13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1080

THE ROLE OF THE TENSION STRENGTH IN THE COLLAPSE MECHANISM OF UNREINFORCED BRICK MASONRY CONSTRUCTIONS

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SUMMARY

This paper shows the importance of the tension strength in the in-plane collapse mechanism of brick masonry structures. It is usually to consider brick masonry as non-tension material or as isotropic material. However, these two considerations often are not valid. Brick masonry is an orthotropic material, which presents distinct directional properties. These characteristics are important to define the collapse mechanism of brick masonry constructions. This study shows that the tension strength is an important parameter in the study of the brick masonry structures. This variable influences the type of collapse mechanism and the damage pattern of the unreinforced brick masonry structures.

INTRODUCTION

Masonry is a non-homogeneous material with two constitutive elements: blocks and mortar. The mortar has different functions inside the masonry, i.e. it forms a layer to put the block and permits a uniform transmission of the internal forces. It is important to remark that the mechanical properties of the masonry do not depend exclusively on the mechanical properties of the constitutive materials, as well as depend on the arrangement of the blocks at inside of the masonry. It is usually to consider the masonry as non-tension material or as an isotropic material. However, these two considerations often are not valid. We must remind that the brick masonry is an orthotropic material, which presents distinct directional properties due to mortar (head and bed) joints that act as planes of weakness.

We must have in mind, that the damage pattern is influenced by the material characteristics [1,2]. For example, the response of the semi-circular arches is modified if the non-tension or low-tension strength assumption is taken into account. Genna et al. [1] comment that the non-tension model should be rejected as a useful tool for some problems. According to Boothby [3], Heyman's assumptions seldom give realistic assessments of real structures.

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On the other hand, observations of seismic effects on unreinforced brick masonry structures show that the in-plane damage is due by tension or shear stresses and seldom times by compression stresses. However, when we work with masonry material, the elastic properties and the compression and shear strength are always known; while, tension strength is seldom studied with accuracy. Sometimes non-tension material is considered or a low percentage of the compression strength is taken into account as tension strength (1 – 10%). But the tension strength has a principal role in the collapse mechanism. This study shows the role of the tension strength in the in-plane collapse mechanism of the unreinforced brick masonry structures and shows the importance to assign a correct value of tension strength to the masonry material.

MICRO-MECHANICAL BEHAVIOUR OF BRICK MASONRY

Interaction between blocks and mortar is very complex since the difference in stiffness and strength between both components and the interlocking of the blocks, produced by the arrangement inside masonry. This interaction is known as micro-mechanical behaviour and causes the orthotropic behaviour in this material [4]. It is clear that in an analytical model, the discretization of each block and each joint becomes impractical in case of real masonry structures. Thus, it is necessary to consider the material as homogeneous, by describing the heterogeneous behaviour of masonry in terms of average stresses and strains.

By using the homogenisation theory for periodic media, we can take into account the micro-mechanical behaviour in the average material properties, such as the elastic constant and the plastic behaviour. In general, the identification of the mechanical parameters of the masonry material can be performed by means of a computational approach in which it is considered the response of a sub-domain of the periodic composite material that include all the component materials and that constitute the entire structure by periodicity [5, 6]. In this study, the average mechanical properties are found by means of a generalised plane strain finite element model adopting the proper loading and periodic boundary conditions [7]. The analytical model is bigger than the unit cell in order to understand better the interaction between blocks and mortar. The mesh used in the analyses is depicted in Figure 1.b. The geometry of traditional Italian bricks, arranged in running bond, has been adopted for the blocks: l x d x h = 25 x 12 x 5.5 cm^3. The thickness of the mortar joints is th = 1 cm. The vertical head-joints, interrupted by the bricks, are generally of poor quality and weaker than the horizontal continuous bed-joints. Perfect bond between materials is assumed.

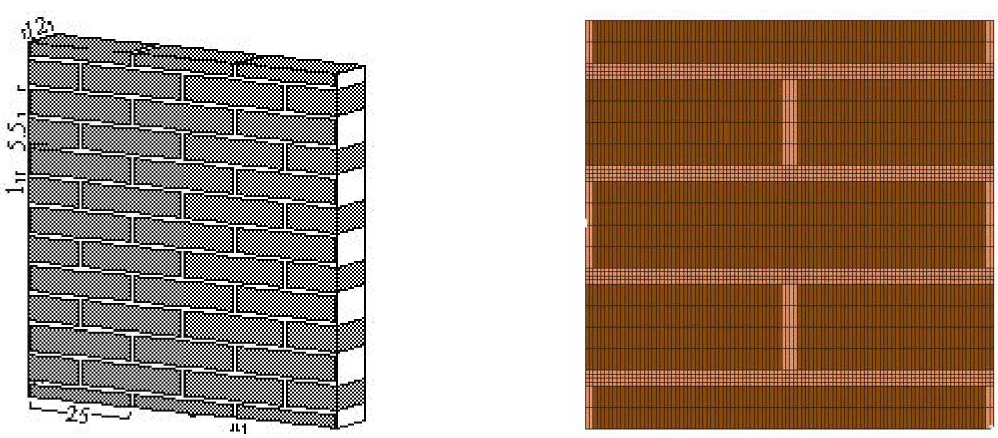


Figure 1. Masonry: a) Running bond arranged, b) Finite element mesh

Bricks and mortar are assumed as isotropic with $\nu = 0.1$. The plastic behaviour of both materials is defined by Drucker – Prager yield criterion with tension cut-off available within Abaqus finite element code [8]. The values that define the mechanical behaviour are reported in Table 1. Angle β is the friction angle, while σ_c and σ_t are the compression and the tension strength. Isotropic softening is defined for bricks, while a slight isotropic hardening is defined for the mortar joints. The softening and hardening behaviours are defined by a second value of stress σ_y together with the corresponding plastic strain ε_y.

