Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Determination of the Mechanical Characteristics of Masonry Walls of the Traditional Housing in Seville between 1700 and 1900

F. Pérez Gálvez, C. Rodríguez Liñán and P. Rubio de Hita
University of Seville, Technical School of Architecture, Department of Architectonic Constructions, Seville, Spain.

ABSTRACT: Works' results allow operating with geometrical, constructive and mechanical objectives at the moment of restoration of the studied walls and buildings.

The phases have been as follow:

- Analysis of the building, which was going to be restored: constructive characteristics of the studied wall, drawings of damages…
- Extraction and laboratory analysis of small samples of masonry in order to determine resistance characteristics of its materials.
- Applications of accelerometer in order to measure *in situ* the building stiffness, so it will be got a rough estimate of masonry wall's elastic modulus.
- Numerical analysis. Application of Finit Elements Method, obtaining tension maps whether in current condition or in a possible intervention.
- Conclusions. Comparison of maximum tensions in current conditions and after intervention with resistance values obtained in previous studies.

1 INTRODUCTION

Nowadays, in Seville, restoration of structural masonry walls is a problem to solve in order to recover the Historic City Centre. Being interested in protecting and maintaining our historic heritage affects not only monuments but also most of small and modest buildings, which form this City Centre. However, popular architecture is excluded from historic, constructive and structural investigations. Studies and constant recovery of residential tissue formed by a domestic and humble architecture is the best guarantee of preservation of Historic City.

This investigation allows to determine a calculus method, which takes into account all this values that were said before. The aims of the study are:

- Development of a non-destructive and rigorous methodology based on dynamics and chemical mechanic tests and on F.E.M. in order to determine tension state of masonry walls, which belongs to Domestic Sevillian Architecture between 18th and 19th centuries.
- Obtaining a value of Compression Resistance, deformation modulus and tensional state in current and future conditions.
- Starting from the proposed methodology, getting an objective criterion of state and behaviour of masonry walls.

1.1 Study interests and work limits.

The city of Seville establishes study limits, because of the extent of buildings protected by normative and the prolific professional intervention on this field.

In order to valuate the interests of the study, it has been made a meticulous analysis of current residential tissue of the City Centre of Seville. All Plans of Special Protection have been studied, so we could know that structural façade walls that have been studied had to be preserved obligatorily (they where classified as level C, D an D). Approximately, 47 % of damaged buildings are or will be in short or medium time in process of restoration, so it will be necessary a study of stability of masonry façade walls.
This work studies façades formed by structural masonry walls of bricks and lime mortar with specific typology and constructive characteristics. It will be determined its resistant capacity starting from objective analysis of materials that compound the wall, so results will change according to current conditions of elements. It is necessary therefore an individualized study of each element within the defined work.
A methodology is developed in order to verify structural stability of elements by means of comparative studies between current conditions and tensional states for different load hypo these. It is meant to know maximum allowable tensions of walls, starting from a healthy masonry and comparing current conditions to values from tensional maps obtained by F.E.M. (elastic lineal analyse). It has been possible to verify in all cases that maximum tension areas coincide with cracked areas. This is a masonry strain gauge. By any case this study means to know the evaluation of cracked masonry, neither study of tensional re-distribution because of cracks. This will required a non-lineal analysis which is questionable taking into account studied masonry has big heterogeneities.

2 CONSTRUCTIVE AND FORMAL ANALYSE

Work starts from buildings which have a usual formal and constructive typology. In order to value the uniformity of this Domestic Sevillian Architecture between 18th and 19th centuries, shared formal characteristics which has been deeply studied by several authors (4) are summed up:

- Façades: limited by skirting board in the underside and cornice in the upper side. Some Horizontal bands called *impostas* show every floor (two or three) of first *crujía* (space between two structural walls, usually parallel to façade). Openings are usually rectangular they have simple frames painted in other colour different from façade. (Fig.1)

Figure 1 : Façade in Alameda de Hércules st. 45 (Seville).

- Roofs: There are two cases: flat roof and tile roof, depending on water collection outer first *crujía*.
- Patio: It is the most characteristic and fundamental element in the sevillian house. It is essential because of irregular form and depth of parcelling out.

