Zeitschrift: Monuments vaudois. Hors-série
Herausgeber: Association Edimento - pour le patrimoine
Band: 1 (2013)

Artikel: Ethics and materials : some Spanish case studies
Autor: Huerta Fernández, Santiago
DOI: https://doi.org/10.5169/seals-1053497

Nutzungsbedingungen
Die ETH-Bibliothek ist die Anbieterin der digitalisierten Zeitschriften auf E-Periodica. Sie besitzt keine Urheberrechte an den Zeitschriften und ist nicht verantwortlich für deren Inhalte. Die Rechte liegen in der Regel bei den Herausgebern beziehungsweise den externen Rechteinhabern. Das Veröffentlichen von Bildern in Print- und Online-Publikationen sowie auf Social Media-Kanälen oder Webseiten ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Mehr erfahren

Conditions d'utilisation
L'ETH Library est le fournisseur des revues numérisées. Elle ne détient aucun droit d'auteur sur les revues et n'est pas responsable de leur contenu. En règle générale, les droits sont détenus par les éditeurs ou les détenteurs de droits externes. La reproduction d'images dans des publications imprimées ou en ligne ainsi que sur des canaux de médias sociaux ou des sites web n'est autorisée qu'avec l'accord préalable des détenteurs des droits. En savoir plus

Terms of use
The ETH Library is the provider of the digitised journals. It does not own any copyrights to the journals and is not responsible for their content. The rights usually lie with the publishers or the external rights holders. Publishing images in print and online publications, as well as on social media channels or websites, is only permitted with the prior consent of the rights holders. Find out more

Download PDF: 14.02.2026

ETH-Bibliothek Zürich, E-Periodica, https://www.e-periodica.ch

Ethics and materials

Some Spanish Case Studies

Santiago Huerta Fernández

In Navea, north of Spain, a medieval arch bridge shows a visible distortion[1]. A stone falls down from the web of a gothic vault in a big parish church in Burgos **(fig. 1)**[2], and a voussoir falls down from the rib of another gothic vault in Oviedo[3]. An oval dome collapses in Zaragoza, though another four identical domes remain safe[4]. Sometimes the building has to support new, heavier loads. The ruin of the abandoned (since the 19th century) monastery of Melón should be consolidated, some vaults are rebuilt and the visitors can walk over them[5]. A Franciscan Convent is going to be turned into a Cultural Centre, the loads to be supported being multiplied by a factor of two[6]. A little medieval bridge is asked to support the weight of heavy lorries[7]. These are some of the cases I have studied in the last two decades, all of them referring to questions of structural safety.

These are the kind of situations which often occur in the field of Historic Structures. They require a study and an answer. This is no scholarly work (though in some cases new lines of future research will emerge). A judgement must be made by the expert and this judgement affects safety, economy, and in the last instance, people. As there are rarely unique answers, the judgement of the expert, then, can also be deemed as "ethical", if he proposes an intervention that is necessary and adequate (or, recommends no intervention, judging the situation safe), or "non-ethical", if recommends an unnecessary or disproportionate intervention. In relation to the monument, also, the proposal can be judged ethically; any intervention damaging seriously the character of the monument may be labelled un-ethical.

A THEORETICAL FRAME

Any rational answer must be based in some kind of theory. The theory of masonry structures is, indeed, very old: the Pantheon, Hagia Sophia or the gothic cathedrals were not a matter of chance or the result of blind trial, but rather based on the knowledge of a Master builder. This knowledge was not based on the laws of mechanics and strength of materials, but more on a sound knowledge of their craft. The knowledge was codified in geometrical rules: the old masters knew that safety is a matter of geometry. We shall see that this is rigorously correct. Could it have been otherwise? Could any modern engineer or architect, any builder, think that structural design was "a vicious circle of ignorance which remained closed until Galileo cut it"?[8] The extraordinary success of masonry architecture through the ages demands a rational explanation; no construction stands centuries by miracle. We will use now the modern theory of structures. However, any structural theory is particular to the material and structural type: we cannot use elastic frame theory to understand masonry structures.

THE MODERN THEORY OF MASONRY STRUCTURES

Masonry structures are essentially different from the usual modern structures made of steel or reinforced concrete. The usual theory of structures taught in the Schools of Engineering or Architecture is useless to understand the behaviour of masonry architecture.

1 *A stone falls down from the web of a gothic vault in a parish church in Burgos (Photo S. Huerta Fernández).*

In fact, a scientific theory of masonry structures developed since the end of the 17th century (Hooke 1675, La Hire 1695, 1712), was perfected and put to use at the end of the 18th century (Coulomb) and was used for bridge design during the whole of the 19th century. The approach considered the material as discontinuous and looked for equilibrium states in compression. With the arrival of graphic statics (Culmann 1866) engineers and architects were able to obtain easily balanced solutions and, eventually, whole complex buildings were analyzed (Ungewitter/Mohrmann 1890)[9]. Of course, the masonry theory was regarded with great suspicion by the "cultivated" engineers who considered that only an elastic analysis was truly scientific.

