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EARTHQUAKE RESISTANT CONSTRUCTION IN CLASSICAL ROME

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ABSTRACT

A significant number of advancements in construction technique and structural design emerged during Republican and Imperial Roman times. Some of these advances, particularly the development of Roman concrete, led to natural improvements in the aseismic properties of structures. These developments and their role in resisting seismic attack are investigated. In order to better understand the nature of these advances in aseismic construction, a brief discussion of the Roman understanding of earthquakes and their effects is also presented.

KEYWORDS

classical Rome, empirical technology, history, monolithic construction, pantheon, Roman architecture, serendipity

INTRODUCTION

Seismic resistant design, as an applied science, has only come into existence in the twentieth century. Founded on the basic principles of Newtonian mechanics, one can argue that even a cursory understanding of the principles involved in resisting seismic attack have existed for only a few hundred years. Despite this, many of the basic elements of construction technology capable of imparting seismic resistance, have been incorporated in structures dating from Roman times. It is important to appreciate, however, that elements of seismic resistant design inherent in classical Roman structures are little more than serendipity.

The role that Roman society and politics played in the development of new construction technology and methods is paramount. In particular, aesthetics and the philosophical basis of Roman government played a large role in the changes in construction technology evident in Republican (c. 200 to 27 B.C.) and Imperial (27 B.C. to c. 200 A.D) Roman society. Scientific or technological understanding underlying Roman construction technology are entirely empirical in nature. In fact, it has been noted by many scientific historians that "the Romans seem to have cared for science only as means of accomplishing practical work in medicine, agriculture, architecture or engineering." (Dampier, 1936).

This paper investigates developments in building technology which we may now appreciate as contributing to our modern science of seismic resistant design. In addition, the Roman understanding of earthquakes and their effects are also discussed.

Whether Republican or Imperial, Roman state structure was characterised by its ability to organise and govern. The Roman state maintained a large army that could be used for public works and had at its disposal vast numbers of conquered slaves that could be employed as unskilled labour. Pre-Roman construction methods, such as the entabulated form of the Greeks, involved skilled quarrying and cutting of large structural components. This could be ventured only by societies of skilled craftsmen and masons. The Romans, with their armies of unskilled labour, developed a unique construction technique. Under the guidance of a few professionals and an architect, vast quantities of fine construction material were assembled, and construction proceeded as a series of monotonous operations carried out by the massive labour force. The result of this basic shift in construction methodology was a new form of monolithic concrete construction (Harries, 1995).

Roman structures of monolithic concrete are exceptionally rigid, quite different from the earlier Greek structures consisting of stone blocks connected with ductile ties. The respective rigidities of these structural forms were accounted for in the designs of the foundations. In Greek construction, foundations were independent under the load bearing elements of the structure. Because of the ductile nature of the superstructures, unequal settlements or relative ground motions caused little stress in the structure's members. The rigid Roman structures were founded on massive foundation mats, themselves exceptionally rigid, insulating the superstructure from the effects of relative ground displacements. The extent to which the design of foundations was understood and studied far outstripped the contemporary understanding of most other aspects of structural design. This can be seen by the emphasis placed on foundations by Vitruvius in *De Architectura* (e.g.: I 5, III 4, V 3, and VI 8).

Roman Concrete Construction

Monolithic Construction - Roman concrete (Harries, 1995) was placed manually in horizontal courses, alternating layers of mortar and relatively large stone aggregate. The concrete was placed between light masonry falsework which later formed the exterior of the finished walls. The resulting structures appear to be constructed of light masonry, but clearly behave as a monolithic mass. Figure 1 illustrates the method of constructing monolithic Roman concrete. Figure 2(a) shows an example of a seismically induced crack which has clearly propagated through a monolithic media rather than following the edges of the brick falsework and relieving arch (see below), as would be expected in a masonry structure.