Constructive systems have been essential in order to define work within. Studied façade masonry walls present these constructive systems:

- Foundations: There are a prolongation of masonry wall until a firm stratum (1-1,5 m). Sometimes there is a widening of last lines (Fig. 2)
- Masonry: Made of massif bricks of tile works and lime mortar. Dimension: 2 ft (50-60 cm), with horizontal wounds of 3-5 cm and vertical wounds of 2-4 cm. The masonry is fastened but without fixed rule in tie or bond.

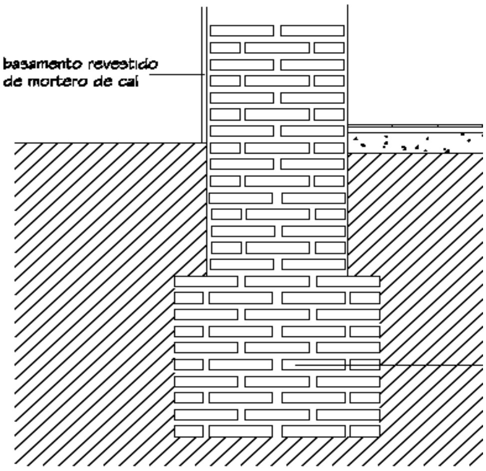

Figure 2 : Generic constructive section of foundations from buildings which belongs to Domestic Sevillian Architecture between 18th and 19th centuries

Figure 3 : Dividing fence fastened to façade in Menéndez Pelayo Avenue 23

- Openings: They are usually made with wooden lintels inside and linteled arches outside. (Fig.4)
- Cornices and impostas: Lines of bricks jutting out 1 ft maximum over façade's plane.
- Balconies: There are a variety of solutions, usually with iron beams layered on the wall. Over them bricks, filling and pavement. (Fig.5)

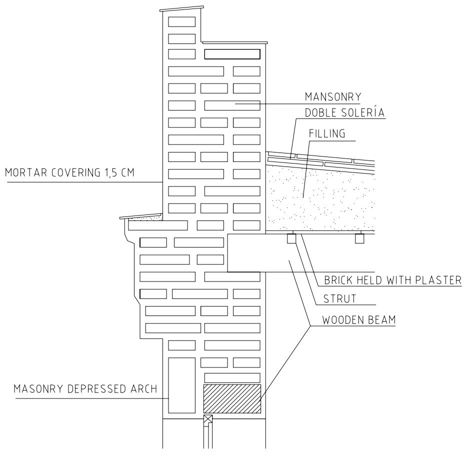

Figure 4 : Constructive section of cornice from Alameda de Hércules st. 45 (Seville)

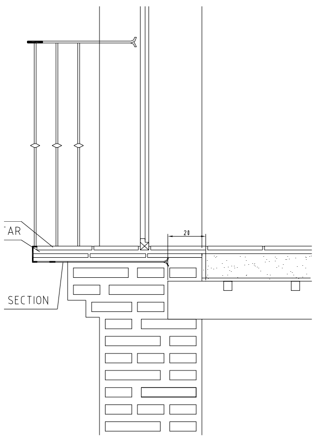

Figure 5 : Constructive section of balcony from Feria st. 97 (Seville)

3 ANALYSIS METHODOLOGY

In order to explain simply this method it will be used one of the studied buildings' façade. Step by step study will follow the process and result's interpretations of Caballerizas st.10-12 building (Seville).

3.1 Historic analysis.

This phase will require the study of historic documentation and will allow the first date of the building. The example is not included in the city catalogue of protected buildings, whose façade does not have singular elements. It is dated back to the 19th century because of its typology.

3.2 Building analysis.

It will be necessary some plans of the building which include floors (Fig.6), façades and an exhaustive drawing of damages of masonry wall which is going to be analysed (Fig. 7).