In the first half of the 20th century a new theory developed : the plastic theory (or limit analysis) emerged as a response to the limitations of elastic analysis. The apparent precision of elastic analysis was demonstrated false when comparing the results of theoretical elastic analysis with the observed deformations in real buildings[10]. Indeed, the system of equations of equilibrium, elastic material and compatibility (boundary conditions) is extremely sensitive to very small changes, particularly of the boundary conditions. It was demonstrated as impossible to know the "true" or "actual" state of the structure, as these small changes are unknown and essentially unknowable.

Two decades of experimental and theoretical work culminated in the 1950's in the formulation of the Fundamental Theorems of Plastic Analysis. The Safe (or lower bound) Theorem solved the problem : a structure is safe if it is possible to find an equilibrium or balanced solution which does not violate the yield condition of the material (for example, in a framed structure, the bending moments are less or equal than the full plastic moment). In 1966, professor Heyman discovered that the Analysis of Masonry structures could be incorporated within the frame of Limit Analysis if the material masonry satisfies certain conditions : 1. masonry is infinitely strong, 2. has no tensile strength and 3. sliding is impossible. A material of this kind is called "standard" and the Fundamental Theorems are true.

The main corollary of the Safe Theorem is that equilibrium analysis is possible (Heyman's equilibrium approach)[11] ; that is, for usual structural assumptions (small deformations, ductile, stable behaviour), to demonstrate that a masonry structure is safe we only need to find an equilibrium solution with compressive internal forces (this validates the late 19th century graphical analysis). There is no need to make statements of compatibility. Equilibrium analysis of structures which supports mainly its load, lead directly to geometrical statements of the same kind as were used by the old Master builders.

The modern theory of masonry structures is ignored or questioned today by many engineers and architects, notwithstanding the overwhelming experimental and theoretical evidence. In what follows I will describe briefly the theory with a view of making some remarks at the end about ethical behaviour in relation to masonry structures.

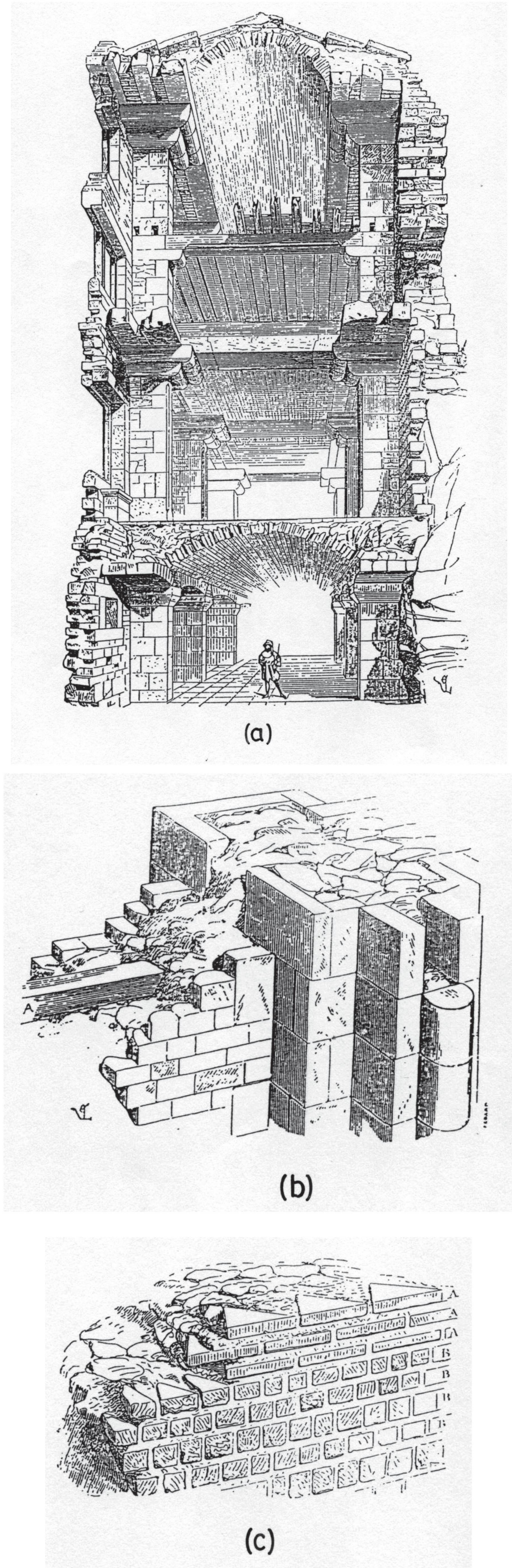
THE MATERIAL MASONRY

The material of historic architecture is not simply stone or brick, but stones or bricks plus a certain mortar and bonded in a certain way. We can produce a great variety of masonry using the same stone, from irregular rubble to ashlar masonry, passing through Roman concrete. Besides, masonry elements are composite structures. Maybe the best example is the medieval wall **(fig. 2b)**. The wall consisted of an external parament, made of ashlar masonry, and circa one foot thick (25-30 cm); the stone is usually of a certain quality as it must withstand the atmospheric agents (wind, rain, freezing). On the interior, we find another parament, maybe of the same thickness or less, usually built with low quality stone as it is protected. Between both paraments there is a filling made of irregular rubble masonry.