Table 1. Mechanical Properties of the Constitutive Materials

Element	E (MPa)	σ_t (MPa)	σ_c (MPa)	σ_y (MPa)	ε_y	β (°)
Brick	5000	1.00	25.0	3.0	5×10^{-3}	20
Horizontal Joint	1000	0.10	3.0	3.1	1×10^{-3}	25
Vertical Joint	100	0.01	0.3	0.31	1×10^{-3}	25

Five tests are performed to obtain the mechanical response of the masonry material: two (compression and tension) for horizontal and other two for vertical axial response, and one for the symmetric shear behaviour. The response of the finite element model is shown in Figure 2 and the masonry parameters obtained by the homogenisation are shown in Table 2. It is worth comparing the responses of the different directions. In particular, we note that the parallel direction of bed joints is weaker than perpendicular direction in compression, on the contrary of the tension range. In this particular case, tension strength, in perpendicular direction, is almost 1% of the compression strength; however, for the parallel direction is almost 50% of the compression strength. On the other hand, shear behaviour can be idealized as perfect elastic-plastic material.

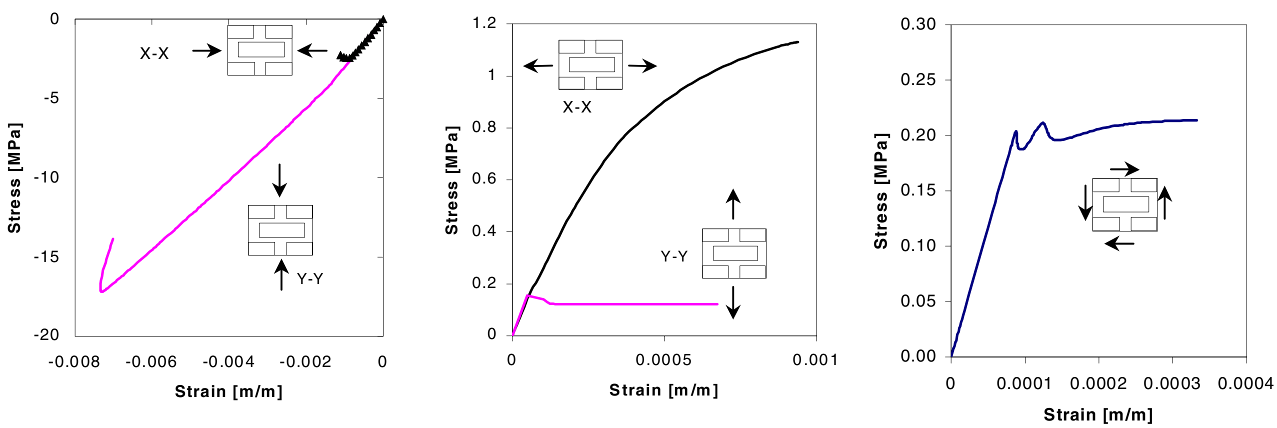


Figure 3. Response of the Finite Element Model: a) Compression, b) Tension, c) Shear

Table 2. Mechanical Properties of the Masonry

	Ex (MPa)	Ey (MPa)	G (MPa)	ν_{xy}	ν_{yx}	
Elastic	2885	3012	1176	0.084	0.088	
	σ_{tx} (MPa)	σ_{ty} (MPa)	σ_{cx} (MPa)	σ_{cy} (MPa)	τ (MPa)	β (°)
Strength	0.15	0.12	2.4	17	0.20	20

In tension range, along the parallel direction of bed joints, we can note that the brick and the head joint are subjected to axial stresses, while the bed joint is subjected to shear stresses (Figure 3.a). Since the shear strength of bed joint and the tension strength of bricks are bigger than the tension strength of head joints, these last joints break first. Thus, the tension strength of the masonry is given principally by the shear strength of the bed joint. For the parallel direction of bed joints, bricks and joints are subjected to axial stresses (Figure 3.b). In this case, the tension strength of the masonry is, principally, given by the tension strength of the bed joints.

As conclusion of this first part, it is important to remark the orthotropic behaviour of the brick masonry material. Axial strength depends on the direction of measure. In particular, it is not correct to assume non-tension or isotropic behaviour for brick masonry. To assume that the tension strength is a low percentage of the compression strength (1 – 10%) is correct only for the perpendicular direction of the bed joints, while for the other direction, this assumption must be rejected.

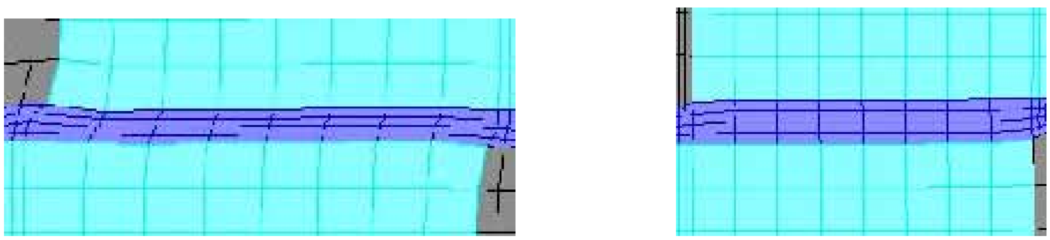


Figure 3. Deformed in tension: a) parallel to bed joint, b) perpendicular to bed joint

THE RIGID ELEMENT METHOD

The evaluation of seismic vulnerability of masonry structures requires peculiar procedures. In this field, there is the need of models that are simplified enough to allow parametric dynamical analyses, but should also account for the peculiar behaviour of the masonry material subjected to cyclic loadings that cause heavy mechanical degradation. In particular, Casolo [9, 10, 11] has developed an analysis method, the Rigid Element Method (REM), which considers the masonry structures as a series of rigid elements. The parametric study, presented in this paper, was performed with this simplify method. A briefly description about the rigid element method is now made:

Philosophy

The rigid element method idealizes the masonry structure as an assemblage of rigid elements. These elements are quadrilateral and have the kinematics of rigid bodies with two linear displacements and one rotation (Figure 4.a). Three devices (springs) connect the common side between two rigid elements or the restrained sides. These connections are two axial devices, separated by a distance $2b$ that take into account a flexural moment, and one shear device at the middle of the side (Figure 4.b).

