Design guideline for brick enclosures with continuous air chamber

0. Abstract

Brick façades enclosures traditionally used in residential architecture in Spain generates stability, insulation and waterproofing problems. Self-supporting enclosures with continuous air chamber solves these problems. The aim of this study is to analyze the mechanical behavior of ventilated enclosure to define design guidelines.

The study of a standard three-storey façade using finite element method shows the efforts, displacements and cracking. The areas subject to greater efforts are located on the top floor wall, concentrated around the openings and close to connection keys.

Constructive solutions are proposed to build this enclosure from the foundation to the top of the building. We achieve to solve the requirement of stability, incorporating steel reinforcement in the horizontal mortar joints in cracked areas, as well as insulation and waterproofing.

1. Introduction

Nowadays, ceramic brickwork is used to solve building enclosures and interior divisions, while they are rarely used as the structure of the building. The common brickwork façade is the evolution of the load bearing wall used in traditional architecture. Its aim is to use a skeleton structure, in order to release the enclosure from the structural function [1]. As a result, we have the current façade, which exterior sheet is formed by a face brick sheet that leans on the slab, an air chamber acts as a capillary breaker and as a drain canal [2], a thermal insulation, and an interior brickwork sheet. To solve the continuity of the exterior face brick sheet, the slab front is covered with thinner ceramic pieces.

This kind of façade has shown a high amount of problems. The cause of all these problems are factors related with the shape and the brick adjustments, temperature gradient, and humidity variation [3]. These causes generate a stability problem due to the support of the exterior sheet on the slab. As seen in Fig. 1 this support is supposed to be at least 2/3 the sheet thick. In practice, this restriction is hard to be achieved in a construction site, where in occasions the support width is not enough.

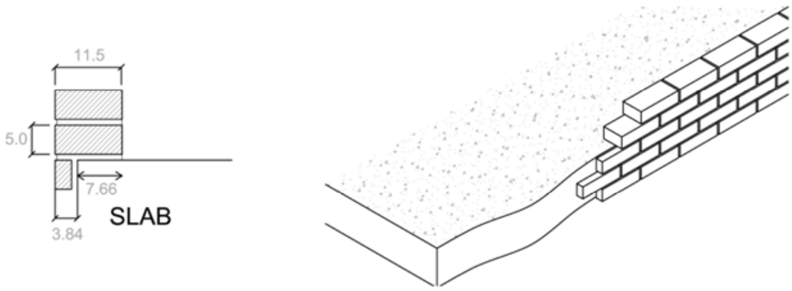

Fig. 1. Support of the exterior sheet

Another problem is the insulation; it becomes a problem because of the difficulty of placing it over the slab edges. The width of the brick support is 2/3 the thick of the sheet, therefore there are 4 cm left to place the insulation and the ceramic covering. There are several alternatives to solve the problem, as using metallic sections to increase this distance without any detriment to the sheet stability. However, by using this solution it becomes difficult to make compatible the deformations on the whole.

Owing to the fact that it has a non-structural character, this kind of enclosures have been built following the instinct and experience of the designer, without any structural stability analysis, as done with the framework. Since the Spanish *Código Técnico de la Edificación* came into effect, between many other aspects, it is mandatory to justify the structural stability of the enclosure [4]. This façade transmits the vertical loads of its dead weight to the slab where it stands on. Horizontal stresses are transmitted to the building structure (columns and slabs) through an arch effect or a slab behavior [4].

For the purpose of solving the traditional facade brickwork problems, it was imported the use of it with a continuous air chamber, which had been largely used in other countries. This kind of enclosure in Spain is formed by an exterior self-supported sheet, a continuous and ventilate air chamber, a thermal insulation, and an internal sheet. There can't be any rigid connections between the exterior sheet and the framework, and must be built with the required joints to permit a free deformation and avoid cracking. The enclosure has to be designed to ensure a continuous exterior sheet beyond the framework. On this case, it's necessary to compose an enclosure with two different sheets separated by an air chamber. As seen in Fig. 2, this enclosure transmits the vertical loads directly to the foundations, and transmits the horizontal loads caused by the wind through the metallic anchorages to the building structure. As the vertical loads increase, the stability against horizontal loads of the enclosure does so [5].

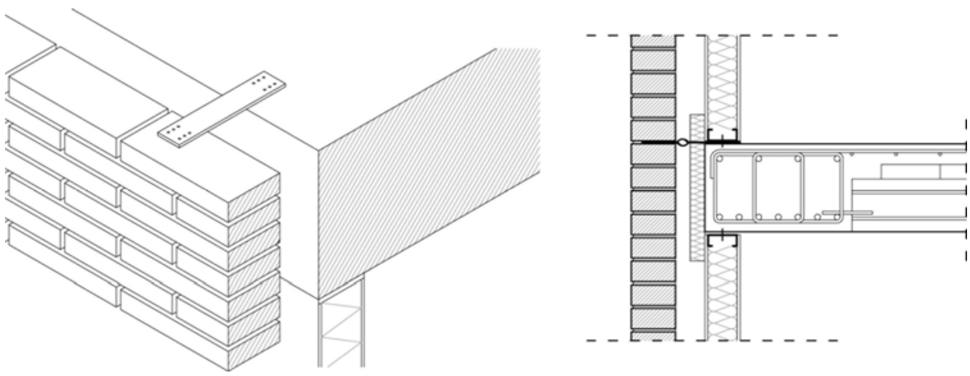

Fig. 2. Enclosure with continuous air chamber

The connection keys are placed along the slab edges, forming horizontal lines, and over the façade columns, forming vertical lines. The separation between vertical keys would be of 40cm and the separation between horizontal keys would be of 60cm [6]. The loads applied to the enclosure are its dead weight and the wind pushing. The dead weight is transmitted to each slab and the wind loads are transmitted to the slabs and columns that surround the enclosure, under these conditions, the stability analysis is carried out as a slab behavior [5]. The determinant mechanical features of the brickwork are its low bending strength and its high stiffness [7]. These features, along with a high flexibility of the slabs, frequently lead to the formation of cracks owing to the bending and shear failure.

