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Morphology of Roman, Islamic and Medieval seismic design: pointed arch and ablaq

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Abstract. In ancient written sources earthquakes were mostly interpreted as a divine punishment for human sins, only few authors instead interpreted the seismic event as a phenomenon independent from human actions. Considering the built architectures as material documents, several examples can be found, suggesting that there was an empyrical knowledge of the consequences of earthquakes on buildings. Modern literature on the topic, mostly within engineering studies, lacking an historical approach, assumes that in ancient times science ignored the physical nature of seismic events and consequently declares that architects couldn't consider dynamics in their projects. The close examination of some examples shows clearly that Roman, Islamic and Medieval architects had an empirical knowledge of dynamics, probably based on post-seismic reconstruction. This knowledge developed through history, so it is possible to outline a history of seismic design way before the Lisbon earthquake (1775), considered by many authors as the beginning of the history of seismic design.

Thou hast made the earth to tremble;
thou hast broken it:
heal the breaches thereof; for it shaketh.

Psalms, 60, 2

Seismic design and ancient material culture

The cultural evolution of earthquake knowledge since ancient times reveals an interesting double track: on one hand the religious culture and on the other the scientific and material culture. The religious culture of pagans, jews, christians and muslims interpreted the earthquake as a divine *sign*, either for an offense to the gods, or as a punishment for human sins: a *sign* that could be answered only in a *mystical-religious* key, with sacrifices or through penances for forgiveness. Nevertheless there was also a ancient scientific culture that tried to explain the nature of earthquakes and a material culture that designed new architectural elements to improve the seismic response of buildings. While the official culture didn't interpret the seismic phenomenon yet, the working culture of builders, understanding earthquakes and showing knowledge of the dynamic behavior of buildings, introduced some innovations to mitigate the effects of horizontal and vertical accelerations that occur when the earth moves. Considering that in the middle ages, during religious persecutions, a supposed knowledge of the nature of earthquakes could have been easily interpreted as witchcraft, we shouldn't be surprised by finding very little written information on the topic. The material documents of built architectures testifies, though, the development of an oral tradition that shared information on the art of building and that could be considered as the innovative motor of Medieval European architecture. Most recent literature on the topic [1] describes ancient times permeated by a *culture of myths* and recognizes the birth of seismic concepts only in modern times following the geological understanding of earthquakes (1850). Some authors instead state that the *history of seismic design* starts with the Lisbon earthquake (1755) [2]. Besides the existance of treatises on earthquakes and architecture in the XVI cent. [2b], which can be considered a good proof of the existence of seismic design in ancient times, if we examine closely the diachronic evolution of architecture we will notice several built examples showing that seismic architecture has always been practiced and has developed gradually as any other branch of science. No matter wether conceived in an empirical manner, or based on a deep knowledge of mechanics [3], these examples are witnesses to the response of the material and scientific culture to the seismic phenomenon. In fact, the invention of empirical solutions is largely due to observation and reasoning about the effects earthquakes: certainly the experience of reconstruction, repair and restoration after an earthquake [4], employing workers in *pre-capitalist* times more than in the construction of the new architectures, was an important moment for the experimentation of new seismic solutions to be verified after the next earthquake. Cairoli Giuliani [5] finds after the Antioch earthquake of 115 AD the first experimentation of new seismic techniques followed by the work of Apollodorus of Damascus, architect of Trajan's markets in Rome and Hadrian's master. There was an ancient theoretical seismic knowledge; several authors wrote about earthquakes, it was definitively an interesting argument for science. We can remember Seneca and Pliny the Elder. For Aristoteles the earthquake was an effect of underground winds, an empirical deduction from the evidence of strong winds before earthquakes: this interpretation should be considered seriously as it finds a cause of seismic phenomena independent from human actions and represents the scientific culture as opposed to dogmatic religious culture. As a working hypothesis, the development of the seismic design could have been influenced by earthquakes, as design was necessary where earthquakes were frequent and of great intensity. Out of the 28 earthquakes with intensity greater than 10, from 500 to 1300 AD, only one – the Sicilian 1189 earthquake – happens to be in Italy (Table 1). Big earthquakes in the Mediterranean basin during the middle ages happened mostly in the middle-east, this explains the reason why seismic design improvements mostly derive from that area.