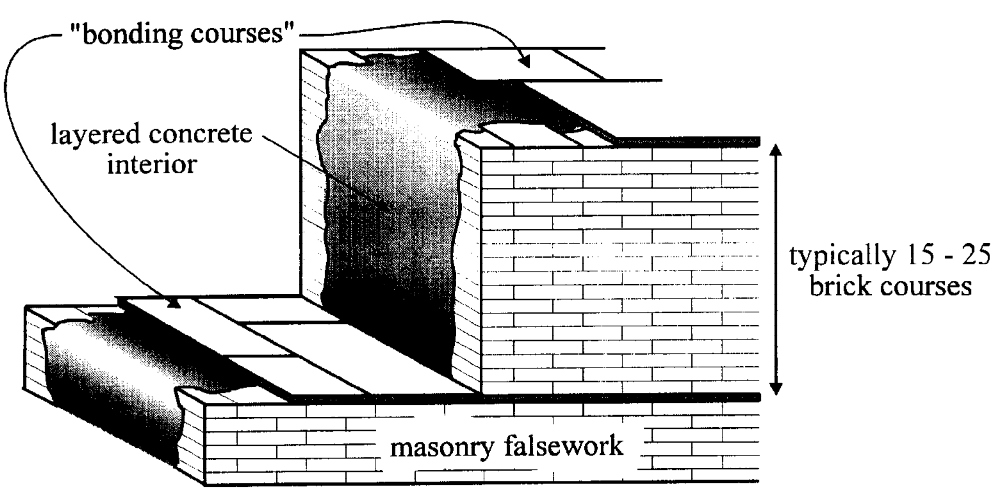
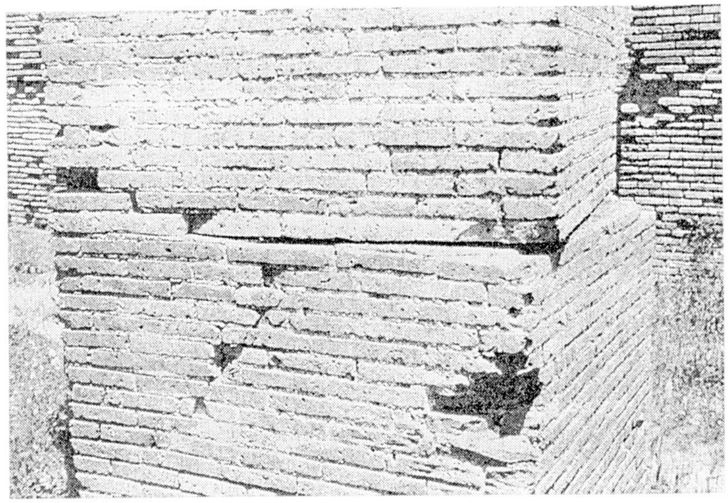


Fig. 1. Construction of Roman monolithic concrete walls

(a) vertical cracking of basilica wall at the Domus Flavia (c. 92 A.D.)



(b) horizontal sliding along "bonding course" of 2 m square pier at Piccolo Mercato, Ostia

Fig. 2. Seismically induced damage in Roman concrete structures (MacDonald, 1982)

"Bonding Courses" - Another unique feature of Roman coursed concrete construction are the so-called "bonding courses" (see Fig. 1). These are courses of flat tiles extending through the width of the member having a vertical spacing of between 15 and 25 brick courses. The purpose of these through-wall courses is uncertain and many structures do not have them. Believed by some, likely including their Roman builders to strengthen the structure, it is doubtful that they serve in any such capacity. As such, the term "bonding course" is a misnomer. It has been suggested that the "bonding courses" reinforced or served to solidify the concrete mass, as such, they are sometimes referred to as levelling or settling courses. The through courses may have been used for levelling and compacting a day's placement of concrete or may simply mark the end of an assigned portion of work (MacDonald, 1982). Others have suggested that they are included to restrict undue settlement during curing. In addition, MacDonald points out that "bonding courses" often form the lower surface of putlog holes, used to support scaffolding during construction.