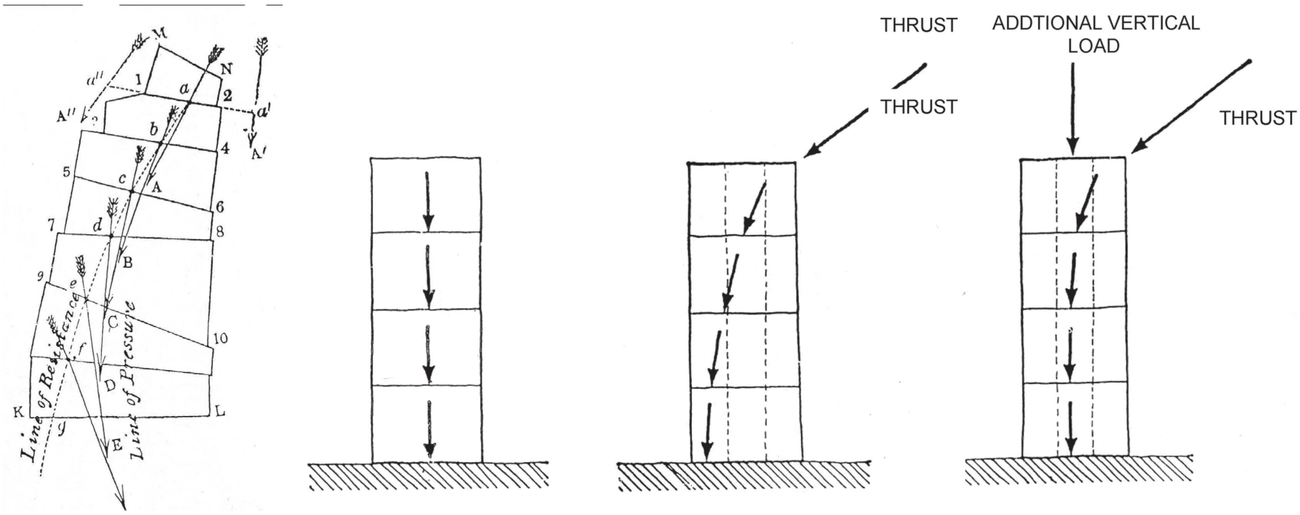
The question is: What properties can be assigned to such a material? The assignment of classical elastic constants will be, simply, nonsensical. The material is by its own nature discontinuous, irregular, with an unknown (and unknowable) internal constitution, cracked, with different qualities of mortar which present, along the centuries, different levels of deterioration. However, we need to make some statements about the material if we want to make a structural analysis. The fundamental statement is evident: Masonry is a material that must work in compression and has no tensile strength.

The next question will be what is the compressive strength of a certain masonry, made of a certain stone with a certain mortar. It is an impossible question to answer due to the essential irregular nature of the masonry. Fortunately, it is unimportant. The stress levels in masonry buildings are vey low and strength is very rarely a problem. Two observations may serve to prove that stresses are very low. First, we can use an 18th-19th century parameter to measure the crushing strength of stone: the height of column of uniform section which will crush at the bottom. The value of this limit height is simply:

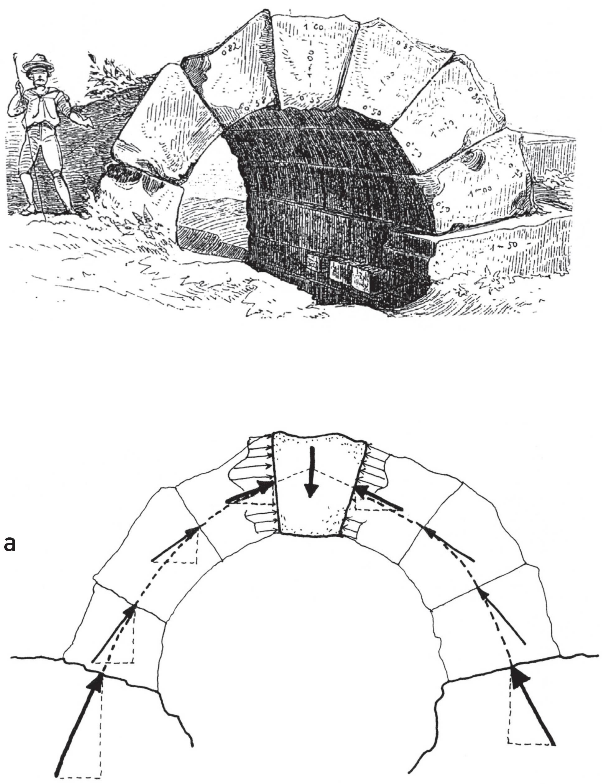
$$h_{lim} = \gamma/\sigma_c$$



2 *a) Section through a medieval building; b) and c) detail of a roman and medieval wall (Viollet-le-Duc 1858).*