Masonry material is considered deformable but this deformation is concentrated in the connecting devices, while the element is not deformable. Each connecting device is independent of the behaviour of the other connecting devices and depends only on the Lagrangian displacements. In other words, the connecting device represents the mechanical characteristics of the masonry material and, at the same time, represents the capacity of the model to take into account the separation or the sliding between elements.

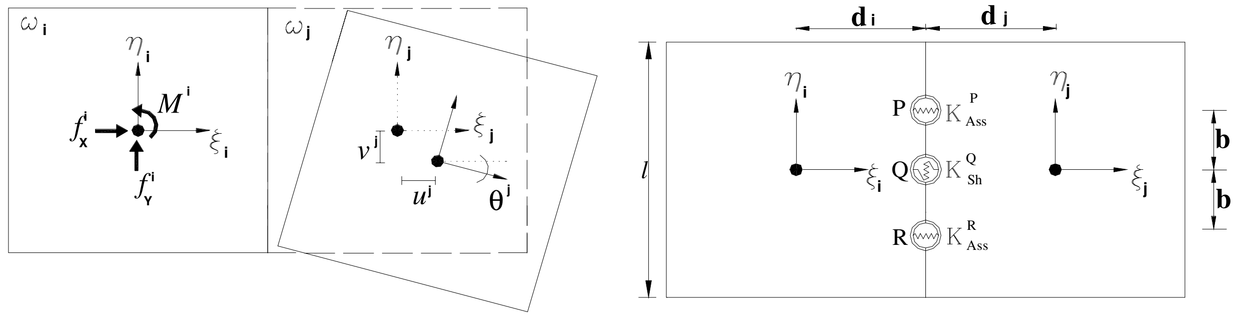


Figure 4. Scheme of a couple of rigid elements a) Displaced, b) Inter-connection

The rigid element method is a semi-continuous model. Whereas a continuous model strictly enforces compatibility between elements sharing common nodes, and in a discontinuous model, the element is free to separate or slide away from other elements. In the rigid element method, relative motion between two adjacent elements can occur. However, initial contacts do not change during the analysis and a relative continuity among elements exists. In fact, overlapping, separation or sliding between two adjacent rigid elements can exist; numerically, these mean compression, tension or shear on the connecting devices.

Each element is assumed independent on its movement, since the masonry structures cannot be considered as a continuum because part of the deformation is accounted for relative motion between elements. Initial contacts do not change in order to simplify the computational effort. This approach has the advantage to allow a simplified description of the elastic-plastic response by defining the elemental behaviour of the axial and shear connections that are considered as separate springs.

Mechanical Behaviour

The elastic characteristics of the connecting devices are assigned with the criterion of approximating the strain energy of the corresponding volumes of pertinence in the cases of simple deformation. Two axial, one symmetric shear, and two in-plane flexural loadings are considered for the parameter identification.

The monotonic and hysteretic constitutive laws are assigned to the connecting devices adopting a phenomenological approach. These laws are based on experimental monotonic and cyclic tests currently available in literature, and should be assigned to rigid elements whose size is approximately comparable to the test specimens in order to limit the problems with size effects. Symmetric stiffness and strength have been attributed to the shear connections. The plastic response of each axial connection is independent from the behaviour of any other connection, while the shear strength is related to the stresses of the axial connections according with Mohr-Coulomb criterion [12]. Peña criterion [13] is used to describe the orthotropic behaviour of the connecting devices. The adoption of this type of device is useful since it allows separate phenomenological descriptions of the hysteresis behaviour of the axial and shears connections.

PARAMETRIC STUDY

In order to study the influence of the tension strength in the collapse mechanism and in the damage pattern of in-plane brick masonry constructions, a parametric study was performed by using a rigid element model. The rigid element method is a simplified method that it allows parametric dynamical analyses, but should also account for the peculiar behaviour of the masonry material subjected to cyclic loadings, by including micro-structure aspects of masonry material [14].

Two in-plane structures were studied under seismic loads (Figure 5). Five different seismic records were used (Table 3 and Figures 6, 7) and five different materials were considered. Elastic parameters, compression and shear strength are considered equal for all materials and their values are shown in Table 2. The difference among the five materials is related only by the tension strength (Table 4). The first material used, named “Orthotropic”, is the material obtained by the homogenisation procedure (Table 2). The second material is considered as “isotropic” and its parameters are equal to the values of the perpendicular direction of bed joints of the orthotropic material, since this direction is the most used to obtain the parameter identification. The third material, called “non-tension”, considers the orthotropic material, but both tension strengths are equal to zero. The tension strengths of the orthotropic material called “Mohr” are obtained considering a linear Mohr – Coulomb criterion without tension cut-off. This assumption is seldom used in practice with this criterion. Finally, a perfect elastic – linear orthotropic material is used just like comparison.

