Investigation on the 2010 Schola Armaturarum collapse in Pompeii

Nicola Augenti

Department of Structures for Engineering and Architecture, University of Naples Federico II, via Claudio 21, 80125 Naples, Italy
Email: augenti@unina.it

Abstract: The headquarters building of a military association named Schola Armaturarum and located in the archaeological site of Pompeii, Italy, suddenly collapsed on November 6, 2010. The structure was almost totally made of rubble masonry walls, some of which having important frescoes, and was partially reconstructed after the Second World War with a new roof composed of reinforced concrete ring beams and one-way joists. As the collapse induced a dramatic loss to the worldwide cultural heritage, the author was appointed by Judicial Authority to investigate the causes and responsibilities of that accident. This paper describes the phases of the investigation, providing detailed information on the structural configuration after collapse and the most probable sequence of damage. The discussion is supported by photos, drawings, and data from site surveys. The main goal of this paper is to shed some light on what happened in Pompeii and to present procedures and techniques used during the investigation.

Keywords: cultural heritage; archaeological sites; Pompeii; masonry constructions; structural failures; collapse; forensic investigation; site surveys; accident reconstruction; structural safety.


Biographical notes: Nicola Augenti is Professor of Structural Engineering since 1980. Since 2008, he is Founder and Director of MSc Program in Forensic Engineering at University of Naples Federico II. Since 2009, he is Founder and President of the Italian Association of Forensic Engineering (AIF). Since 1970, he is technical consulting engineer for Judicial Authority of Public Prosecutor’s offices in many Italian law courts. He was expert witness in investigations and technical consulting engineer for more than 50 catastrophic collapses and hundreds of structural failures. He authored eight books and 168 papers published in peer-reviewed journals and conference proceedings.

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1 Introduction

_Schola Armaturarum_ was built in the ancient city of Pompeii, Italy, in the 1st century AC (Maiuri, 1967). That building was located in the corner formed by two streets named _via dell’Abbondanza_ and _vicolo di Ifigenia_, Region III, insula 3, n. 6 (this motivates the identification code III,3,6 used for building tagging in the archaeological site). _Schola Armaturarum_ was probably the headquarters building of a military association and was used as armour deposit, even though it was known as _Schola Iuventutis_. The building had a single large room with main entrance from _via dell’Abbondanza_, an approximately squared plan with dimensions 9.70*10.00 m², and height equal to 8.90 m. The structure was almost totally made of rubble stone masonry walls with thickness ranging between 420 mm and 630 mm. The door opening was 6.25 m wide.

_Schola Armaturarum_ was buried during the 24 August 79 AC volcanic eruption of Mount Vesuvius and was discovered by archaeologists between 1915 and 1916. Figure 1 shows the building from _via dell’Abbondanza_ (southern façade) during archaeological excavations. Some internal walls and both jambs of the door opening had frescoes in a good state of conservation.

During the Second World War, the building was seriously damaged by an air raid on 19 September 1943 (Figure 2). Between 1944 and 1946, the damaged masonry walls were reconstructed up to their original height and were covered with a reinforced concrete (RC) joist slab composed of eight primary beams with rectangular cross section (330*500 mm² in size) and an upper slab with thickness equal to 100 mm. A further non-structural slab was realised as waterproofing system of the roof. A RC lintel having cross section of 670*650 mm² and clear span equal to approximately 7.65 m was built over the door opening.

The book of building reconstruction works highlights a particularly interesting event: on January 21, 1946 a strong explosion of munitions wagons stored in the Port of Torre Annunziata, a municipality located few kilometres away from Pompeii, caused a significant crack in the original masonry of the eastern building corner. As a result, a shoring system was installed to support the cracked masonry wall.

**Figure 1** _Schola Armaturarum_ during archaeological excavations in 1916
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Figure 2  *Schola Armaturarum* during bomb attacks in 1943

Figures 3 and 4 show the building after reconstruction. In detail, Figure 3 shows the eastern façade and the southern façade with the building entrance from *via dell’Abbondanza*. Figure 4 shows the southern façade with the door opening covered by the RC lintel (photograph taken in more recent times).

Figure 3  *Schola Armaturarum* after reconstruction in the Forties’ of last century
Some maintenance works were performed between 1946 and 2010, some of which were contracted in January 2009 and completed in January 2010. Those recent works were aimed at restoring and maintaining the roof system and basically consisted of the restoration of some RC beams and waterproofing system and slab. Figure 5 shows the western façade and the main façade alongside via dell’Abbondanza during the last maintenance works.