3 *a) Definition of line of thrust (Moseley 1843) ; b) Thrust lines ; buttressing by loading (Gordon 1978).*



a

4 *Equilibrium of an arch (Huerta 2004).*

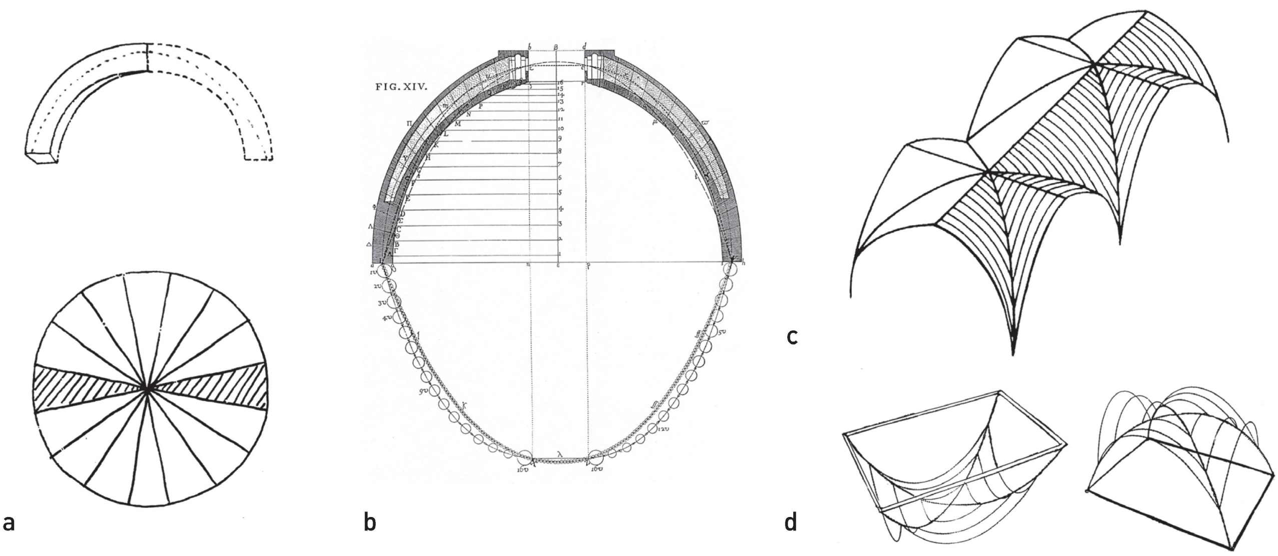
b

where γ is the specific weight and σ_c is the crushing strength. For a medium sandstone with $\gamma = 20$ kN/m^3 and $\sigma_c = 20$ N/mm^2, the limit height is 1000 m or 1 km ! The maximum sizes are one or two order of magnitude over the dimensions of even the greatest masonry buildings and bridges. It is to be expected, then, that stresses are indeed very low. It is remarkable, for example, that Benouville found in his analysis of Beauvais cathedral a stress of only 1.3 N/mm^2 at the foot of the columns supporting the highest gothic vaults (48 m)[12].

EQUILIBRIUM IN COMPRESSION

The requirement that the internal forces must be compressive forces implies that in every joint the stress resultant must be contained within the masonry. If the thrust approaches the border, then, a hinge tends to form. If we consider the material with infinite strength, the thrust could be applied at the surface of the masonry. The locus of the position of the thrust for a certain family of sections is called the line of thrust **(fig. 3a)**. This line is a graphical representation of the equilibrium equations. The material imposes that the line must be contained within the masonry as it appears. When the line of thrust touches the border a "hinge" forms.

Safety, then, is a matter of geometry : it is achieved if it is possible to draw a line of thrust contained comfortably within the masonry. In **Figure 3b**, in the middle, the



5 *Static analysis of vaults using the "slicing technique", illustrated by hanging models: a) and b) Domes (St. Peter's); c) Cross vaults (Heyman 1995; Poleni 1748).*

wall is in a dangerous situation (any increase of the inclined force on top will produce the collapse), though the stresses at the foot may be very low. Curiously, safety is achieved increasing the load on the structure. This device of buttressing by loading was well known by the old master builders[13]. In a buttress subject to a certain load the line of thrust is unique: we can calculate in every section the position of the stress resultant (however, we will be in trouble if we try to know the stress distribution, which will be greatly influenced by the actual constitution of the joint, the presence of stone wedges, the partial degradation of the mortar, the irregularities of the stone beds, etc.). The buttress is a statically determined (isostatic) structure.