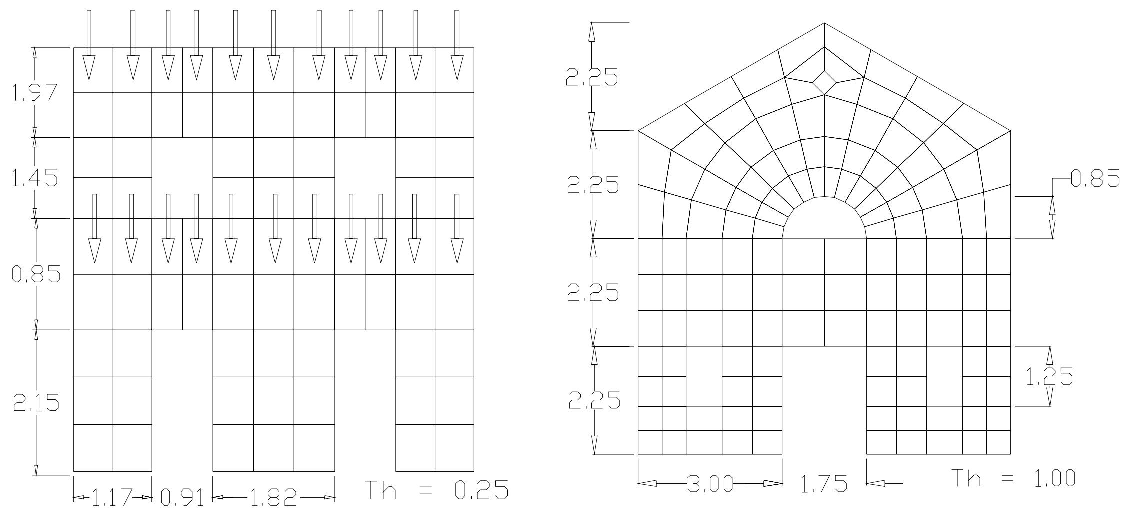


Figure 5. In-plane Masonry Structures studied: a) House Wall, b) Church Façade

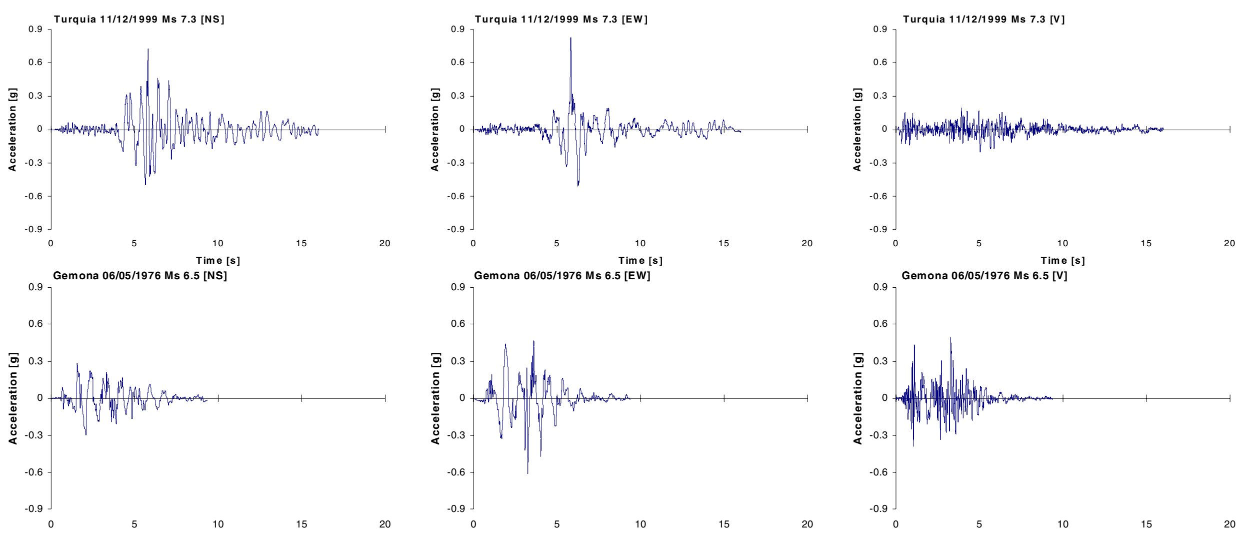


Figure 6. Seismic Records: a) NS, b) EW, c) V

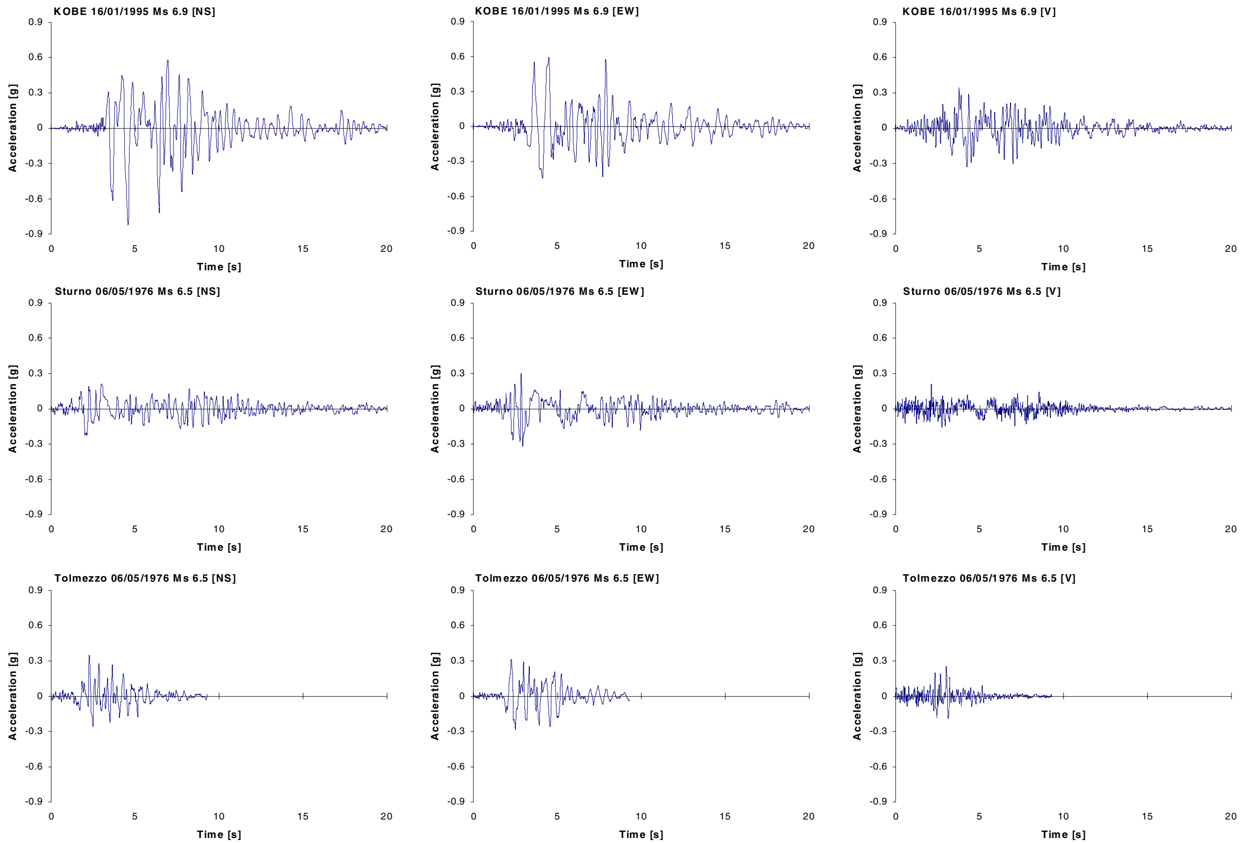


Figure 6. Seismic Records: a) NS, b) EW, c) V (Continuation)

Table 3. Principal Parameters of the Seismic Records

Record	Country	Date	Magnitude	Maximum Acceleration (NS, EW, V) [g]		
Bolu	Turkey	11/12/1999	7.3	0.73	0.81	0.20
Gemona	Italy	06/05/1976	6.5	0.30	0.61	0.49
Kobe	Japan	16/01/1995	6.9	0.82	0.60	0.34