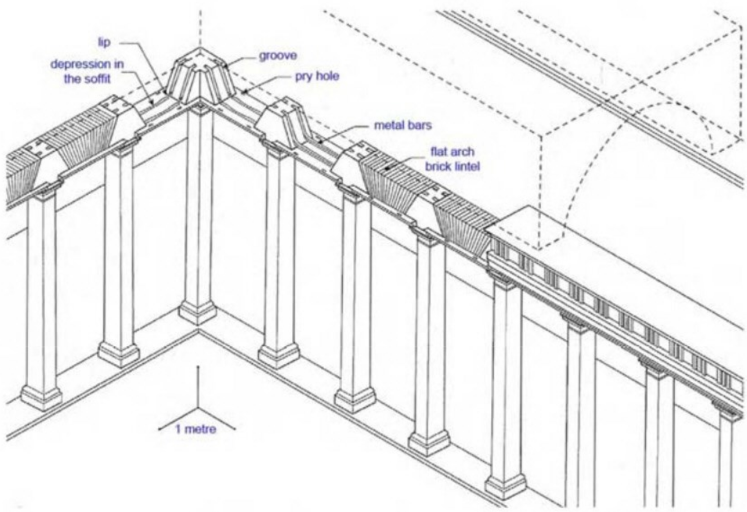

Fig. 1 Hall of the Doric Pilasters in Hadrian's Villa (125-133 AD): lintel with metal connections [6].

Table 1 Earthquakes in the Mediterranean basin, Io > 10, (500-1300 AD) [7].

Date	Io	Me	Location	Country
1296 07 17	10	6.3	Bergama	Turkey
1269 04 17	10	6.3	Cilicia	Turkey
1254 10 11	10	6.4	Erzincan	Turkey
1213 06 22	10	6.4	Isauria	Turkey
1202 05 20	10	7.6	Lebanon	Lebanon
1170 06 29	10	7.7	Syria,Lebanon	Syria

1169 02 04	10	6.4	Sicilia orientale	Italy
1157 08 09	10	6.4	Tall Harran	Syria
1121 12 18	10	6.4	Samah	Turkey
1115 11 29	10	6.3	Yakapinar	Turkey
1114 11 13	10	6.3	Maras	Turkey
1045	11	6.8	Erzincan	Turkey
926-927	10.5	6.6	European Turkey	Turkey
893 12 27	10	6.4	Artasat	Armenia
863 02 13	10.5	6.6	Artasat	Armenia
740 10 26	10	6.4	Yalova	Turkey
735	10	6.4	Vajoc' Jor	Azerbaijan
679 04 03	10.5	6.6	Sürüç	Turkey
601, 602	10.5	6.6	Turkey, Syria	Turkey/Syria
588 10	10.5	6.6	Antioch	Turkey
570	10.5	6.6	Antioch	Turkey
557 12 14	10	6.4	Yesilköy/Küçük Çekmece	Turkey
551 07 09	10	6.4	Beirut	Lebanon
551	10	6.4	Chaeronea	Greece
526 05 29	10	6.4	Antioch	Turkey
523/525	10.5	6.6	Aysehoca	Turkey
518	10	6.4	Skopje	Macedonia
502 08 22	10	6.4	Akko	Lebanon

Symmetry and earthquakes: from Roman techniques to the Islamic development

The ancient predilection for architectures with symmetrical plans is derived from the empirical observation that symmetrical buildings do better withstand earthquakes, as reflected in modern equivalent static analysis: the coincidence between the center of gravity and the centre of stiffness in plan, in case of horizontal accelerations, does not produce a twisting moment and generally contributes to the resistance of the building. The observation of consequences of earthquakes on buildings brought to the consideration that symmetrical buildings have more resistance. When the direction of horizontal acceleration coincides with the axis of symmetry the response is even better, so as many axis of symmetry a building has, as many possible directions of acceleration can be resisted by its configuration. The polar plan, adopted for religious buildings in most cultures, is interpretable as the most seismic resisting configuration used for collective and symbolic buildings.