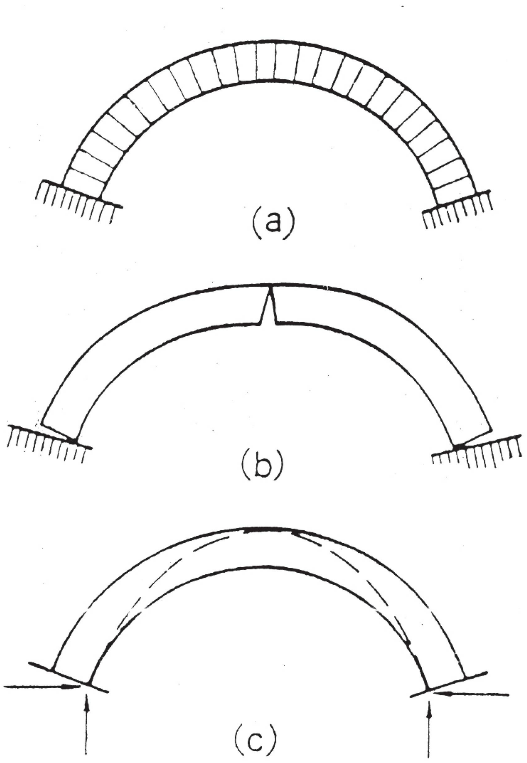
EQUILIBRIUM OF THE ARCH

With the arch it is different. Simple static considerations will show that it is possible to draw infinite thrust lines within the masonry, corresponding to infinite possible equilibrium solutions in compression. The arch is a statically indeterminate, hyperstatic, structure. We can examine briefly the statics. In **Figure 4**, we have an Etruscan voussoir arch. Stones were cut and set on a centring. When the centring is lowered the stones tend to fall but remain static due to the mutual thrusts which equilibrate from voussoir to voussoir. If we establish the equilibrium of any voussoir, we will see that the horizontal component of the thrust must remain constant: the thrust at the abutments is an inclined force, "the arch never sleeps", always is thrusting against the abutments.

The study of the equilibrium of more complex forms of vaults can be reduced, thanks to the Safe Theorem, to the study of a system of arches or blocks. Then, we may imagine a dome divided in arches by cutting it for meridian planes. Every two opposed lunes or "orange slices" form an arch; if the thrust line is inside the arch then, the dome divided in arches is stable and, per force, the real dome must be stable. In the case of a gothic cross vault, we may cut also the barrels into elementary arches which transmit their weight to the diagonal arches and, then, to the springing **(fig. 5)**. Again, a hanging model helps to understand the equilibrium (hanging models were used extensively by Gaudi to design his masonry structures).

CRACKS

An arch thrust against the abutment **(fig. 6a)**. The forces are transmitted to the foundations and eventually must be resisted by the soil. To produce the stresses to equilibrate these forces the soil must consolidate and settle. The arch in the figure must adapt to a certain increase of the span. To do this, the arch cracks: a crack form at the keystone, opening downwards, and two other cracks at the springing (in this case) opening upwards **(fig. 6b)**. The cracks can form because of the properties of masonry: very good (infinite) compressive strength, no tensile strength and no sliding. Three hinges form and the three-hinged arch is perfectly stable. Any movement of the abutments will cause a certain pattern of cracks. However, never more



6 *Cracking of a masonry arch due to a small yielding of the abutments (Heyman 1995).*

than three hinges form, and the arch remain stable, being unaffected by these small movements. In every case, there is a different thrust line, that is, a different solution of internal forces in equilibrium with the loads. The changes are drastic: a joint which in one case has a central thrust may have, after a little movement, a hinge.

Now, the crucial point is this: very small movements of the abutments (changes in the boundary conditions) lead to radical changes in the internal forces. And these movements are impossible to predict. The usual assumption of an arch on rigid abutments (no displacement, no rotation) is just impossible to obtain in practice. Cracking is what gives plasticity to masonry. Cracks are not the prelude of the ruin, nor dangerous, but they are natural in a no-tension (unilateral) material. The possibility of cracking is essential to the survival of any masonry structure. Besides, cracks give us most valuable information on the behaviour of the structure.

The different types of vaults have different patterns of cracking. For example, in domes, the usual crack patterns correspond to a small yielding outwards of the dome supporting structure (maybe a drum). These tiny radial displacements will inevitable produce meridian cracks. This happened in the dome of the Pantheon **(fig. 7)**, when the plaster was removed for restoration at the beginning of 20th century, large cracks appeared. It is obvious that these cracks occurred during the period of settlement of masonry and foundations, say, 20 years after the termination of the building. They have been present, though hidden, for more than 1900 years. May we agree that they are not dangerous?

Gothic vaults present also typical cracks. The drawing by Abraham shows the three main types of cracks: keystone cracks, Sabouret's cracks and wall cracks **(fig. 8)**. Heyman has explained their origin as a consequence, again, of a small yielding of the abutment system. These cracks are necessary for the structure to adapt to the "aggression" of the environment, and, as with the cracks in arches and domes, not only are not dangerous, but they give plasticity to the structure. In many cases, the cracks has been filled and covered by plaster, but the eye of the expert will find them.