Sturno	Italy	06/05/1976	6.5	0.22	0.32	0.21
Tolmezzo	Italy	06/05/1976	6.5	0.34	0.30	0.24

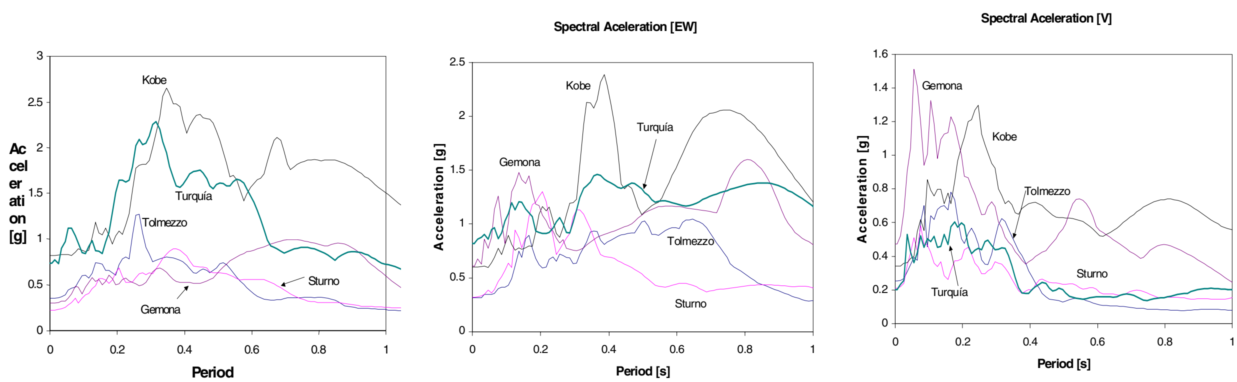


Figure 7. Spectral Response: a) NS, b) EW, c) V

Table 4. Tension Strength

Material	σ_{tx} [MPa]	σ_{ty} [MPa]
Orthotropic	1.13	0.14
Isotropic	0.14	0.14
Non-tension	0.00	0.00
Mohr	1.82	1.82
Linear	---	---

House Wall
The first structure studied was a House Wall (Figure 5.a). The expected behaviour of this structure is a mix of tension (rocking) and shear. It was discretized by 79 elements (237 DOF). Results obtained with Gemona EW + V records are the only one shown.