On 6 November 2010 at 2:14 am, the building suddenly collapsed without causing victims only because the archaeological site of Pompeii was closed to visitors during that night. Figure 6 shows the building debris from the same viewpoint of Figure 5, alongside via dell’Abbondanza.

Figure 4  *Schola Armaturarum before collapse*

![Schola Armaturarum before collapse](image)

Figure 5  *Schola Armaturarum during the last maintenance works*

![Schola Armaturarum during the last maintenance works](image)
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Figure 6  Schola Armaturarum in the aftermath of collapse (view from via dell’Abbondanza)

Figure 7 shows the collapsed building from the north. Both Figures 6 and 7 show the white PVC sheets used to protect the building debris, and particularly the wall frescoes, from heavy rains. It is emphasised that most of walls made of rubble stone masonry were found to be piles of intact stones that were not bonded each other as a result of the loss of cohesion within mortar joints. Only a small fraction of walls reinforced with clay brick masonry layers were found to be divided in a number of blocks after the building’s collapse. This is clearly shown in Figure 8 in which building debris can be observed in detail. The loss of cohesion within the mortar is demonstrated by the fact that stones were found to be intact, whereas just the mortar suffered degradation. As a matter of fact, the masonry did not crush as a consequence of stones’ rupture but its failure was caused by the loss of connection between stones. This is consistent with typical observed damage to rubble stone masonry assemblages with weak mortar, as also shown by recent post-earthquake field missions in historical urban centres (see e.g. Parisi and Augenti, 2013).

Soon after the accident, the Public Prosecutor’s office of the law court of Torre Annunziata seized the site of Schola Armaturarum and promoted a judicial investigation to identify the causes and responsibilities of the collapse. The author of this paper, as founder and director of post-graduate MSc Programme in Forensic Engineering at University of Naples Federico II, Italy, was appointed as the technical consulting engineer of the Judicial Authority. This paper is an extension of a conference paper presented at the IF CRASC ‘15 Congress in Rome, Italy. More details on the case-study structure and forensic investigation are provided. Further documentation cannot be presented as it is a part of the ongoing criminal procedure.

Figure 7  Schola Armaturarum in the aftermath of collapse (north view)
2 Forensic investigation

The forensic investigation started on 25 November 2010 and ended on 15 March 2012 when the author released a report of 260 pages and 8 annexes, including the minutes of consulting operations, reference points in plan, documents cited in the report, photographic documentation composed of 530 images, photogrammetric surveys, and technical notes of legal parties. Further collapse phenomena occurred in the same period in the archaeological site of Pompeii and were also assigned to the author of this paper for forensic investigations.

Figure 7 shows the collapsed building as well as adjacent buildings from above and the north, as they were found at the beginning of forensic investigation. The latter began with the seizure and collection of the whole documentation related to the history of Schola Armaturarum and the works carried out on that building between 1916 (i.e. at the time of building discovery) and the first months of 2010. The author gathered witness depositions, photographs and documents on both structural and conservation conditions of the building in last months before the collapse. Given that some forensic operations could have not been repeated after their modifications to the site, the building was accessed by the author in the presence of technical consultants and lawyers of people under investigation. The following people was inquired by the Judicial Authority: the person who proposed the maintenance works completed in 2010, the designer, the responsible of the work process, the director of works, the director of the construction company, the director of the technical office, the director of the archaeological site of Pompeii, and the supervisor of the archaeological site.

In order to prepare a documentary evidence for subsequent criminal process, a laser scanning survey of the collapsed structure and surrounding area was carried out before debris removal, identifying the soil chorography on the western side of the building. That survey provided a virtual three-dimensional representation with a high level of detail. That representation shows the size and location of any structural component involved in the collapse mechanism and can be viewed at any time, especially during the criminal process. The same survey can be used to derive the original plan and sections of the building.
A first stage of controlled demolition of the building debris was then performed by manually removing all stones and smaller material above the collapsed elements. On one hand, ancient stones were put apart inside a fence in order to reuse them during reconstruction. On the other hand, small pieces of concrete were considered as waste. That modus operandi highlighted the parts of rubble stone masonry walls which were still standing, as well as components of the RC roof and RC lintel above the door opening. Those operations were suspended many times to allow archaeologists to restore small pieces of wall frescoes that were partially destroyed as a result of collapse. Paintings over undamaged walls were preserved by gluing textile sheets over them and creating a protective system made of wooden panels.