The distortion of the vault may give rise to some local problems, particularly if the vault has suffered abandon and the entry of water. The joints may have deteriorated, the mortar partly disappeared, and, eventually, some stone from the webs or the ribs can fall down. This will not compromise the stability of the vault as a whole; though it is potentially dangerous to the prayers **(fig. 1)**. A master mason, working on a light scaffold, will easily "re-position" some stones and replace the deteriorated mortar or even light up some ribs or keystones so that the vault recovers its geometry and strength.

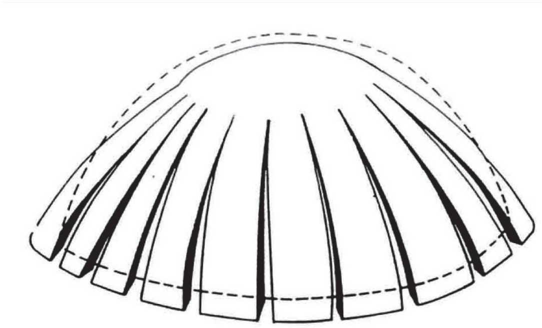
Any masonry building is also cracked as before and the cracks may be visible, or they can be hidden behind plaster or a new ashlar parament. Viollet-le-Duc expressed beautifully this capacity of masonry buildings to adapt themselves to a changing environment:

> Ce squelette est rigide ou flexible, suivant le besoin et la place; il cède ou résiste; il semble posséder une vie, car il obéit à des forces contraires, et son immobilité n'est obtenue qu'au moyen de l'équilibre de ces forces (…)[14].

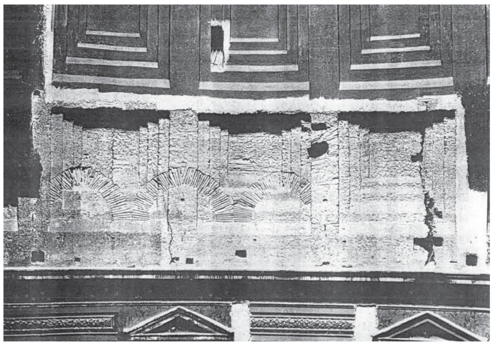
FEAR, IGNORANCE AND ETHICS

At the beginning of this contribution we have described some problems of intervention. I believe that now we may have another perspective. There are several possibilities.

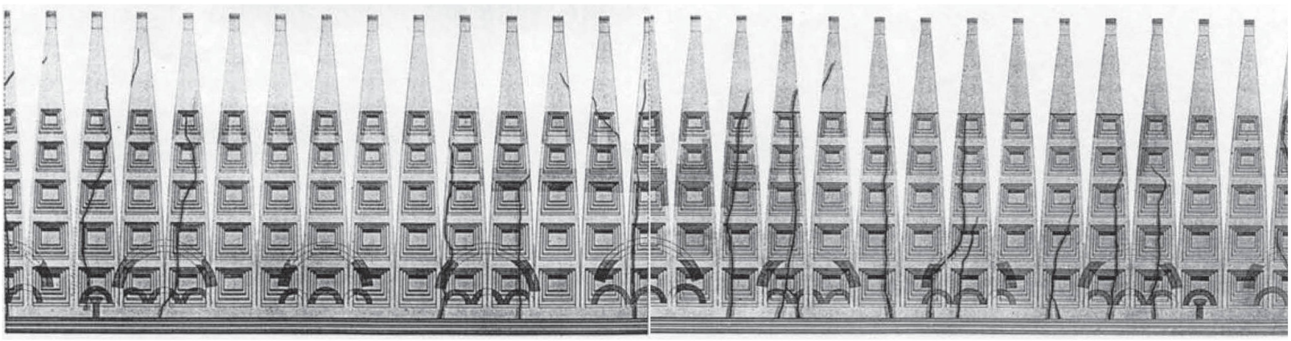
It may be that there is no problem at all (the medieval bridge is stable and has been in its distorted form for a



b



c



7 *a) Typical cracks in a dome (Heyman 1995) ; b) and c) Cracks in the Pantheon. The cracks were hidden until the removal of the plaster for restoration (Terenzio 1933).*

several centuries) ; the problem may be local (the voussoir or stone which falls down from a gothic vault) ; the problem may have been produced by a badly made intervention (the removal of some wooden struts which supported the heavy lantern of the dome in Zaragoza) ; and, finally, it may be that the situation is serious (there is real danger, the structure can collapse and could provoke loss of life).

In the case of a necessary intervention, there are also some possibilities. It may be that the problem is originated by a concrete factor that can be solved readily with safety and economy of means. But the same problem can be solved at great expense, making unnecessary studies, dismounting a big part of the structure, erecting heavy scaffolds… Also, the proposed intervention can be respectful towards the monument, without modifying its nature, or may be aggressive, introducing arbitrarily large amounts of modern materials. The expert, then, is handling not only a technical problem, but an ethical problem. We may all agree that a big unnecessary intervention is non-ethical. That to solve a non-existent problem is non-ethical. That to promote an expensive invasive intervention when a more cheap and respectful one is possible is non-ethical. That to involve the mass media to alarm the population, when there is no such urgency, is non-ethical. It will also be non-ethical not to denounce a really dangerous situation ! We are faced with fear, ignorance and greed.