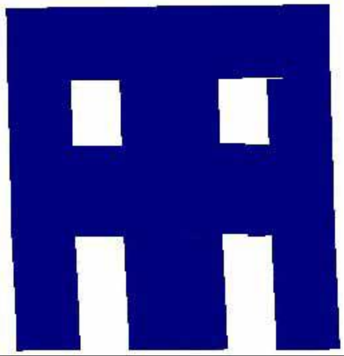
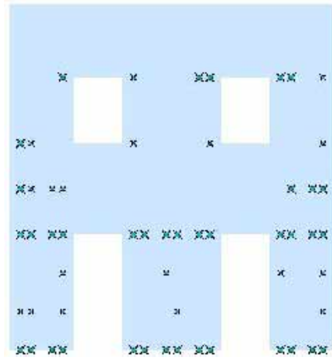
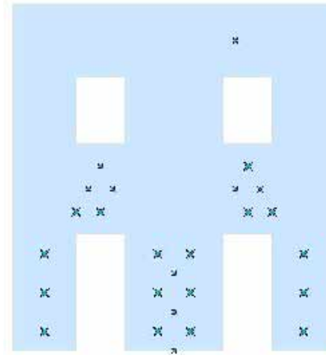
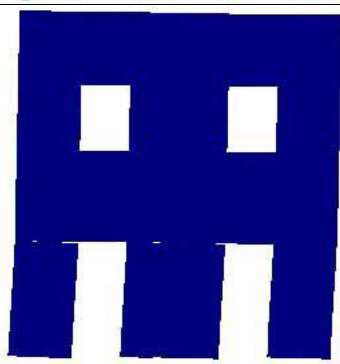
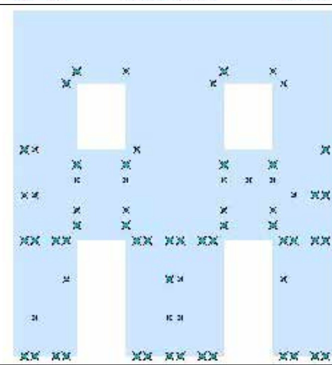
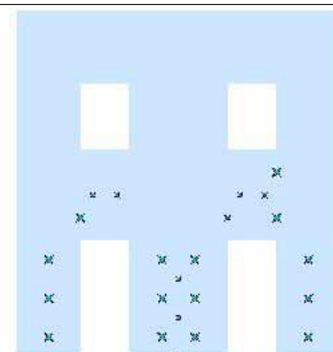
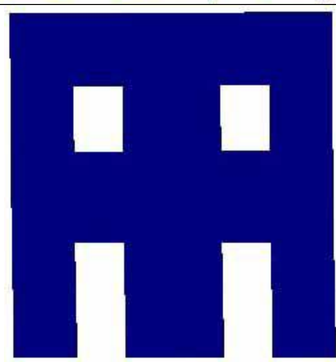
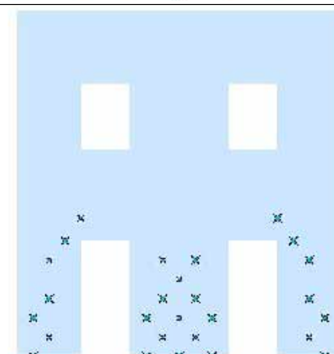
The maximum response of the models are shown in Table 5. *Sx* and *Sy* are the horizontal and vertical displacement of the second floor, while *Fx* and *Fy* are the shear base and vertical force. Isotropic material presents less error than other materials, respect to orthotropic material. Greater error is obtained with non-tension material, since the structure fails at 2.06 seconds of the record. Error is similar when linear or Mohr material is considered, since little shear damage is obtained with Mohr material.

Table 5. Maximum response of House Wall

Material		*Sx* (mm)	Error (%)	*Sy* (mm)	Error (%)	*Fx* (Mpa)	Error (%)	*Fy* (Mpa)	Error (%)
Orthotropic	max	11.4	---	2.71	---	-24.9	---	159	---
	min	-10.3	---	-0.6	---	-479	---	-155	---
Isotropic	max	8.21	-27.98	1.85	-31.73	-36.4	46.18	144	-9.43
	min	-5.91	-42.62	-0.55	-8.33	-467	2.57	148	-4.52
Mohr	max	2.25	-80.26	0.01	-99.63	-16.1	-35.34	177	11.32
	min	-2.94	-76.31	-0.57	-5.00	-455	-0.5	-173	11.61
Non-tension	max	14.9	Failure	2.4	Failure	-85.6	Failure	126	Failure
	min	-17.3	Failure	-0.6	Failure	-431	Failure	-116	Failure
Linear	max	2.24	-80.35	-0.01	-100.37	-34.2	37.35	190	19.50
	min	-2.19	-78.73	-0.53	-11.67	-424	-11.48	-174	12.26

Table 6 shows the damage pattern obtained with Gemona record. In any case compression damage is not found. When orthotropic material is used a mix damage of tension and shear is obtained. The shear damage is found on pillars and on the architraves, while tension damage is found on base and top of pillars and only horizontal tension damage is presented. Shear damage on pillars is found when Mohr material is used, while tension damage does not present. The damage pattern found with isotropic material is similar to the orthotropic material, however vertical tension damage is found on architraves. These elements show slight shear damage. On the other hand, the structure fails under Gemona record when non-tension material is considered. In this case, non-tension material must be rejected, since non-cohesion among parts of the structure causes the failure.

Table 6. Damage Pattern of House Wall

Material	Deformed	Tension	Shear
Orthotropic			
Isotropic			
Mohr			
Non-tension		Failure	Failure

Similar results are obtained with orthotropic or isotropic materials. However there are some differences that they are necessary to remark. The principal difference is on the architraves. Since little horizontal cohesion exists on isotropic material, a kind of rocking in architraves is developed. This causes smaller shear damage on these elements (Table 6).

Figure 8 shows the curves Base Force – Top Displacement of the wall with orthotropic and isotropic material. Both horizontal curves (Figure 8.a,b) present a typical "S" form when rocking is developed, however it is more important when orthotropic material is used. Vertical response is greater too with orthotropic material than isotropic material.