At the end of the first stage of investigation, the configuration of collapsed structure was completely determined as shown in Figure 9, which is a picture taken from the north-west side. The undamaged parts of the four masonry walls, together with the roof system composed of RC beams and slab, emerged.

**Figure 9** Roof after removal of small-size debris

In detail, the roof fell down to the ground by splitting in two parts: one included the first six primary beams and the slab, the other one was composed of the last two beams to the north and the respective part of slab. This means that during the collapse phenomena the roof split in two parts between beams 6 and 7. Photographs and geometric surveys were performed during the entire duration of the forensic investigation, both considering the elements still placed on site and those removed after the collapse. Material samples were taken out from the waterproofing slab of the roof and their weight was measured. Therefore, the first stage of investigation allowed the configuration of the collapsed structure, namely the location of walls and roof after collapse, to be determined. A new laser scanning survey of the site was carried out at the end of the first investigation stage, in order to provide a proof to the subsequent criminal process.

The second stage of investigation consisted of the removal of masonry pieces collapsed over *via dell’Abbondanza* (i.e. in the east-west direction) and *vicolo di Ifigenia* (i.e. in the north-south direction). Then, the RC roof slab was totally removed. Figure 10 shows the site during those operations from the west. After that the RC slab was removed, the exact location of the primary roof beams after collapse was detected through a detailed geometric survey of single components. Concrete cores and samples of reinforcing steel bars were also extracted. Material samples were subjected to
compression and tensile tests in the laboratories of the Department of Structural Engineering of University of Naples Federico II, Italy. Those experimental tests provided valuable data on mechanical strengths and elastic properties of materials extracted from Schola Armaturarum (Augenti, 2004). Figure 11 shows the primary roof beams from the west, highlighting the holes of concrete cores. The third (and last) laser scanning survey was carried out at the end of the second investigation stage in order to provide further documentation about the building debris after its removal.

Figure 10  Roof during investigation

After that those operations ended, the author proposed to carry out an on-site uniaxial compression test on a rubble stone masonry specimen to be taken out from the remaining part of a load-bearing wall of Schola Armaturarum. No damage to the archaeological site would have been caused because the load-bearing wall was reconstructed in 1946. On-site testing could allow the estimation of the load-bearing capacity of masonry walls which were reconstructed in that area after the Second World War. This activity has never been carried out inside the archaeological site of Pompeii. It would have provided valuable information to the forensic investigation and, more in general, on the safety level of other domus which were covered by heavy RC roofs in the past.

Figure 11  Primary beams of the roof (western view)
To carry out the proposed experimental test, a masonry wall with no damage and squared façade of approximately 1 m² was isolated from the rest of a load-bearing wall. An appropriate experimental set-up was designed and was composed of a steel frame which was assumed to be simply fixed to the ground and loaded by a concrete reaction mass to provide contrast to a hydraulic jack on top. The latter would have been positioned between the reaction mass and the specimen subjected to on-site testing. A displacement-controlled monotonic loading up to early crushing of masonry was expected and the deformation of the masonry wall would have been monitored in real time through displacement transducers. Until now, this test has not yet been performed as a result of the opposition of Pompeii’s office of cultural heritage, but this could be possible during the criminal process.

The forensic investigation presented above allowed the author to identify the causes and responsibilities of the collapse. Nonetheless, responsibilities cannot be discussed in this paper because the criminal process is still ongoing.

3 Sequence and causes of collapse

To support the considerations reported below, the discussion on the sequence and causes of collapse are related to a simplified model of the structure. Figure 12 provides sketches of the main stages in which the collapse mechanism can be decomposed. The sequence of images allows a reconstruction of the collapse event similarly to the original technique of cartoons.

The information provided by on-site surveys and a comprehensive analysis of documents collected during forensic investigation indicate that the most probable source of collapse was masonry crushing in the eastern load-bearing wall of *Schola Armaturarum*. That wall was located in front of *vicolo di Ifigenia* and close to the building corner of *via dell’Abbondanza*, namely a street reconstructed soon after the Second World War. According to collected documents, the collapsed masonry wall was heavily pre-damaged and supported by a shoring system after a strong explosion of munitions wagons occurred in January 1946 in the Port of Torre Annunziata.

The most probable sequence of collapse is summarised below:

Stage 1: Initial masonry crushing in the eastern load-bearing wall located in front of *vicolo di Ifigenia* and close to *via dell’Abbondanza* (Figure 12a).

