of the excepted one under service loads, equal to 2.90 mm. (f_t in MPa and E in GPa)

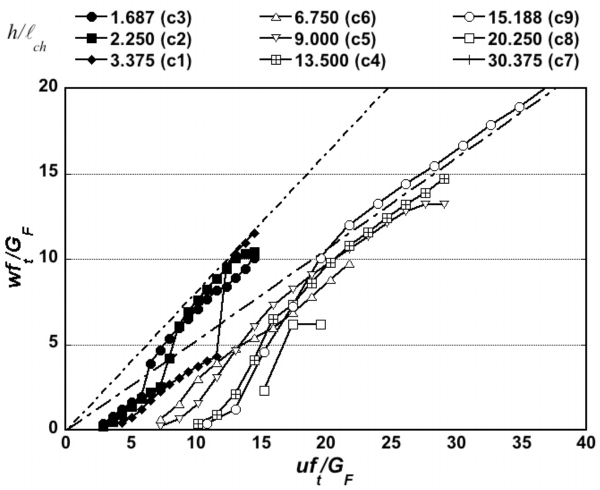

Figure 7: Relation between the maximum crack width w and the maximum imposed displacement u

e. Although all the numerical study was done in 2D, i.e. for panels with total support over end beams, it can detect correctly the main zones of cracking.
f. For the geometry under study, the parametric study shows that two kinds of overall behaviour can be found: one for larger values of h/ℓ_{ch} for which the dominant crack is always one at a bottom corner of the window, an another for smaller values of h/ℓ_{ch} for which the horizontal bottom crack forms and becomes dominant after a certain threshold displacement.
g. The methodology used in the present investigation can be used as a numerical design method for the crack width of masonry panels.

ACKNOWLEDGMENTS

The authors gratefully acknowledge partial financial support for this work form GOP Project Consulting (Spain). The present work was conducted within the framework provided by the projects DUMEINPA (S-0505/MAT-155), sponsored by the Comunidad de Madrid, Spain, and SEDUREC (CSD2006-60), integrated in the Spanish National Research Program CONSOLIDER-INGENIO 2010.

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