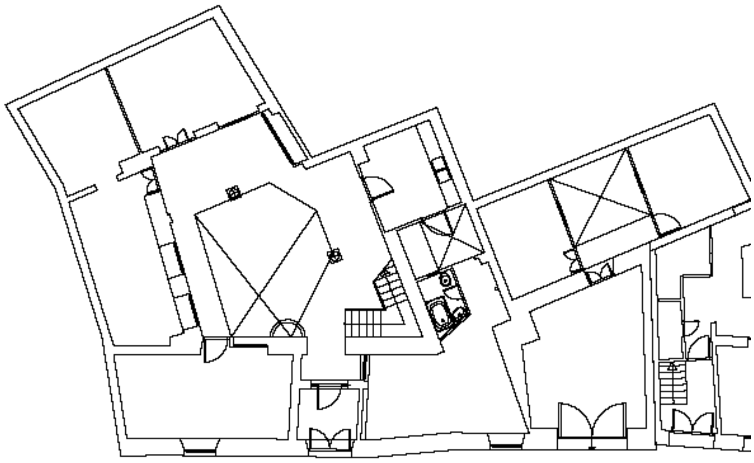

Figure 6 : ground flor. Caballerizas st. 10-12. Current conditions.

Figure 7 : Drawing of damages. Caballerizas st. 10-12 (Seville)

At the same time, it will be analysed constructive section of the façade in order to obtain some data about thickness, wounds, openings, cornices, floors, foundation and roof. This phase allows to verify constructive similarities between all studied buildings which belong to the same epoch.

3.3 Knowing the intervention proposal

In this study it must be done several trials taking into account different hypotheses in the numeric model of the wall in order to obtain different answers under different load situations.
All this information are the necessarily preceding for getting a simple calculus model which will simulate as accurate to real conditions as possible. Geometry, loads and links are extremely important when this model is reproduced.

3.4 Extraction of samples and laboratory analysis.

In our example we obtained the following results(Tab. 1,2,3,4):

Masonry geometry: bricks of 54 cm thickness, joined with lime mortar:

- Handmade massif brick of (29 ± 2) x (14 ± 1) x (5 ± 2) cm.
- Horizontal wounds: 4 ± 1 cm.
- Vertical wounds: 5 ± 2 cm

Table 1 : Chemical composition of mortar.

SAMPLE	CARBONATE CONTENT $\%CO_3Ca$	CARBONATED CALCIUM OXIDE CONTENT (first lime dosification) %CaO	NON CARBONATED CALCIUM OXIDE CONTENT %CaO
A	39,29	25	2,99
B	41,96	30,5	7,00
C	45,11	28,6	3,34
D	49,20	32,5	4,95
E	47,43	27,1	0,54
F	35,88	24,6	4,51
G	42,26	22,7	0,00

Table 2 : Initial dosage lime/dry goods.

SAMPLE	VOLUME LIME / ARID
A	1/3
B	1/ 2,27
C	1/ 2,49
D	1/ 2,07
E	1/ 2,69
F	1/ 3,06
G	1/ 3,40

Table 3 : Physical and mechanical characteristics of mortar.

SIEVE UNE 7050	% SIEVED MATERIAL						
	A	B	C	D	E	F	G
5	92	91,9	93,6	91,5	88,7	95,6	81,9
2,5	84,2	81,4	87,9	76,4	70,0	89,2	72,6
1,25	79,3	73,8	82,3	66,6	59,3	83,4	66,9
0,63	72,6	65,8	73,5	56,4	51,8	75,8	60,8
0,32	58,9	52,5	56,6	40,8	42,6	63,1	51,2
0,16	44,9	42,3	45,9	31,6	44,8	51,0	43,5
0,08	36,2	35,2	35,4	25,8	27,0	37,0	34,1

Table 3 : Physical and mechanical characteristics of bricks.

MÉDIUM COMPRESIÓN STRENGHT N /mm2	TIPYCAL DEVIATION N /mm2	CHARACTERISTIC RESISTANCE N /mm2
26,3	7,6	13,84

From results it follows that:

- Mechanical resistance of bricks is good.
- Proportion of lime oxide non-carbonated is very low, even 0 % in some samples. In normal conditions, this proportion should be 50% for the first 100 years old, so our building is, at least, 100 years old.
- Lime mortar has been dosed correctly (1:3 in the origin) but they have so much content of fines: between 25 % and 37 %.
- We obtain allowable compression resistance by means of results of its components' resistances (3). In these cases we obtain values between 0,21 and 0,4 N/mm^2 for walls with the same slimness and without any traction resistance (characteristic resistance is between 0,84 and 1,6 N/mm^2 (4).