FEAR

The main problem is fear, and cracks are a good example to gauge the fear and its consequences. We have seen that cracks are natural in a non-tension material. Cracks are "good" because they afford the building the possibility to adapt to the aggressions of the environment. Cracks give a lot of information with reference to the actual behaviour of the structure.

This contrasts radically with our appreciation of cracks. We labelled cracks as "lesions" or "damages"; we speak of "pathologies", pathology being the study of diseases. Old buildings are cracked and, therefore, are "ill", and they require urgent intervention. We try to stop the cracks in many fanciful ways, perhaps "nailing" the crack with cramps (a popular and completely useless intervention which will break the stones). Cracked arches are many times stitched with steel or carbon fibre bars, anchored with Portland cement (before) and, now, with epoxy. The aim is to convert the arch in a monolith which weakens and eventually damage the arch, because it reduces or eliminates its plasticity. A cracked building, completely safe, may be the object of intense (unnecessary) study, simply because the cracks are interpreted as a sign of danger and of future ruin.

IGNORANCE

The origin of the fear which cracking produces lies in our ignorance of the true nature of masonry. There are no excuses for this ignorance. Cracks were considered as something normal by all the writers on architecture and construction. Only in very special cases, like in St. Peter's, the cracking caused some concern [15].

As we have seen the theory of masonry arches and vaults is three hundred years old. The modern theory which explains the crucial role of cracking in the plasticity of masonry buildings is already fifty years old. We may enunciate a law, analogous to the sentence cited by Tredgold (1831) with reference to the ignorance of practice of some engineers (mainly French): "the stability of a building is inversely proportional to the science of the builder". Paraphrasing this, we may say: "the knowledge about masonry structures is inversely proportional to the fear of cracks".

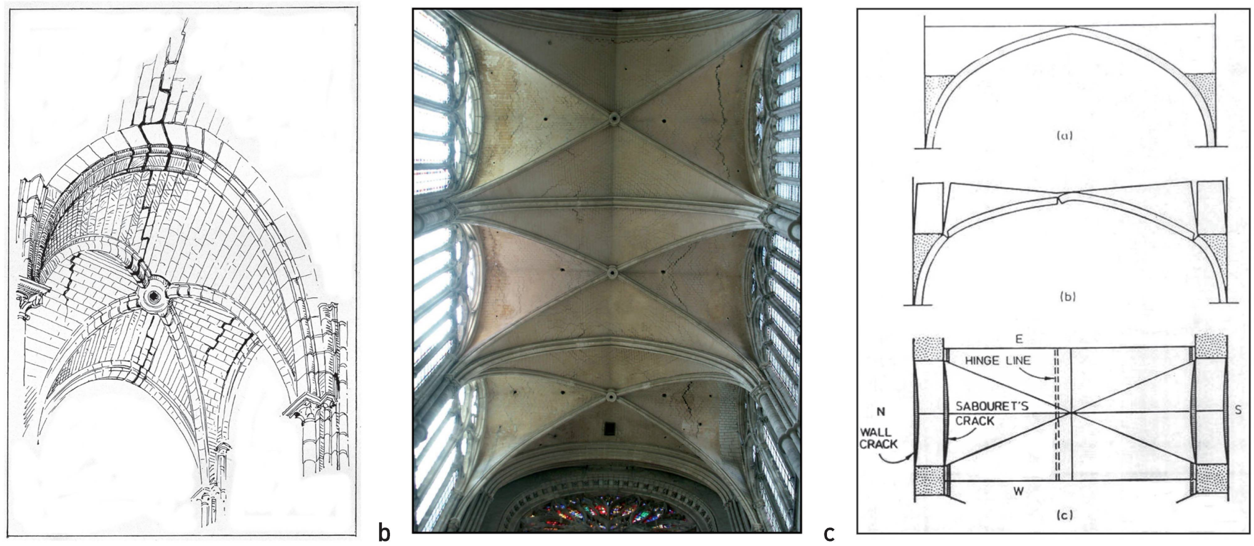
Ignorance leads to fear. The reaction to fear is "defensive", and it may be "aggressive". We see in many interventions today the consequences of both responses. Suddenly, buildings which have stood for centuries with minimal maintenance are in imminent danger. However, the force of gravity has not changed sensibly, nor the usual loads of wind, snow, etc. It also does not appear that the seismic risk has increased.

The tempo of a big substantial maintenance intervention was, historically, around 100-150 years. In the Pantheon, the previous intervention to that of Terenzio was ca. 1750[16]; Piranesi drew the rotating scaffold for the restoration of the intrados which represented the hidden relieving arches at their springing. It is significant that he drew no cracks! Thanks to the high-tech approach of intervention, we have divided this tempo by a factor of five. Anyone working in restoration is repairing buildings which were repaired 20 years ago and it is not uncommon that part of the intervention is trying to remove the "reinforcement" added before.