The roman engineering culture used several elements to compensate the horizontal accelerations, i.e. metal joists connecting stonework in walls [8], arches and entablatures, the progressive reduction in height of the specific weights of building materials, as in the Pantheon, or the choice of building materials with different specific weights in different parts so to control the dynamic response, as in the Flavian Amphitheater in Rome [9]. Another consideration should be mentioned about the *opus graticium or craticium*, half-timbered in English, *fachwerk* in German, [10] as well as base isolation using stones without mortar [11, 12, 13], since ductile structures dissipate more energy than rigid ones and in earthquakes energy dissipation is fundamental for resistance

Seismic origin of pointed arches

The arch with a variable section – a round arch in the intrados and an extrados with a pointed profile – widespread in the XIII century in the Apennine area (Toscana, Marche and Umbria) could be derived from the Moorish arch through Spain. There are two different Italian arches, largely used from the middle ages until the Renaissance classical revolution, that were conceived as a melioration of the rounded arch: the so called *Florentine arch*, basically an arch with circular extrados and intrados but with an extrados centre slightly upward, and the so called *Italian pointed arch*, with rounded intrados and lancet extrados. These two different but similar configurations, requiring a large expense in cutting the voussoirs, for sure were not decorative choices but rather an empirical static melioration of the rounded arch.

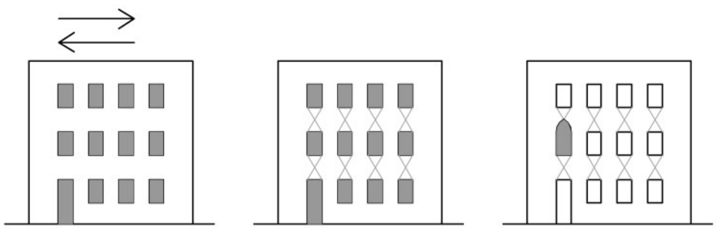

Fig. 2 Horizontal shear stressed wall, cracking pattern, lintel collapse generating pointed arch profile (Author's drawing, 2014)

The observation that arches usually brake in the intrados close to the key-stone, suggested the idea of enlarging the arch in that area. Do these arches really act as more resistant than the rounded ones? This is an answer that engineering studies should consider. Examples are windows and doorways in Palazzo Medici Riccardi, designed by Michelozzo di Bartolomeo (1445-1460), or the arches of the windows and the main entrance of Palazzo Vecchio in Florence, designed by Arnolfo di Cambio in 1299, or Palazzo Strozzi begun in 1489 by Benedetto da Maiano. This same variable section of the arch, but with a different shape, is found also in the *Moorish arch*, and since this kind of arch became a stylistic character of Islamic architecture, together with the raised arch concept and the *joggled voussoirs,* we can hypothesize that all these elements have seismic functions and can be interpreted as an evolution of roman architecture. The Gothic arch is considered by many historians as a technical improvement of the rounded arch, derived from the experience of Islamic builders in Spain. The opening in a wall with a pointed shape can be interpreted as a seismic design element: if we consider the breaking mechanism of a horizontal shear stressed wall with rectangular windows, with the typical crosses, and imagine that the triangular part over a rectangular window detaches from the wall, we obtain a pointed arch window. Derived from the empirical observation, the experience of repairing a damaged window may have suggested the change of the form of the wall opening. The introduction of rose windows in the facades of medieval churches lightens the pediment which is not connected with other stone elements and often rotates out of his plane following a horizontal acceleration. The close observation of damage after an earthquake spots the breaking of the upper part or the facade of churches as very common; the horizontal acceleration impressed by the earthquake to the front wall, capsizes the pediment and its upper part rotates outside of its plane. The round *oculi* inserted in the upper part of the pediment, and later the rose window, don't only have a decorative function but also act in lightening the upper part of the facade wall.

From joggled voussoirs to *ablaq*

The use of *joggled voussoirs* for lintels and arches was first developed by Roman engineers, we can find an early example in the eastern entrance of the Sabratha Amphitheatre (II cent. AD) in Libya [14]. The function of this very expensive kind of stonework was to ensure the connection of voussoirs in case of horizontal movements during an earthquake, preventing single elements from sliding downwards after decompression. It was intended in the beginning as a substitute for metal connections, after the crisis of the Roman Empire in III cent. it was difficult to handle great quantities of metal. Starting from the Roman experience this technique was widely adopted, such as in the lintel of the *Porta Aurea* of Diocletian's Palace in Split (305 AD) [15] or in the inside lintels and outside arches of the Mausoleum of Theodoric in Ravenna (520 AD) [16].