3.5 Applying Accelerometer.

In order to measure wall stiffness in situ, dynamic vibrations system is reproduced with as much sensibility as it is necessary for activating with movements, which are produced by traffic and wind. The aim of this non-destructive test is to measure structural stiffness with an approximated estimate of a period. Starting from these data masonry's Elastic Modulus will be got.
Frequency value was between 0,65 and 0,8 Hz, or at the same way, a period of 1/0,8=1,25 s.
It is estimated the period that should have building nowadays, considering 11,30m height and 18,50 m length. The wall is not fixed at the upper end because there is no join with floors.

*T = 0,06*H*((H/(2*L+H))/L)0,5 = 0,076 s*

Dividing real period with the one that should have the building, we obtain a proportion of 16,44, or at the same way, structural stiffness is 1/16,44 times that should have. So façade is untied and made of materials with low Elastic Modulus.
Masonry Elastic Modulus is obtained by means of:

$$T = 2\pi / w = 2\pi\sqrt{\frac{m}{E_d I}}$$

Where E_d = 1.564.847 kPa = 1564 N/mm². Static Elastic Modulus is approximated Dynamic one divided by 2,5 = 625-1000 N/mm².

In order to determine deformation of masonry and Elastic Modulus we could also use lightly destructive tests in situ (flat jack), if material's conditions allow it.

3.6 Numeric Analysis. Apply of F.E.M to structural masonry walls.

To understand masonry walls' behaviour is necessary to consider it as an elastic material, that is to say, material lose their form when they receive loads. So it can be used concepts as tension and deformation. Lineal elastic study reveals possible equilibrium stratums by means of maps of traction and compression maximum tension distribution. It shows how masonry works, giving a general vision of tension concentration's areas and therefore cracking areas.
It should be necessary to reproduced with accuracy geometric and structural characteristics of building in order to simulate its real behaviour. Previous tests, links between wall and floors and party walls.

3.6.1 Geometrical model of masonry.

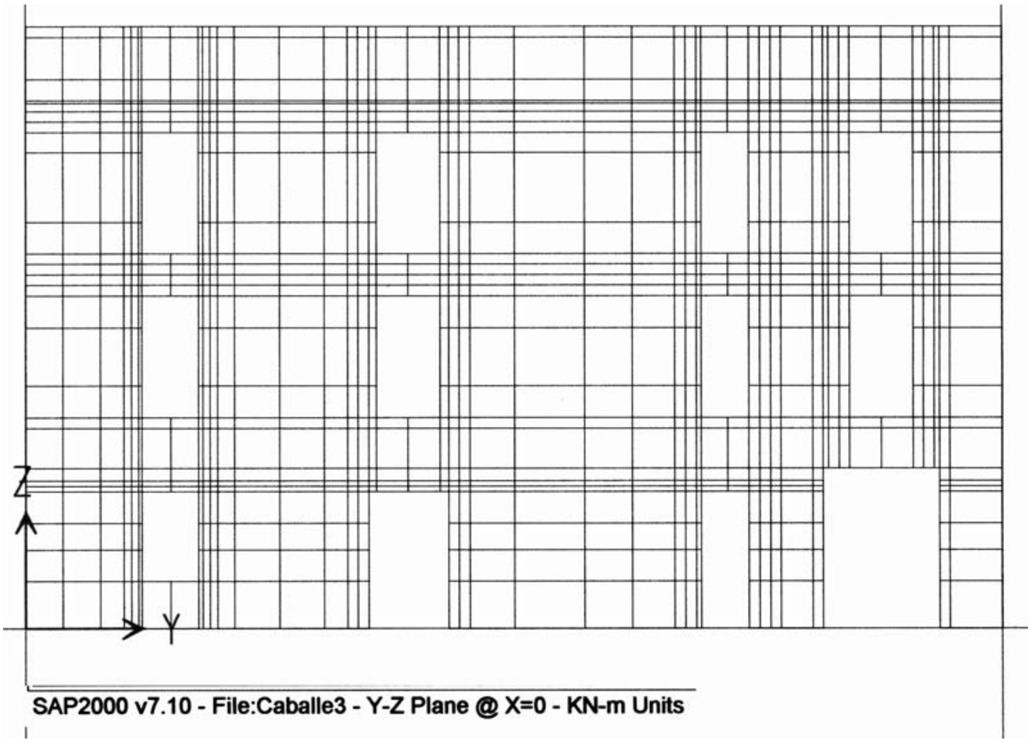

Figure 8: Model of façade. Caballerizas st. 10-12 (Seville)

3.6.2 Starting data and load hypotheses.
In order to obtain lineal static answer, it has been previously introduced masonry data obtained by F.E.M..