2. Facade stability: definitions and parameters

The non-bearing enclosure has to satisfy the mechanical requirements, being the most important the stability [8]. Stability requirement is satisfied if the equilibrium can be found between actions and reactions. As seen in Fig. 3 the loads the enclosure has to stand are its deadweight and the horizontal loads due to wind action.

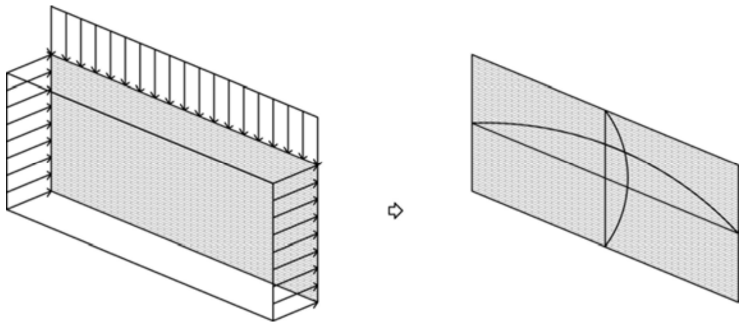

Fig. 3. Actions on the enclosure

The conventional façade is built confined by the framework of the building. In this situation, its stability against horizontal actions is checked trough the flexion behaviour of the wall, or as an arch that rests on the both sides [4]. The horizontal support of the exterior sheet is usually 2/3 its total width. This way the resultant of all the vertical loads leans on the slab.

The enclosure with continuous air chamber is also a non-bearing enclosure. In this case, the dead weight is transmitted directly to foundations and the horizontal loads are transmitted to the framework of the building through several keys. Against the wind pressure, the keys are compressed, so they should be stiff enough [9]. When the wind suctions, then the anchorages will be tensioned.

On the highest floors, the enclosure is lightly loaded, and it’s simply bended. As we get closer to the bottom border of the façade, the dead weight of the enclosure increases, leading to a bidirectional bending behaviour. The effect of the dead weight improves the bending strength of the wall [8] [9]. Assimilating the behaviour of the façade as a slab, the effect of the dead weight makes the enclosure to behave as a compressed beam, so as the compressed area increases while the tensioned area is reduced. This way, the cracking area is reduced as well (Fig. 4). Nevertheless, the effect of the dead weight, owing to the self-bearing characteristic, can lead to a section failure if there are too many floors. This facade typology is used for less than 14m high.

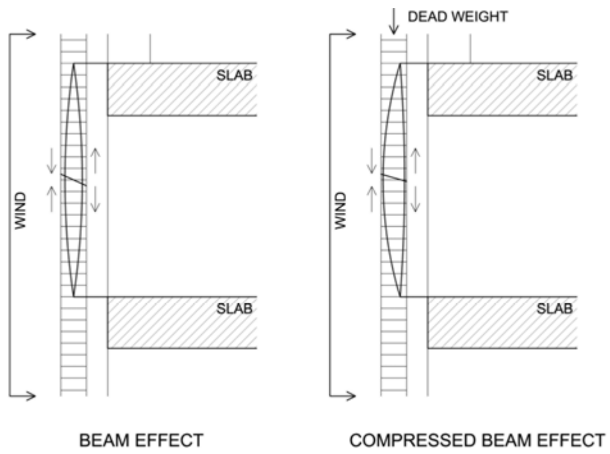

Fig. 4. Dead weight effect

In order to carry out a finite element analysis, enclosures would be included in the structural typology of slabs, as it cannot be modelled as an arch [9]. The bottom border of the façade is considered as perfectly built-in as rotation is not possible. Connection keys are considered as points in the enclosure where the movements are restricted in the perpendicular direction. The keys that join the exterior sheet of the enclosure to the building framework, are sited horizontally over the slab edge every 60cm, and vertically over the façade columns every 40cm.

3. Experimental

The aim of de experimental part is to model an usual geometry for a enclosure with continuous air chamber, to find the most stressed zones and to propose a constructive answer to them.

The façade to study corresponds to three floors standard building with usual dimensions of floor height, distance between pillars and opening sizes.

The modeled façade constructively consists of a face perforated brick exterior sheet, a ventilated and continuous air chamber, air tight insulation layer and inner leaf constructed with plasterboard panels fixed to a metal substructure (Fig. 5). The outer sheet rests on the top border of the fundation and is anchored to the building structure by keys.