"Bonding courses" interrupt the structural integrity of the concrete and provided surfaces upon which the bearing masses may move in the event of lateral seismic load. This is evident in Fig. 2(b) where the upper part of a 2 m square concrete pier has twisted on the flat surface of "bonding course" tiles. Such a mechanism is capable of absorbing large amounts of energy and imparting a degree of ductility to the structure while relieving stresses in the structural mass.

Relieving Arches - Masonry relieving arches are also common in very large Roman walls. These arches, similar to those seen in some dome structures (see below), were likely provided as a more efficient means of carrying the loads of the concrete mass before it had hardened. Superficial, or falsework arches offer no structural benefit once the concrete has cured. Less common through-wall arches, however, do serve to improve the ductility and lateral load carrying ability of wall structures.

Coigning - Coigning, or interlocking of brick courses at the junctions of walls, was a typical practice likely stemming from the need to stabilise the masonry falsework before the concrete was placed. The coigning of corners has the advantage of improving the structural integrity of the walls and promoting the efficient composite action of multiple wall systems under lateral seismic load.

Figure 3 shows a section of the remaining walls of the Capitoleum at Ostia, erected in about 120 B.C. "Bonding courses" and relieving arches are apparent as well as the putlog holes. It is clear that these features were practical, rather than aesthetic, as plaster or some similar wall covering was invariably used in Roman buildings. The remains of the plaster wall are evident on the lower reaches of the walls shown in Fig. 3.

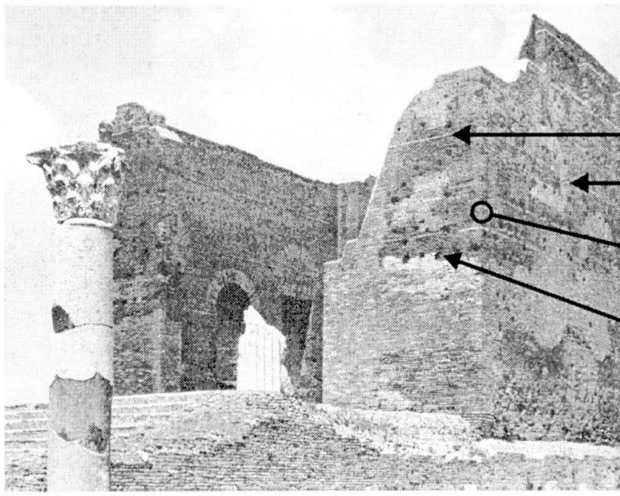


Fig. 3. Capitoleum at Ostia (c. 120 A.D.) (Boethius and Ward-Perkins, 1970)

Vaulted Construction

The development of monolithic concrete construction, marked a significant improvement in the degree of structural integrity which could be achieved. Structural integrity, once provided by bearing and friction, was now incremented by the cohesion and homogeneity inherent in the concrete mass. The Roman adoption of the vault form from the Etruscans was probably purely for aesthetic reasons. Etruscan masons were skilled builders of both corbelled and barrel masonry vaults. The introduction of Roman concrete allowed vaults having larger spans to be easily constructed. By early Imperial times, vaulted spans had almost completely replaced the more cumbersome entabulated spans, in public structures.

Vaults, constructed of monolithic concrete, are exceptionally stable, offering resistance to both gravity and lateral loads with a relatively small structural weight. The eventual proliferation of vaults, however, is more likely a result of aesthetic, rather than technical, considerations.