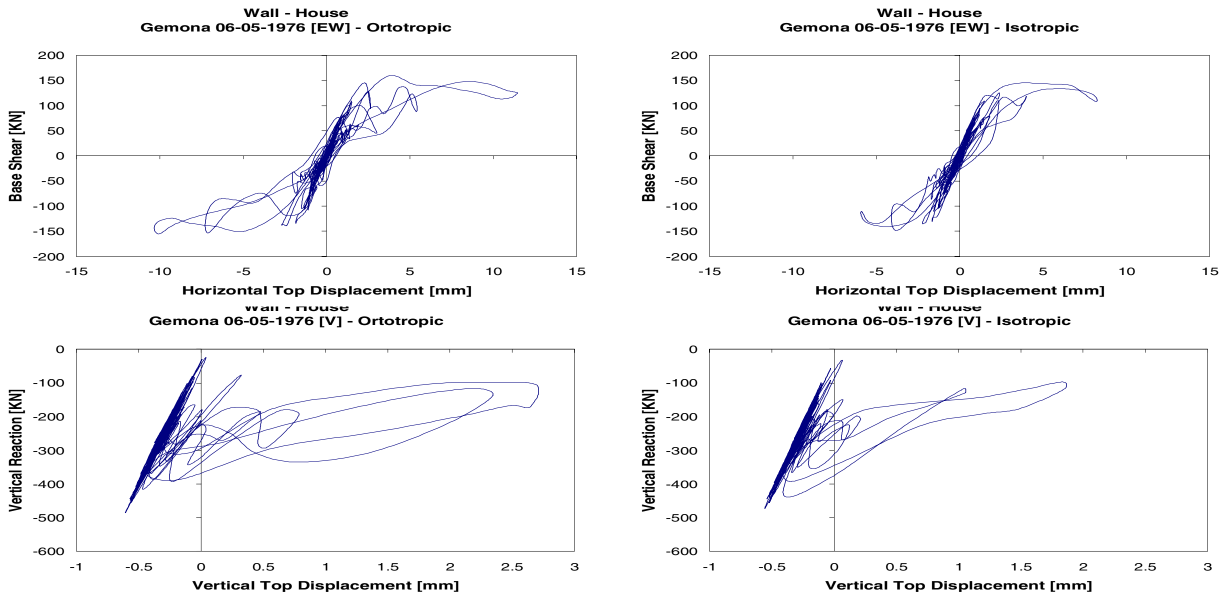


Figure 8. Base Force – Top Displacement curves: Horizontal a) Orthotropic, b) Isotropic and Vertical c) Orthotropic, d) Isotropic

Church Façade

The other structure studied was a Church Façade (Figure 5.b). It was discretized by 134 elements (402 DOF). Results obtained with Kobe NS + V records are the only one shown. The maximum response of the models are shown in Table 7. Isotropic material presents less error than other materials, respect to orthotropic material. Greater error is obtained when we use non-tension material, since the structure fails at 4.64 seconds of the record. Error is similar when linear or Mohr material is considered, since little damage is obtained with Mohr material. In fact, when Mohr material is used practically elastic – linear response is obtained.

Table 7. Maximum response of Church Façade

Material		*Sx* (mm)	Error (%)	*Sy* (mm)	Error (%)	*Fx* (Mpa)	Error (%)	*Fy* (Mpa)	Error (%)
Orthotropic	max	2.99	----	0.26	----	694	----	-524	----
	min	-4.25	----	-0.42	----	-785	----	-1270	----
Isotropic	max	2.90	-3.01	0.12	-53.85	715	3.03	-599	14.31
	min	-3.52	-17.18	-0.36	-14.29	-755	-3.82	-1220	-3.94
Mohr	max	1.64	-45.15	-0.18	-169.23	672	-3.17	-616	17.56
	min	-1.86	-56.24	-0.37	-11.90	-757	-3.57	-1230	-3.15
Non-tension	max	3.91	Failure	2.88	Failure	487	Failure	-506	Failure
	min	-13.3	Failure	-0.44	Failure	-655	Failure	-1300	Failure
Linear	max	1.37	-54.18	-0.18	-169.23	597	-13.98	-614	17.18
	min	-1.68	-60.47	-0.36	-14.29	-750	-4.46	-1220	-3.94

Table 8. Damage Pattern of Church Façade

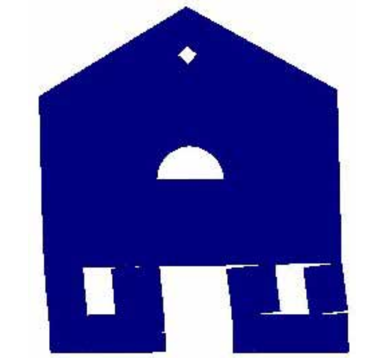
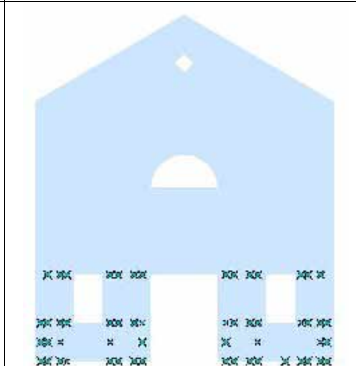
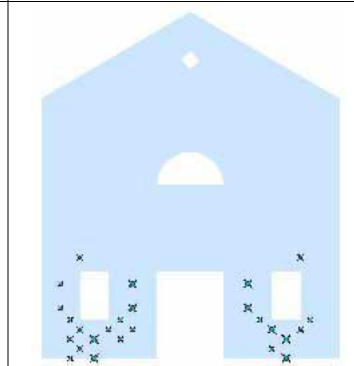
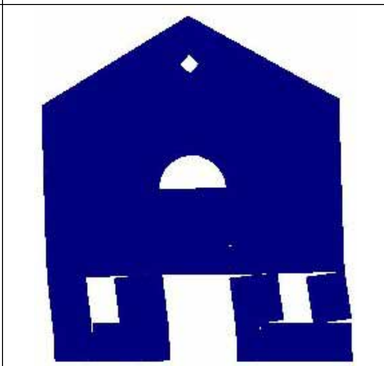
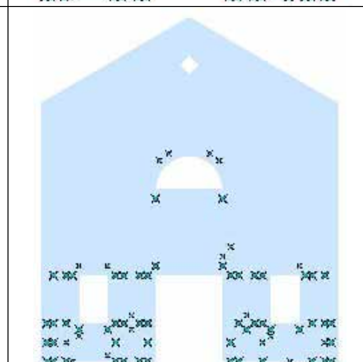
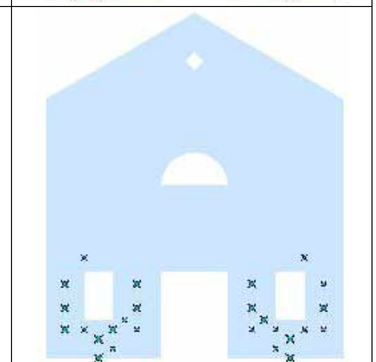
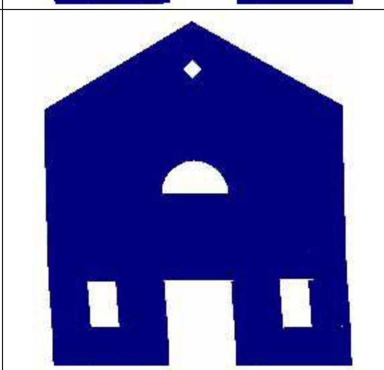
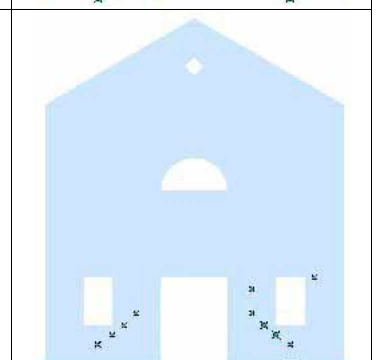
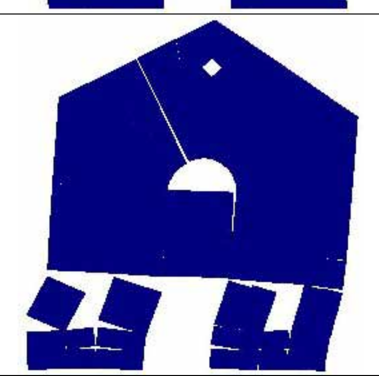
Material	Deformed	Tension	Shear
Orthotropic			
Isotropic			
Mohr			
Non-tension		Failure	Failure