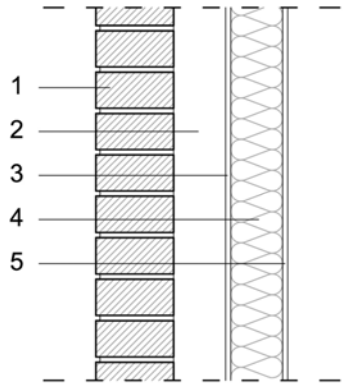

Fig. 5. Composition of the studied façade, vertical section: (1) face brick; (2) ventilated air chamber; (3) waterproof panel; (4) insulation layer; (5) plasterboard

Behavior analysis for the proposed enclosure is made using the Finite Element Method. The calculation software used to get the loads, movements and cracking of the façade has been the ANSYS. This calculation software uses the Finite Element Method which takes into account all types of non-linearities, plastification and failure. We will use an element type, called Solid65, which is capable of cracking in tension and crushing in compression. We have to calibrate the material to encompass all materials forming the brickwork (ceramic and mortar). The starting hypothesis for finite elemen modeling are:

3.1. Brick masonry features

The masonry consists on perforated ceramic brick and cement mortar with a resistance of 5 N/mm^2. The data that define the behavior of the brick leaf to study are taken in part from the study by professor Brencich and de Felice[10], and the study carried out by professor Dilrukshi, Dias and Rajapakse [11]:

- Density: 18 KN/m3
- Elastic Modulus: EX: 2GPa
- Poisson’s Ratio: 0,2
- Shear transfer coefficient in open crack: 0,25
- Shear transfer coefficient in close crack: 0,6
- Uniaxial Tensile Strength: 0,3 MPa

3.2. Wind load.

The horizontal loads to be carried are wind loads. Wind speed in Valencia has a maximum peak of 54 Km/h (15,0 m/s), values from 2010-2011 (Fig.6) [12]. The wind pressure, according to CTE-DB-AE [4] implies to the climate zone where is located the city of Valencia a wind speed of 26 m /s, which is higher than those provided by the State Meteorological Agency.

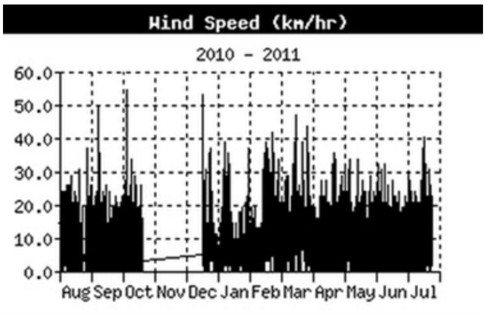

Fig. 6. Wind speed during 2010-2011 period in Valencia (Spain)

So the wind pressure will be: qe = qb ce · cp values being taken:

- Dynamic wind pressure q_b: 0,5 kN/m2
- Coefficient of exposure c_e: 2
- Wind or pressure coefficient c_p: 0,8 / -0,5

So we will have a characteristic action of the wind in pressure 0,8 kN/m^2 and -0,5 kN/m^2 in suction.

We have to check the pressure and suction keys, but as the suction is less, if it satisfies pressure, it satisfies suction. Furthermore, due to the pressure can appear the buckling, which does not happen when the key is tensioned into the suction.

3.3. Modelling

Brickwork is a composite formed of bricks and mortar. It can be modelled in different approach levels. In Fig. 7 it can be seen the different types of models.

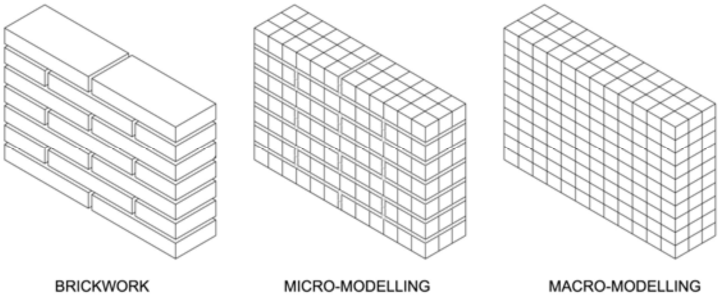

Fig. 7. Types of modeling

The first level is the macro-model. Bricks, mortar and the interface bricks-mortar are enclosed in an homogeneous element.

A more detailed level is the micro-model. Bricks, mortar and the interface between them are modelled as independent elements. We can distinguish between two kinds of micro-modelling. The first one is the detailed micro-model, where bricks and mortar are continuous elements and the interface is represented by non-continuous elements. The second one is the simplified micro-model, where materials are represented by a continuous element, and the behaviour of the mortar joints and the interface brick-mortar is separated by discontinuities [13].

Micro-modelling is suitable to simulate the behaviour of detailed or small parts of the brickwork, as brickwork supports, openings or lintels. It is required a large analysis task and it is difficult to establish a model. Macro-modelling, a general continuous model, is suitable to study the brickwork compound [14] [15].

Taking into account the features of each kind of model, the present document adopts the macro-model. Macro-modelling is the solution that fits between precision and efficiency [13].

3.4. Model calibration

Before putting into practice the macro-model for the studied enclosure, we compare cracking results of a real building with modelled one with the Finite Element Method, used in this research. This way, the composite model will be calibrated.

The building used as comparison model is sited in Spain, in the city of Valencia. It is a building with a reinforced concrete framework and a brickwork façade, composed by an exterior 11cm hollow brick sheet, non-ventilated air chamber, and an interior 7cm brick sheet. On the south facade of the building some cracks were found, as seen in Fig. 8. These cracks start from the corners of the openings, which are the weakest areas.