Roman Monolithic Domes

Arguably, the monolithic dome is the single most important architectural development of the Roman Architectural Revolution (c. 58 - 138 A.D.). Concrete domes were formed over falsework supported by timber frames in a manner similar to that discussed above. "Ribbed" domes were constructed with vertical courses of tiles, in the form of ribs running from their apex to base or in the form of relieving arches. Like the "bonding courses" of walls, these were likely thought to reinforce the dome structure. It is more likely that the ribs were included either to simplify the falsework or to compartmentalise the concrete mass, making it easier to place and compact (MacDonald, 1982), and to control the effects of shrinkage. There was no apparent rule-of-thumb for including ribs, they were alternately used or neglected in domes of all sizes. "Ribbed" domes often also included pilasters in the dome drum. This sort of construction, with pilasters and relieving arches or ribs may represent an intermediate step in the evolution from entabulated structures to the monolithic envelopes of later domes.

Roman domes are typically spherical, thus minimising thrust forces at the top of their drums. To further minimise these forces, Roman domes are often tapered up their height as the bearing requirements decrease. In addition, grading of aggregate is used in some dome structures; with lighter materials being used closer to the apex. The combination of tapering of the shell and grading the aggregate result in smaller thrust forces,

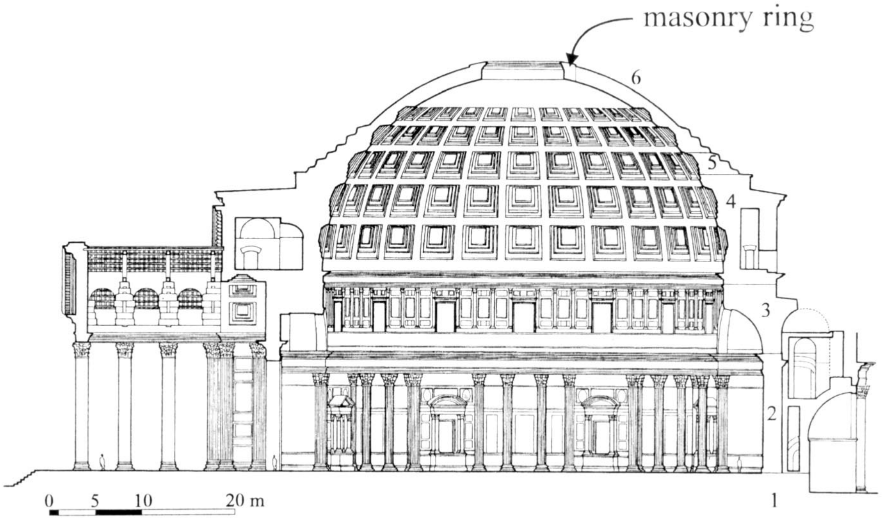


Fig. 5. Section through the Pantheon (128 A.D.)

dome structure without internal masonry ribs. Certainly, it is likely that the extent of the coffering will allow some rib action to be developed, and likely impart additional ductility to the dome structure.

The Pantheon dome shows no damage due to seismic action. Some cracking, indicating a torsional response of the drum near the dome-drum interface has been noted (this damage is not visible and we must rely on reports from a 1930's rehabilitation project (Terenzio, 1933)). The reported nature and characteristics of the cracking suggest that they are a result of the considerable eccentricity introduced to the structure by the inclusion of the massive portico (see Fig. 5, left side). Despite this relatively minor damage, the Pantheon remains an exceptional example, not only of Roman architecture, but of Roman seismic resistant construction.

EARTHQUAKES AND ROMAN SOCIETY

As has been mentioned, developments in seismic resistant construction during Republican and Imperial Rome, represent little more than serendipity. Nonetheless, a number of significant changes in construction practice and technique came about in this time. It is informative to briefly investigate the Roman understanding and response to earthquake phenomena, in order to understand the society from which these developments evolved.

Rome is located in a relatively severe seismic zone. A modern Catalogue (1991) of events lists seven "large events" centred in Rome since Imperial times and as many as 32 "significant events" in the immediate vicinity of Rome. Records dating from Imperial times indicate 14 events described as "damaging" or "destructive" occurring in the first three centuries A.D. The catalogue suggests that at least fifteen percent of these events would exceed a magnitude of 6 on the Richter scale.