Table 8 shows the damage pattern obtained with Kobe record. In any case compression damage is not found. The structure fails when non-tension material is considered. In general, slight shear damage is found for this structure and the principal damage is due by tension. However, when Mohr material is used tension damage is not found. On the other hand, damage pattern is similar when orthotropic or isotropic material is used; but some differences can be found. Tension damage is grater when isotropic material is considered , diagonal tension cracks appear on the upper opening.

Figure 9 presents the curves Base Force – Top Displacement of the façade with orthotropic and isotropic material. Both behaviours are similar. However, inelastic response of the façade with orthotropic material is bigger than when isotropic material is considered; in particular with vertical response. The minimum vertical displacement is 0.26 mm with orthotropic material, while the same displacement is 0.12 mm with isotropic material.

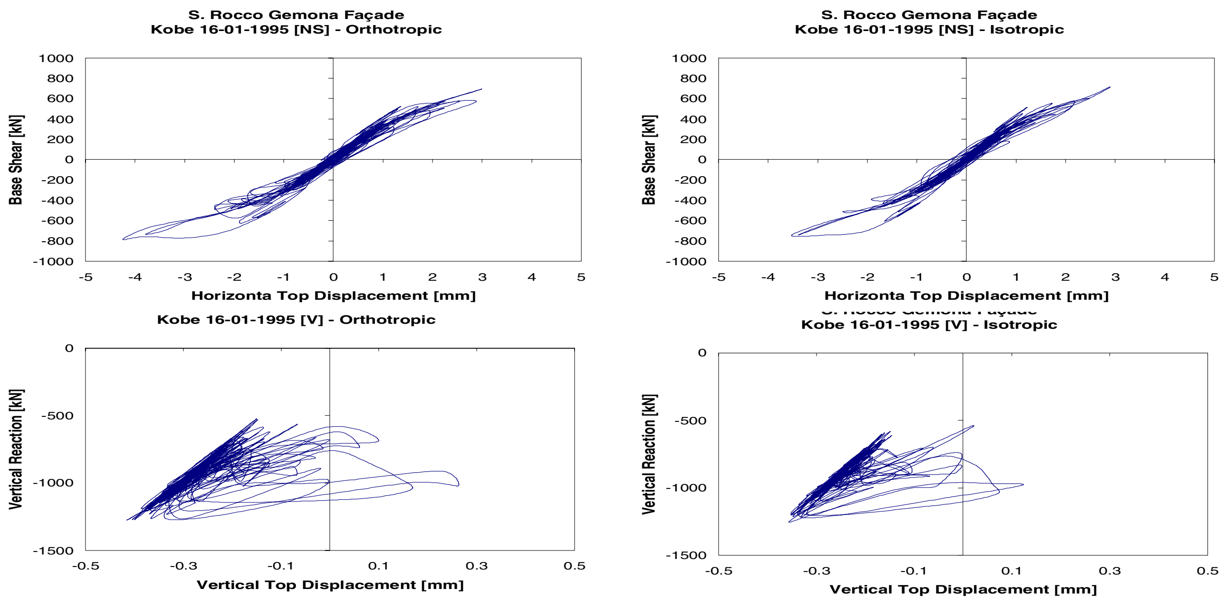


Figure 9. Base Force – Top Displacement curves: Horizontal a) Orthotropic, b) Isotropic and Vertical c) Orthotropic, d) Isotropic

CONCLUSIONS

The tension strength along the parallel direction of bed joints is given principally by the shear strength of the bed joint, while for the parallel direction, the tension strength is given by the tension strength of the bed joints. In the case studied here, tension strength in perpendicular direction of bed joints is almost 1% of the compression strength, while for the parallel direction the strength is almost 50%.

By using a rigid element model, a parametric study was performed. These first results show that non-tension material must be rejected as valid assumption; since this assumption would be equal to consider non-cohesion among different parts of the structure. On the other hand, to consider linear Mohr – Coulomb criterion without tension cut – off must be rejected too. This assumption results on very large tension strength and only shear damage is found.

Damage pattern and maximum responses are similar when isotropic or orthotropic material are used. However, some important differences are found between both behaviours. Thus, it is not recommended to substitute orthotropic behaviour with isotropic behaviour; even if it could be used when orthotropic parameters are not known.

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