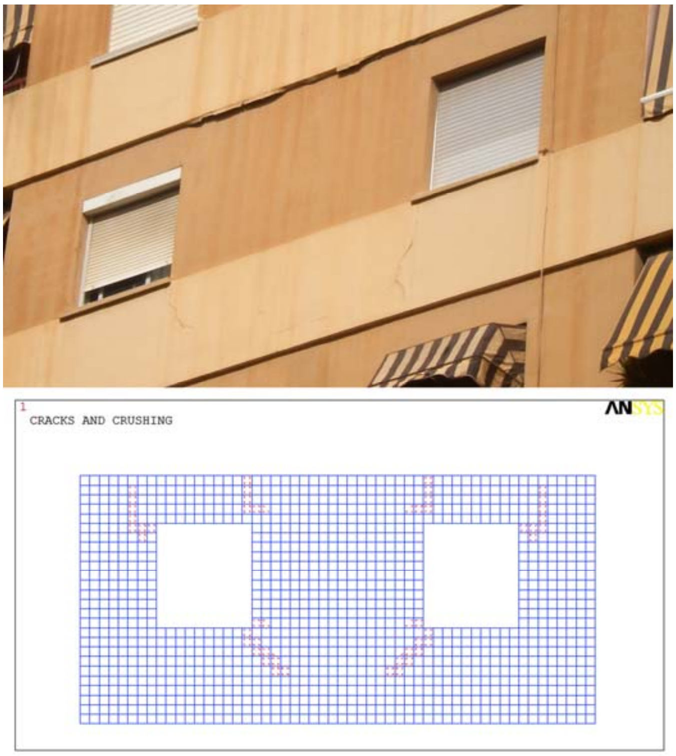

Fig. 8. Experimental and modeling cracks

Once the data was taken from geometry and materials, a finite element model was built. This model was loaded by the dead weight and horizontal loads due to the wind action. Loads increased until first cracks appeared. Cracks, as happened in real life, started on the opening corners and moved forward perpendicularly to tensioned areas. Fig. 8 shows the cracks appeared when the displacement was applied to the model. The results obtained from this model significantly matches with the results obtained from the experimental research.

3.5. Geometry

The studied geometry is a three-storey residential building with three commercial premises on the ground floor. This typology is largely used in hosing buildings in Spain. A central part of the enclosure is to be analysed, as seen in Fig. 9. This brickwork is 9,2m high, with a 2,90m vertical clearance on the ground floor and 2,50m on the rest of the floors. The distance between columns is 6m. Openings on the ground floor are sized 2,8 x 2,2m and 1,8 x 1,1m on the rest of the floors. Lintels are solved with a reinforced concrete joist. Openings size is higher than 10% of total size of the wall in order to increase the effect of it. According to the CTE-SE with this size of openings the edges are considered free edges.

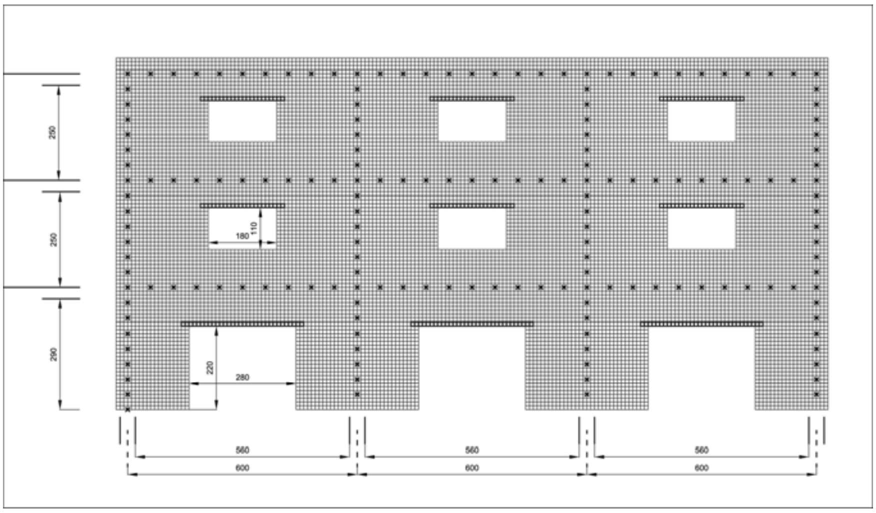

Fig. 9. Geometry

The exterior sheet of the enclosure is connected to the slabs and the façade columns through connection keys. These are sited along the slab front every 60 cm, and over the façade columns every 40 cm.

4. Results and discussion

The obtained results correspond to the wall of the central span of the proposed geometry. The enclosure has continuity on both the left and right. This section is selected because it corresponds with a standard one of a larger building.

4.1. Stress

In the analysis we obtain the stress state corresponding to the wind pressure. It is represented by contour maps graphics for stresses in Z (fracture in a plane parallel to horizontal joints) and stresses in X (fracture perpendicular to the horizontal joints).

In Fig.10 (1) are shown stresses in the Z axis corresponding to fracture plane parallel to horizontal joints. In the key areas, where the enclosure has restricted its displacement in the axis perpendicular to itself, tension stresses appear on the outer face and compression stresses on the inner. These tension stresses are the maximum on this axis, which causes cracks in this area. In the center of the walls appear compression on the outer face and tension in the interior. Stresses in the center of the wall increase considerably in the upper floor because this doesn't have a top floor that balance it and also has less vertical load of dead weight.