Despite the apparently regular seismic activity in early Rome, reportage of events is relatively sparse. In a survey (Newbold, 1982) of five ancient annalists (Thucydides, Diodorus, Livy, Tacitus and Dio), spanning 600 years of historiography covering Greece and Rome[1], only 43 references to earthquakes are made. Of these references, the most often reported features of the events are structural damage (42%), rehabilitation (18%) and associated portents (28%).

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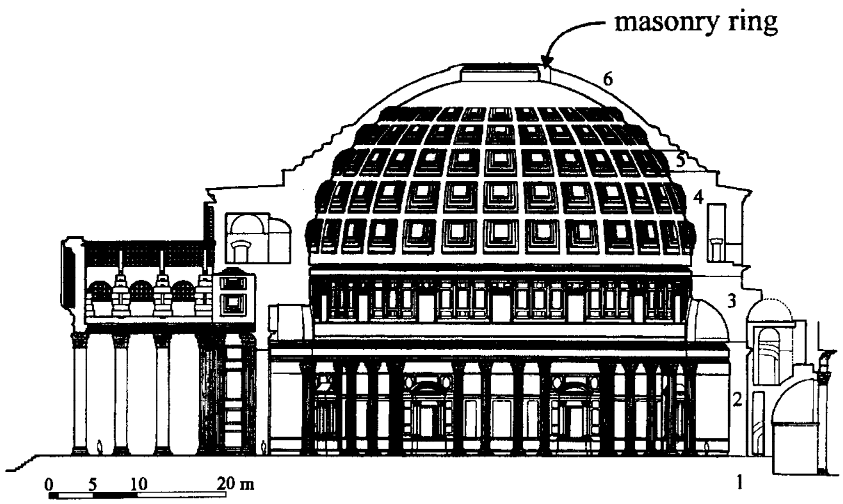
[1] the life spans of the annalists considered are as follows: Thucydides: c.460 - c.400 B.C.; Diodorus: c.90 - c.30 B.C.; Livy: 59 B.C. - 17 A.D. (or 64 B.C. - 12 A.D.); Tacitus: c.58 - c.115 A.D.; and Dio: ? - c.230 A.D.



Grading of Aggregate Material:

1 - basalt and travertine
2 - travertine and tufa
3 - tufa and clay brick
4 - clay brick
5 - clay brick and pumice
6 - pumice

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The God Poseidon - Roman Understanding of Earthquakes

The Roman understanding of earthquakes was based almost entirely on the belief that they were due to divine intervention. For example, Livy (xliii 13) tended to see earthquakes as signs that something had gone wrong with the relationship between men and gods. Dio (lxxviii 25) viewed earthquakes as premonitory signs and manifestations of divine interest in human affairs. Diodorus (xi 63, xv 48-49) is explicit in his belief that earthquakes were due to divine anger at human sinfulness. Only Diodorus (xv 48) acknowledges other possible paradigms for the causes of earthquakes, although he does not elaborate:

> *These disasters have been the subject of much discussion. Natural scientists make it their endeavour to attribute responsibility in such cases not to divine providence, but to certain natural circumstances determined by necessary causes...* (xv 48. 4)

In the Roman pantheon of gods, Poseidon is the god of earthquakes of water. That Poseidon causes earthquakes reflects a crude attempt to explain the phenomena that earthquakes were due to the action of water in some way (Seneca, *Naturales Quaestiones*, 6. 6). The relationship between earthquakes and water, particularly tidal waves, was clearly observed by Thucydides:

> *At about the same time, while the earthquakes prevailed, the sea at Orobiae in Euboea receded from what was then the shoreline, and then coming on in a great wave overran a portion of the city. One part of flood subsided, but another engulfed the shore, so that what was land before is now sea...*
>
> *At Peparethos likewise there was a recession of the waters, but no inundation; and there was an earthquake...*
>
> *And the cause of such phenomenon, in my opinion, was this: at that point where the shock of the earthquake was greatest the sea was driven back, then, suddenly returning with increased violence, made the inundation...* (III lxxxix. 2-5)

This is one of the only attempts made to explain observed earthquake related phenomena. Although the tidal phenomena and apparent change in coastline are properly attributed to the earthquake (in this case, the 464 B.C. Sparta earthquake), there is no explanation offered nor understanding apparent for the event itself.