In the example it has been considered following data:

- Specific weight of masonry: 1800 Kp/m^3
- Thickness of wall: 54 cm.
- Elastic Modulus: 1000 N/mm^2
- Rigid link between wall and floor and we consider there is no coactions in normal direction in the link between façade and party walls.
- One load hypotheses is considered. It is called Caballe2 and includes permanent weight of wall + floor and pavement. (current conditions)

3.6.3 Interpretation of results. Correlation between tension graphics and masonry conditions.
Starting from introducing data in the calculus program, results obtained are showed in maps of minor principal tensions (compressions) and major tensions (tractions) for studied hypotheses (Fig. 9 and 10)

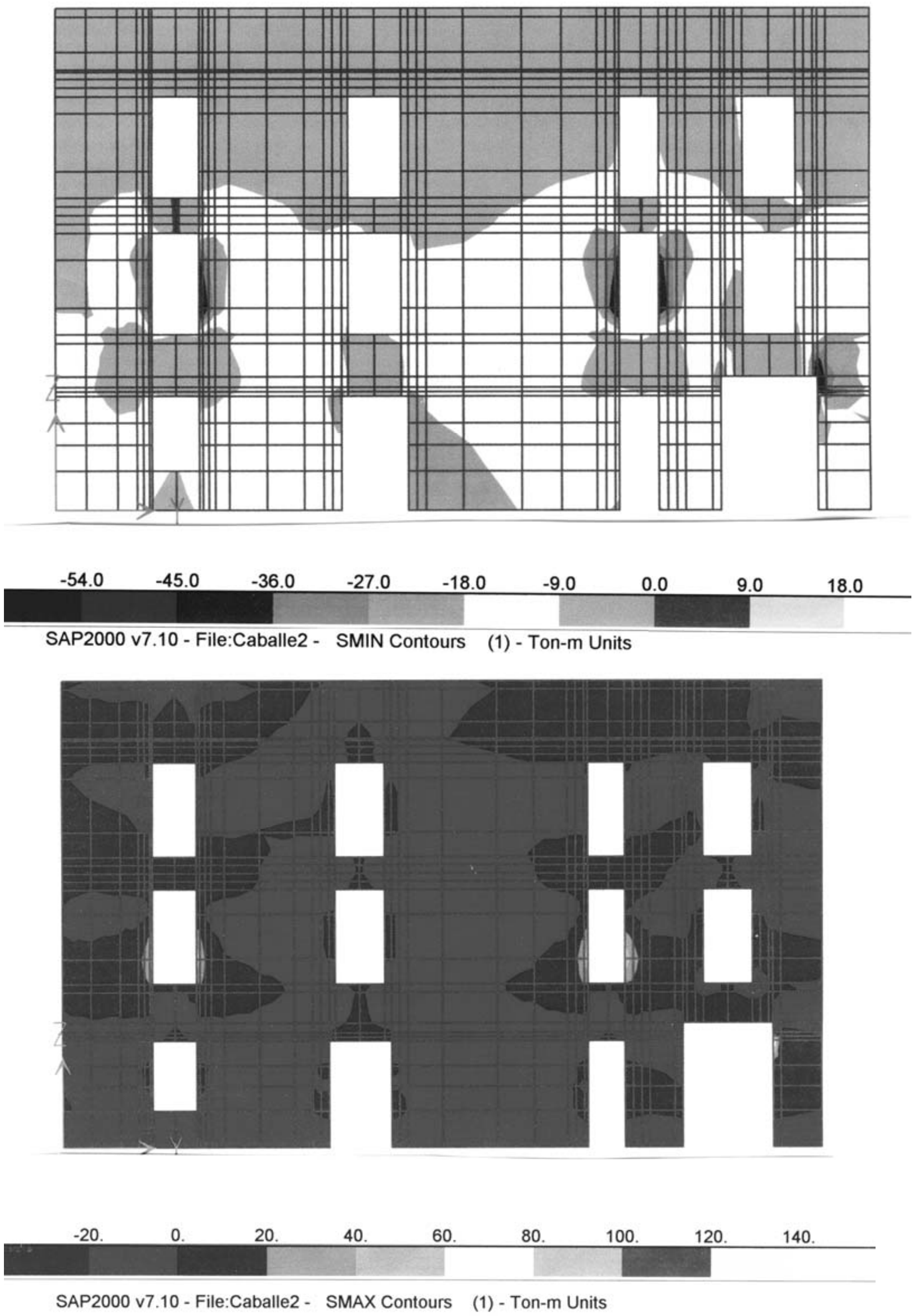

Figure 10 : Diagram of maximum tension (Tractions). Hypotheses 1. Caballerizas st. 10-12 (Seville)

These diagrams show:
Maximum compressions are produced in ground floor along vertical size of the withiest door at right. Its value is around 1,4 N/mm^2 . Maximum traction is produced in the lintel of openings and is about 0,6-0,8 N/mm^2.
Interpretation of analysis by means of F.E.M. of tensional conditions of wall and results of lightly destructive tests show that:

- There are some areas which work 1,4 N/mm^2 by compression of 0,8 N/mm^2 by traction, when it is determined an allowable compression resistance of 0,21 to 0,4 N/mm^2 and null traction.
- Disproportion between how masonry resists and real tensions justify its bad conditions in the areas where maximum tensions are concentrated (cracks, fissures, detachments, curvature of complete masonry walls).
- Appearance of cracks and fissures has created loose areas in the wall, plastic ball-and-socked joints, and lack of continuity, which difficult forecasting the behaviour of the wall when a future intervention will modify current load conditions.
- In this case the wall works at its resistance limit. Security only could be guarantied if the intervention respects links between elements, without increasing loads and without doing any modification of existent openings.

4 CONCLUSIONS