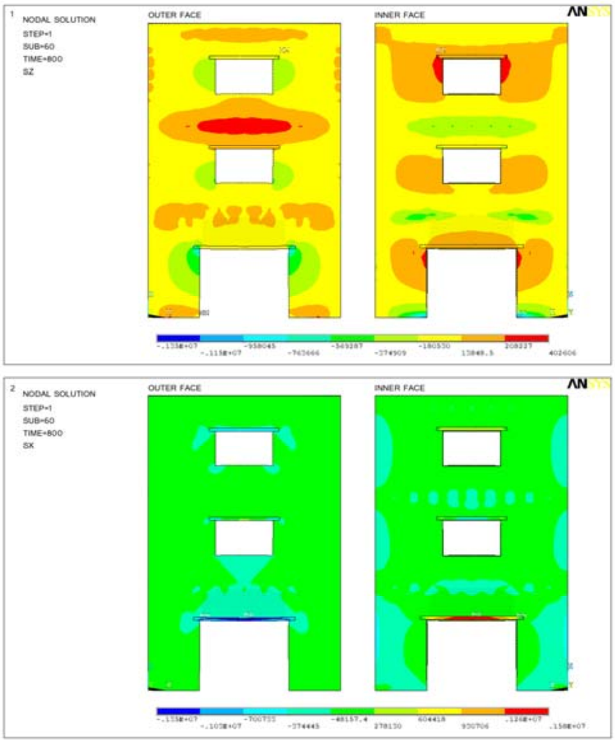

Fig. 10. Enclosure stress

In Fig.10 (2) are graphed the X-axis stresses on the outer and inner face of the brick sheet. The figure shows the bending perpendicular to horizontal joints. Tension stresses appear on the outer side in the area of keys subject to pillars and on the inner side in the center of the walls around the openings. The top wall has increased tensions both in keys and in the center of the span. The larger opening in the ground floor induces a stress concentration in the lintel.

4.2. Displacement perpendicular to the enclosure

The analysis carried out with the Finite Element Method in addition to showing the stress state of the enclosure allows us to analyze the displacements that have occurred.

Fig.11 shows the displacements in a continuous enclosure with no openings. The action of the dead weight stabilizes the enclosure making it to work better in bending. Because of this the ground floor wall is the less deformed. Also the proximity to the foundation, where the movement is restricted, makes it to deform less. The most deformated wall is in the upper floor plant, mainly due to two reasons. First, in this situation the wall doesn't have continuity in the upper side to balance the positive bending. Furthermore, this wall has the same wind load than the rest but the effect of dead weight is lower. The higher the ledge is more balanced will be the top floor deformation. The first floor wall is in an intermediate situation. This area has continuity up and down, therefore, have a lower positive deformation in the center of the span. Also the dead weight is starting to gain in size which increases the flexural strength of the wall.

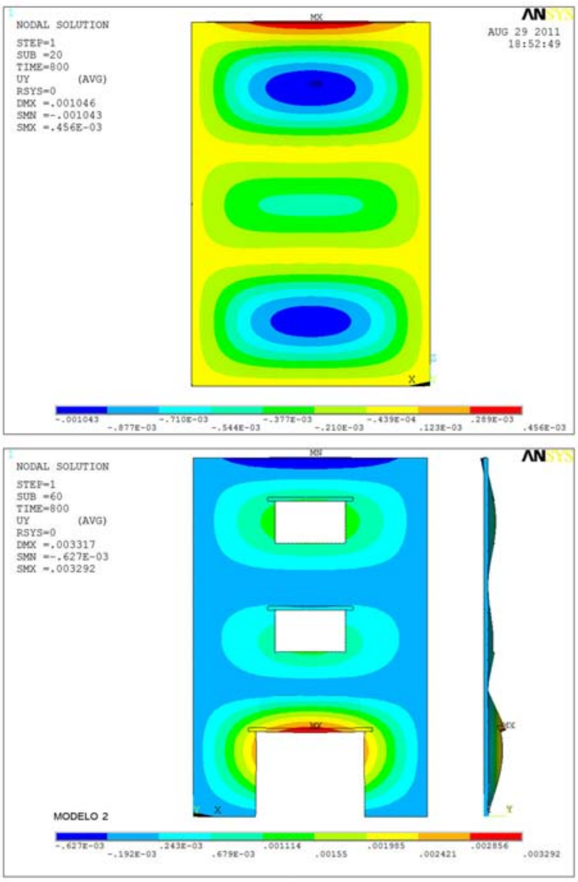

Fig. 11. Enclosure strain

The Fig.11 shows the horizontal displacements of the enclosure due to a load of 800 N, service load according to standards, in elevation and profile view.

In the studied façade the ground floor wall has a larger deformation due to the bigger opening that causes the lintel to move inland. The wall is less rigid with greater free perimeter length. To improve this situation we should reinforce with steel the lintel area.

In Fig.12 are shown the displacement of two points of the enclosure respect to the load until failure. Point A, corresponds to the midpoint of the jamb of the opening on the top floor. It is the major deformation zone that appear. The point B corresponds to the midpoint of the jamb of the opening on the first floor.