ETHICS

We have, then, a problem of ethics. We must change our attitude to historic masonry buildings, increasing our knowledge about them. If the reaction to ignorance is fear, the reaction to knowledge is respect and appreciation. This knowledge is contained in the old architectural and engineering treatises which has survived partially in certain masonry circles and is evident in the buildings themselves. This knowledge allowed the maintenance of historic architecture for centuries or millennia. There are a lot of arguments in favour of the use of traditional techniques whenever possible. Modern techniques should be used with moderation.

Finally, we should mention a taboo topic in restoration: the problem of greed (money). This is also big business, like urban planning or residence construction, which moves huge amounts of money. In many occasions, the experts working in this field suffer a lot of direct or indirect pressure to make great, massive and expensive interventions. We should be aware that it is not uncommon that a cocktail of "ignorance, fear and greed" occurs. It should be counteracted by knowledge, respect and responsibility, the goal being always the adequate maintenance and care of our monuments[17].



8 *a) Cracks in gothic cross vaults (Abraham 1934); b) Cracks in Amiens (Photo I. Tarrío); c) Explanation of the origin of the cracks (Heyman 1995).*

NOTES

1 Santiago Huerta Fernández, Gema López Manzanares & J. I. Hernando García, *Informe sobre la estabilidad del Ponte Navea (Ourense)*, Technical Report, Universidad Politécnica de Madrid, Dirección Xeral do Patrimonio Cultural, Xunta de Galicia, 1999.

2 Santiago Huerta Fernández, Gema López Manzanares & E. Redondo Martínez, *Informe sobre la estabilidad de la iglesia de Santa María*, Technical Report, Universidad Politécnica de Madrid, Consejería de Educación y Cultura, Junta de Castilla-León, 2001.

3 Santiago Huerta Fernández, *Informe sobre las bóvedas del convento dominico de Nuestra Señora del Rosario*, Technical Report, Universidad Politécnica de Madrid, Dirección General de Cultura de la Consejería de Cultura del Principado de Asturias, 2002.

4 Santiago Huerta Fernández & Gema López Manzanares, *Estudios estructurales previos a la restauración de la iglesia de Santo Tomás de Villanueva (La Mantería) de Zaragoza*, Technical Report, Universidad Politécnica de Madrid, Instituto de Patrimonio Histórico Español, 2001.

5 Santiago Huerta Fernández, *Estudios de análisis estructural y consolidación del Monasterio de Melón (Ourense) como asistencia técnica a la ejecución del proyecto de consolidación de la ruina*, Technical Report, Universidad Politécnica de Madrid, DICSA, 2003, 2004, 2010.

6 Santiago Huerta Fernández & E. Rabasa Díaz, *Informe sobre la estabilidad y consolidación de las bóvedas del claustro de Sant Bonaventura de Llucmajor (Mallorca)*, Technical Report, Universidad Politécnica de Madrid, Servicios de Mantenimientos Llabrés Feliú, S. L., 2006.

7 Santiago Huerta Fernández, M. Durán Fuentes & Gema López Manzanares, *Informe sobre la estabilidad del Ponte de Vilanova en Allariz (Ourense)*, Technical Report, Universidad Politécnica de Madrid, Sociedade Pública de Investimentos de Galicia, 2001.

8 William Barclay Parsons, *Engineers and Engineering in the Renaissance*, Cambridge 1976 (1st. Ed. 1939).

9 Jacques Heyman, *Basic Structural Theory*, Cambridge 2008; Santiago Huerta Fernández, "The Analysis of Masonry Architecture: A Historical Approach", in *Architectural Science Review* 51, 2008, pp. 297-328.

10 Jacques Heyman, *Structural analysis: a historical approach*, Cambridge 1998.

11 Santiago Huerta Fernández, "Mechanics of masonry vaults: The equilibrium approach", in *Historical Constructions 2001. Proceedings of the 3rd. International Seminar (Guimaraes 7-9, November),* ed. by P. B. Lourenço and P. Roca, Universidade do Minho, 2001, pp. 47-69.

12 Léon Benouville, «Étude sur la cathédrale de Beauvais», in *Encyclopédie d'Architecture*, IV, 1891-1892, pp. 52, 60-62, 68-70, Pl. 159-161.

13 Santiago Huerta Fernández, *Arcos, bóvedas y cúpulas. Geometría y equilibrio en el cálculo tradicional de estructuras de fábrica*, Madrid 2004.

14 Eugène-Emmanuel Viollet-le-Duc, *Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle*, Paris 1854-1868.

15 Giovanni Poleni, *Memorie istoriche della Gran Cupola del Tempio Vaticano*, Padova 1748.

16 Alberto Terenzio, «La restauration du Panthéon de Rome», in *La conservation des monuments d'art et d'histoire*, Paris 1933, pp. 280-285, Pl. 25, 26.

17 James Edward Gordon, *Structures, or Why things don't fall down*, Harmondsworth 1978; Jacques Heyman, "The Stone Skeleton", in *International Journal of Solids and Structures* 2, 1966, pp. 249-279; Jacques Heyman, *The Stone Skeleton. Structural Engineering of Masonry Architecture*, Cambridge 1995.