The Roman Response to Earthquakes

Although the Roman understanding of earthquakes is rather ephemeral, the response of the governing powers, whether Republican or Imperial, was quite pragmatic. Rehabilitation efforts figure prominently in many annals. The importance that Roman society placed on rehabilitation is a "mark of an age that saw disasters as opportunities for impressive displays of government largesse and philanthropy" (Newbold, 1982). There is no apparent reaction, in either the form of policy changes or any other measures aimed at preventing recurrences of damage, to earthquakes in Roman society. Conversely, Roman building and property laws clearly evolved many provisions aimed at prevention of fire and flood damage (Hermansen, 1982). It is of interest to note, however, that the causes of cataclysmic fires and floods were viewed in a similar manner as those of earthquakes.

CONCLUSIONS

The Roman Architectural Revolution not only marked a watershed in architectural theory and practice but also in structural engineering. The development of monolithic concrete construction and the resulting introduction of new structural forms relying on cohesion and homogeneity, had the inherent advantage of being able to efficiently resist seismic attack. Although this benefit was empirical at best, and most likely nothing more than serendipity, the strong, versatile structural forms which arose survived and evolved into some of the basis of what we call seismic resistant design.

REFERENCES

Blake, M.E. (1959). Roman Construction in Italy from Tiberius through the Flavians. Carnegie Institution, Washington DC.

Boethius, A. and Ward-Perkins, J.B. (1970). Etruscan and Roman Architecture. a volume of the Pelican History of Art, Penguin, USA.

Cary, E. (1914). Dio's Roman History. Loeb Classical Library, Harvard University Press.

Catalogue of Earthquakes and Volcanic Eruptions. (1991). Swiss Reinsurance Company.

Corcoran, T.H. (1972). Seneca - *Naturales Quaestiones*. Loeb Classical Library, Harvard University Press.

Dampier, W. (1936). History of Science and its Relations with Philosophy and Religion. MacMillan, New York.

Foster, B.O. and Sage, E.T. (1922). Livy. Loeb Classical Library, Harvard University Press.

Harries, K.A. (1995). Concrete Construction in Early Rome. Concrete International, January 1995, pp 58-62.

Hermansen, G. (1982). Ostia: Aspects of Roman City Life. University of Alberta Press.

Jackson, J. (1931). Tacitus. Loeb Classical Library, Harvard University Press.

Kirikov, B. (1991). History of Earthquake Resistant Construction from Antiquity to Our Times. english translation by P.I. Zabolotniy (1992), published by Instituto de Ciencias de la Construccion Eduardo Torrojo for the 10WEEC, Madrid, July 1992.

MacDonald, W.L. (1982). The Architecture of the Roman Empire. Yale University Press.

Morgan, M.H. (1914). Vitruvius's *De Architectura* (The Ten Books on Architecture). Dover Publications (1960), New York.

Newbold, R.F. (1982). The reporting of earthquakes, fires and floods by ancient historians. Proceedings of the African Classical Associations, Vol. XVI, pp 28-36.

Oldfather, C.H. and Sherman, C.I. (1933). Diodorus of Sicily. Loeb Classical Library, Harvard University Press.

Smith, C.F. (1919). Thucydides. Loeb Classical Library, Harvard University Press.

Stierlin, H. (1984). Hadrien et l'Architecture Romaine. Payot, Paris. (in French)

Terenzio, A. (1933). La restauration du Panthéon de Rome. La conservation des monuments d'art et d'histoire. L'Institut de coopération intelectuelle, Paris. pp 280-285. (in French)

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