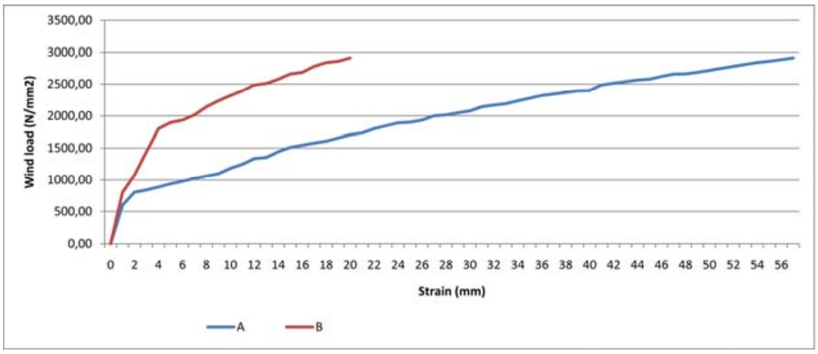

Fig. 12. Stress/strain curves

The graph shows a significant increase in displacement at Point A once the horizontal load of 650 N is exceeded. From this point small increases in load will cause further displacement, with a stable trend to failure. The cause of this increase in deformation is due to the appearance of numerous cracks in the wall that reduce the stiffness. Point B, located on the first floor, has a displacement under the point A. For standard wind load, 800 N, point A has moved 2 mm, and point B has moved 1 mm.

4.3. Cracking

Parallel to the study of stresses and strains we have made the analysis of cracking in the enclosure. Crack appears when it exceeds the tension strength of the brickwork somewhere. These cracks indicate the points where the enclosure needs a reinforcement by steel rods to absorb these tensions without cracking the masonry. The brickwork is considered in the macro-modelling as a homogeneous material. The crack, therefore, part of both the brick and mortar.

The Fig.13 shows the evolution of cracking as the perpendicular load increases on the enclosure until the failure. The first cracks appear around the connection keys with the building structure and the opening vertices in the top floor. These cracks appears for a load of 800 N, which is the characteristic wind load according to standards. With increasing wind load these first cracks grow in path. When we get a load of 1700 N, more than 200% of the characteristic load, cracks appear from openings on first floor and ground floor. All cracks are growing in number and size until the failure.

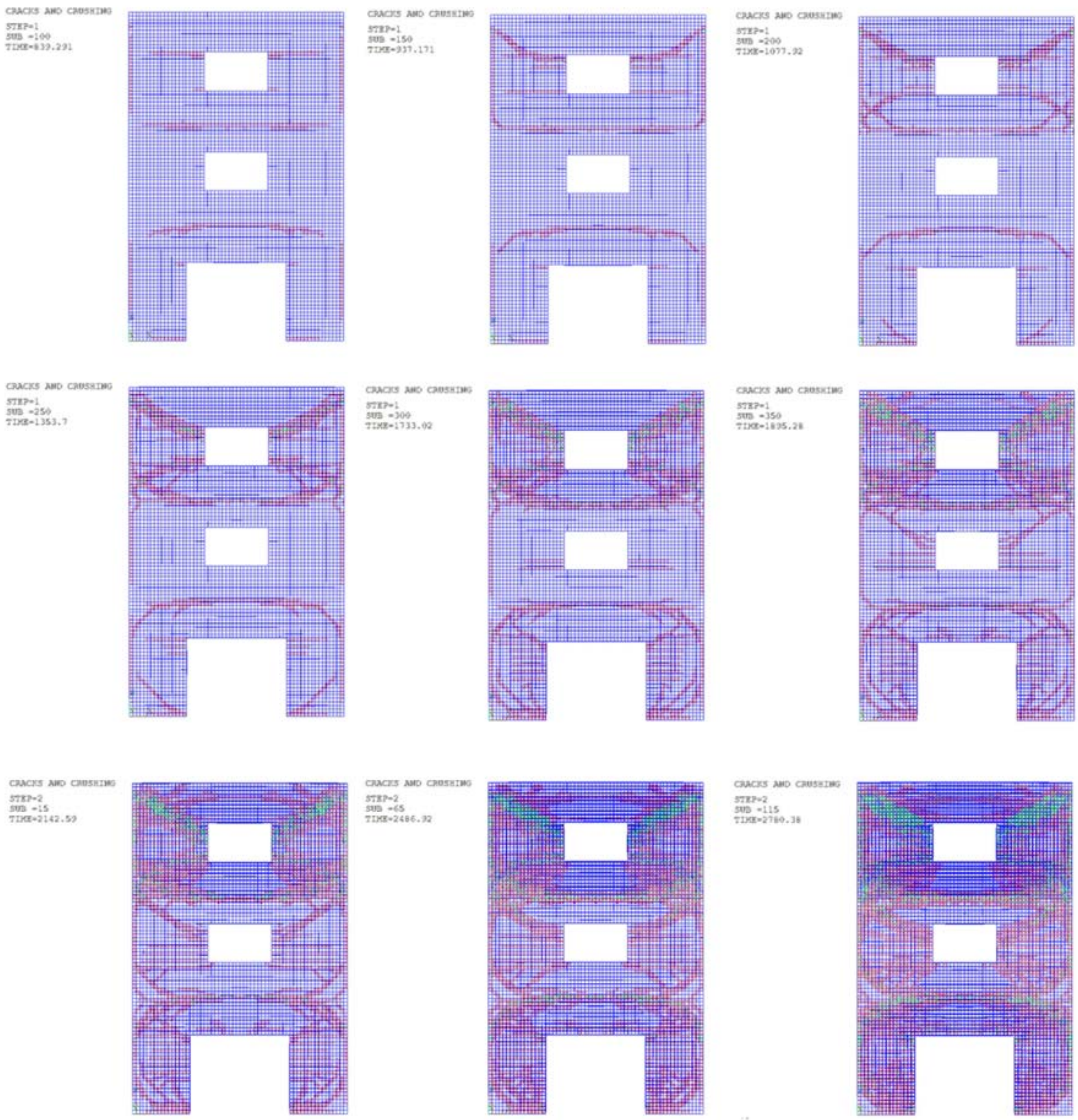

Fig. 13. Evolution of cracking

5. Design guidelines and constructive recommendations

The aim of the study is to suggest a series of design and construction recommendations of practical significance, based on the experimental results and the existing design guidelines, regarding all components of the façade from street level to the top of the building, including discontinuities such as windows or doors.