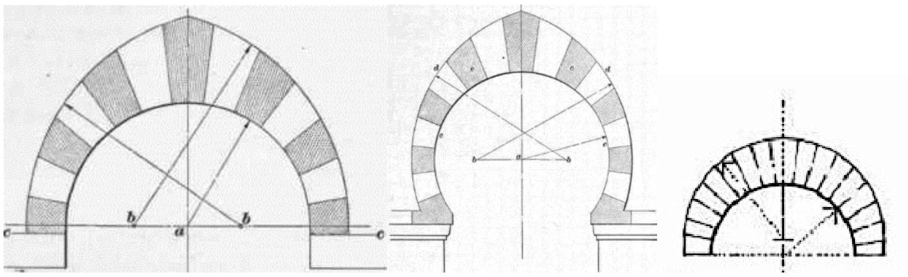

Fig. 3 Italian pointed arch; Moresque arch; Florentine arch; entrance to the Cathedral of Prato, lintel with joggled voussoirs, XIV cent.

Fig. 4 Rusāfah, city wall, north gate, VI cent.; Bāb al-Futūh, Cairo, 1087; Aleppo gate to the citadel, XVI cent.

We can also find this same stonework in the Byzantine *praetorium* of Halabiye [17], built in Syria during the rule of Justinian I (545 AD) and described by Procopius [18]. The technical device was later imported into Islamic architecture with the name of *ablaq.* The first known example is the lintel over the southern gate to the Qasr al-Hayr al-Sharqi in Syria, built by the Umayyad caliph Hisham ibn Abd al-Malik (728-729 AD). It can be found in several other Islamic buildings such as the gate to the Fatimid walls of Cairo, Bāb al-Futūḥ, (1087 AD), becoming later a typical expression of Ayyubid architecture in XII century, and in the XIII century of the Mamluk architecture. It is reasonable to hypothesize that examples found in western architecture derived from models, invented by the Romans, developed in the Islamic world, and then imported back to Europe through Spain, Pisa, Venice, Amalfi, and the crusaders. There is an example of a spatially complex bichrome joggled lintel in the transect entrance to the Prato Cathedral (1317-1386) or in the lintel below the XV century Foscari arch in the ducal palace of Venice. The vertical progression of the openings from single to multi-light in most medieval bell towers in Italy, such as the Bell tower of S. Apollinare Nuovo in Ravenna or the Pomposa abbey bell-tower, is in fact a device to reduce gradually the mass of the structure in height so to reduce horizontal accelerations. It is clearly a seismic design principle that became later a stylistic trait of romanic bell tower architecture. We can thus consider the experience of rebuilding after an earthquake as the premise for the seismic melioration of architecture even today [19, 20, 21].

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PREFACE

S.M.ART. BUIL.T. "Structural Monitoring of ARTistic and historical BUILding Testimonies" is a project founded by the European Territorial Cooperation Programme Greece-Italy 2007/2013 and leaded by the Polytechnic of Bari. The core idea of "S.M.ART. BUIL.T." is risks prevention, which concerns not only the prevention of loss of lives and properties, but also the preservation of artistic and historical buildings from natural hazards.

Architectural heritage is an important part of the history and identity of Italy and Greece, contributing to their economy and well being. On the other side, ancient buildings suffer a high vulnerability to dynamic loads, which may induce an unpredictable partial or total collapse. Recent past experience after L'Aquila earthquake strongly evidence this problem.

The main objectives of the international project "S.M.ART.BUIL.T." are the implementation of procedures for the structural monitoring, the seismic vulnerability assessment, the development of guidelines for strengthening and repair of the historical buildings (in Trani and Corfu). The project aims at providing to technical officials of the territorial authorities of Puglia and Ionian Islands Regions some indispensable training tools for the development and/or validation of structural restoration projects and seismic rehabilitation of historical buildings. Most of buildings of artistic value, in the two historic centers, are invariably built of masonry, a material as old as the civilization and with a 10,000 years record of success and lasting qualities, representative of a widespread typology in the Mediterranean area.

The final step has been the International Conference titled "HISTORICAL CENTRES AMONG CULTURE, ART AND TECHNIQUES: A NEW PARADIGMA FOR RISKS PREVENTION THROUGH STRUCTURAL MONITORING", which also represents the most important action of diffusion activities of the S.M.ART.BUIL.T. project.

The Final Conference has been open to all experts in the following topics: seismic and structural monitoring, historical and artistic heritage, computational and technological issues applied to historical heritage, in order to exchange experience of correlated research areas. The main purpose has been to make the conference a forum for dissemination of the latest scientific and technical developments and for exchange of new ideas in emerging topics of the project.

The main conference topics has been divided into three areas and chapters, following the three main souls of the project:

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2. STRUCTURAL AREA
3. COMPUTATIONAL AND TECHNOLOGICAL AREA

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Table of Contents

Chapter 3: Computational and Technological Area