- This method is developed for a specific area and architecture with similar formal, constructive, and material characteristics. Its necessary an individualized study of buildings that includes historic information, plans, visual inspection of current conditions and constructive study.
- It is essential using lightly destructive techniques, such as extracting samples, in order to approach masonry's resistance parameters. In those cases in which masonry homogeneity, material's quality and economy allow it, it is recommended using flat jack in order to obtain better results of its deformation.
- Applying *accelerometer* is a good technique which can determine structural stiffness, and the answer of buildings when there are horizontal loads, as well as links between wall to reproduce model and to obtain elastic modulus.
- Lineal static modulus obtained by means of F.E.M. is enough to get comparative values between tensional current conditions and after a future intervention, verifying that cracked areas are the same as those ones whose sections have maximum allowable loads.

REFERENCES

Oñate,E.: Cálculo de estructuras por el método de elementos finitos. CIMNE, 1998.

Como , M.; Ianniruberto, U. ; Imbimbo, M.: A rigid plastic model of the under-excavation technique applied to stabilise leaning towers. Historical Constructions. Possibilities of numerical and experimental techniques. Guimaraes 2001.

Lourenço P.B.: Análisis of historical constructions: from trust-lines to avances simulations. Historical Constructions. Possibilities of numerical and experimental techniques. Guimaraes 2001.

Sierra Delgado, J.R. La casa en Sevilla 1976-1996. Ed. Fundación El Monte y Electa Sevilla 1996.

NBE FL-90 . Norma Básica de la Edificación. Muros resistentes de fábrica de ladrillo. Ministerio de Obras Públicas y Urbanismo, 1991.

Soto Pardo, M. Reforma de edificios antiguos. El rasgado de huecos en muros de carga. Informes de la Construcción, Vol. 37, nº 374, 1985.

Jaramillo Morilla, A. Método probabilístico de estimación de las acciones sísmicas. Tesis doctoral. E.T.S.A. de Sevilla 1983. Capítulo V.

Instituto Eduardo Torroja: P.I.E.T.70. Obras de fábrica. Instituto Eduardo Torroja. Madrid 1971.