5.1. Constructive application of the analysis

In view of the results obtained by the Finite Element Method with respect to efforts, displacements and crack the authors consider to insert the steel reinforcement in the horizontal mortar joints. The Fig. 14 indicates the position of the reinforcement regarding the cracking.

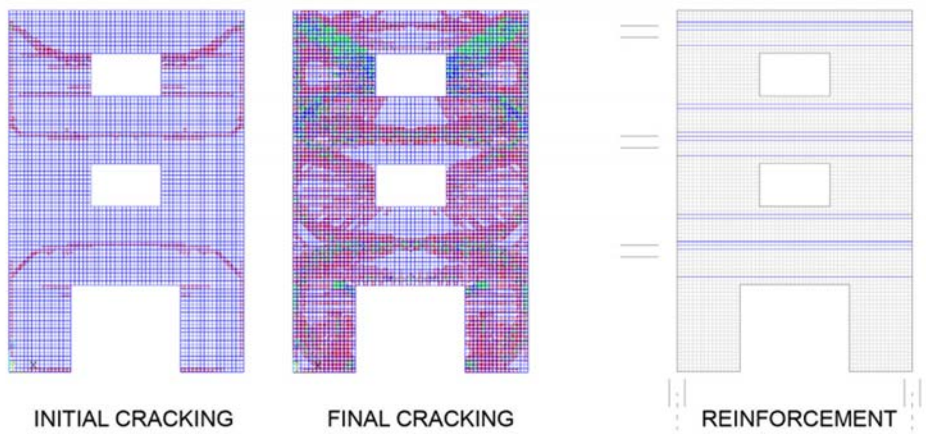

Fig. 14. Reinforcement of the enclosure

The steel rods are placed in the mortar joints. Due to thin thickness of mortar joints, reinforcement should be small diameters [16]. The proposed reinforcement consists of two steel rods 4 mm in diameter in the horizontal mortar joint. In addition to the small thickness of the mortar, the bricks absorb moisture, therefore, need to protect the reinforcement from corrosion. Protection can be done with galvanized steel, epoxy coating on zinc or stainless steel reinforcement. [17].

5.2. Building bottom

The enclosure may accomplish the requirement of stability. It also comply the conditions of waterproofing and insulation. The impermeability condition is resolved by placing a waterproof sheet on the outer layer, linked to the inner layer creating a sealing board. The waterproof membrane can be flexible or rigid, depending on their suitability for placement.

At the bottom of the façade we must place the waterproof membrane to collect the water flowing the outer sheet and we have to channel it through the chamber air, reaching the lower base and can be evacuated to the outside. In the Fig.15 A the membrane is located in the street level.

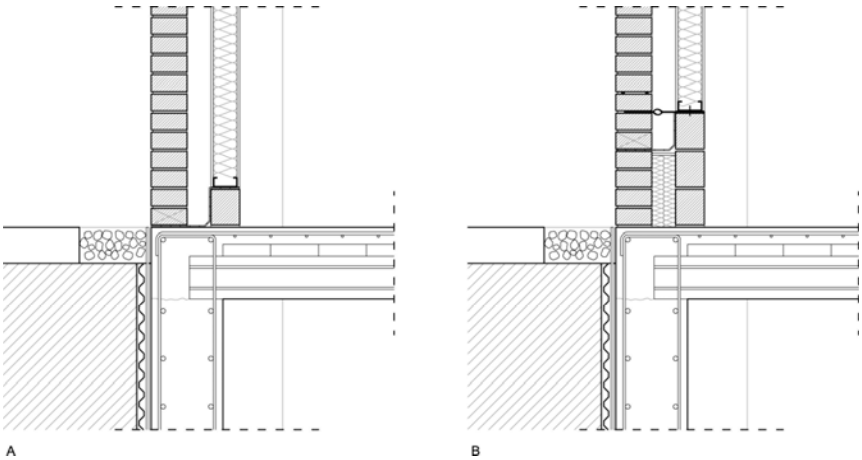

Fig. 15. Bottom border of the façade

If the waterproof membrane is placed at a height of 30 cm above the pavement, to prevent from water splashing, and the material used is a rigid waterproof, we don't ensure the transmission of loads. A line of keys from the outer to the inner sheet solves the problem. These keys are located at a distance of 40 to 60 cm and a diameter of 4 to 6 mm, to be embedded in the mortar joints (Fig. 15 B).

This line of keys, replacing the lack of continuity of brickwork due to the placement of the waterproofing, requires reinforcement in horizontal joint immediately above the disposal of the keys.

5.3. Windows

The outline of the openings are reinforced with rods as show in Fig. 16. Reinforcement must be provided on the ledgem in the order of four steel rods of 4 mm diameter. Above the lintel we also have to place this reinforcement. These areas are under tension stress.

The design recommendations are appropriate in cases where the window opening can be considered small and does not break the continuity of the brickwork. According to the Eurocode

(EC-6), in the case of small openings they are not considered, since it has little effect on the resistance of the wall.

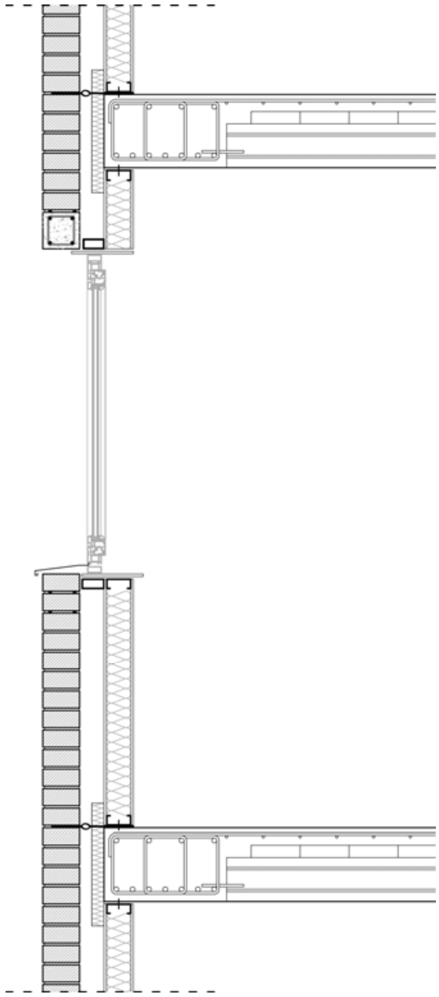

Fig. 16. Opening windows detail

The availability of wood or metal frames in the openings, the resistance of the frame with the resistance of the masonry will generally be sufficient to offset the loss of resistance by inclusion of the opening.

5.4. Top wall and building top

In the area of the ledge of the last section of the enclosure we will place reinforcement embedded in horizontal joints which will be interrupted in case of existence of openings. This ledge area is defined by a 90 cm strip above the slab (Fig.17).

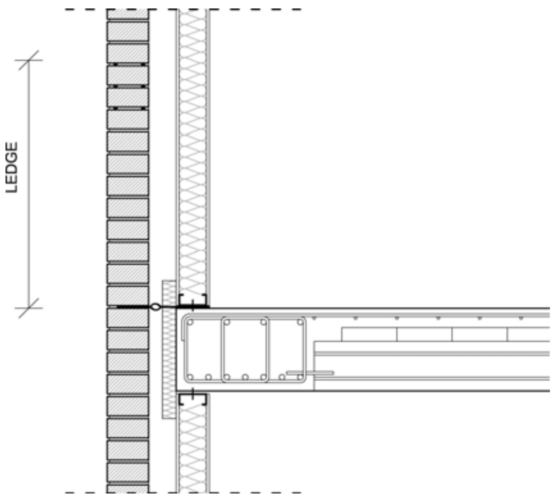

Fig. 17. Last floor wall

The part of the wall on the top floor is that is worse because it gives the least dead weight [5]. Then the design is conditioned to have a small ledge that gives continuity to the masonry and serves us to close the cover. It must have keys on slab level and at the coronation of the wall (Fig.18).

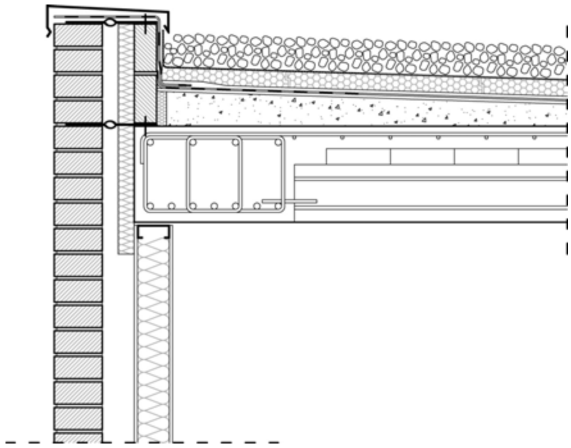

Fig. 18. Building top

6. Conclusions

The traditional way to build a brick façade in Spain, supported on the floors, has a number of problems solved with a freestanding enclosure with continuous air chamber. This system meets the requirements of stability, insulation and waterproofing required for half-height buildings.

This way of constructing the outer sheet of the enclosure leads to a different mechanical behavior of the same. After conducting an analytical study using finite elements we have obtained efforts, displacements and cracks in the brick façade.

Keys are used for connection from the building structure to the exterior sheet of the enclosure. These keys are located on the axis of the exterior pillars of the wall and slab fronts. These keys are responsible for transmitting the horizontal forces due to pressure / suction of the wind to the building structure. Under these conditions the study is done by taking the behavior of brickwork like a slab. The vertical load of dead weight improves brickwork stability assimilating their behavior to a tightened beam.

The top wall is the worst because of a lack of continuity up to balance the positive bending and also due to lower dead weight to be supported by the wall. It aims to improve the conditions of this wall by increasing the ledge and anchoring the coronation of the wall with keys to prevent movement of the free edge.

The incorporation of the openings shows a stress concentration in areas with larger holes and a significant increase in displacements. In the studied building type, with large openings in ground floor, large deformations occur at this point.

From these data we have proposed a number of constructive recommendations in terms of streamlined construction details for the actual implementation of the enclosure in order to optimize the response to wind of this type of construction.

Constructive recommendations solve the starting of the enclosure from foundations, the blind wall type, wall with holes and the top of the façade, taking into account the conditions of stability, waterproofing and insulation.

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