Stage 2: South-eastward rotation of the roof system which induced an outward overturning mechanism of the building corner composed of regular masonry (Figure 12b).

Stage 3: Roof system translation toward *vicolo di Ifigenia* (to the east) as a result of the horizontal component of the action associated with the rotation mechanism in Stage 2. The northern wall provided contrast to that translation. In such an evolutionary stage, the weakest element of the roof system was a part of RC slab between beams 6 and 7, which fractured (Figure 12c). On-site debris surveys confirm this mechanism, evidencing an eastward translation of most part of the roof (including beams 1 to 6) with a remaining part consisting of beams 7 and 8 to the north.

Stage 4: Slight movement and gradual collapse of western wall caused by vertical load eccentricities induced by roof translation (Figure 12d).
Stage 5: Collapse of most part of western wall induced by the loss of support to the edge roof beam on western wall, slab fracture between beams 6 and 7, and presence of a small opening alongside via dell’Abbondanza at the intersection with western wall (Figure 12e).

Stage 6: Roof collapse after its eastward translation and loss of support to the west side. Then, the roof still had partial support only by the residual eastern wall (Figure 12f).

On-site evidence provides a clear confirmation of this sequence of collapse.

**Figure 12** Most probable scheme of damage sequence
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Alternative scenarios were not possible according to the following considerations:

- The structural failure of the RC roof system did not cause the building collapse because the roof did not suffer any fracture although it fell down from a height of approximately 8.60 m.

- Earthfill pressures on the masonry wall was not a realistic source of collapse as well. Indeed, only one load-bearing wall was subjected to earth pressures but it was located to the west side and the earthfill in contact with that wall was consolidated since at least twenty centuries. In addition, no sign of earth slide able to produce thrust forces on the western wall was detected on site. Removal of debris outside Schola Armaturarum demonstrated that the earthfill on the west side did not show any sign of failure and its free surface was almost everywhere below the residual height of the collapsed wall. Finally, most part of debris from the western wall was found to be outside the building. This fact is not compatible with a wall failure induced by earthfill pressures as the latter would have forced the masonry wall to collapse inside the building.

- Heavy rainfall occurred some days before collapse but they cannot be considered to be a source of collapse as their intensity was almost zero during the last 92 hours before the accident.

Dealing with the masonry crushing that induced the collapse, the stress levels corresponding to the loads expected at the time of collapse were compared to a nominal compressive strength of the building’s masonry (Augenti, 2004). Gravity loads on the building roof were estimated as follows: self-weight of internal and external RC roof beams equal to 3.30 kN/m and 4.50 kN/m, respectively; self-weight of RC roof slab equal to 2.50 kN/m²; self-weight of waterproof system equal to 3.80 kN/m²; and self-weight of masonry bond beam on top equal to 6.93 kN/m. Then, average compressive stress levels were computed at several heights of masonry walls and ranged between 0.056 MPa on top of walls (i.e. height of 7.70 m from the base) and 0.235 MPa at a height of 0.5 m from the base of walls. Those stress levels are associated with an ideal loading scheme with compressive pressures that are uniformly distributed on top of masonry walls. Conversely, a compressive load eccentricity equal to 1/6 of the wall thickness induces a doubled level of compressive stresses. The latter significantly increase if the load eccentricity rises, causing partially effective cross sections over the wall height. It is thus expected that the nominal compressive strength of masonry was attained. This assumption is substantiated by the fact that the RC roof system was found to be in safe conditions according to structural computations. In detail, experimental tests on samples of reinforcing steel and concrete taken out from the collapsed structure provided respectively a mean yielding stress equal to 377.70 MPa and a mean cubic compressive strength equal to 9.70 MPa. A geometrical survey of the RC roof beams was also performed, evidencing a T-shaped cross section with the following properties: depth equal to 500 mm; flange and web thickness equal to 100 mm; width equal to 133 mm; length equal to 9.25 m; concrete cover equal to 25 mm; longitudinal reinforcing steel area equal to 793 mm² on top and 1360 mm² on bottom; and steel stirrups with diameter equal to 8 mm and spacing equal to approximately 300-400 mm. For the sake of simplicity, a single roof beam was considered; it was assumed to be simply supported and subjected to
a uniform load of 11.68 kN/m. The analysis of that simplified model provided a maximum bending moment equal to 124.92 kNm. As the resisting bending moment of beam cross sections was found to be 197.30 kNm, the demand-to-capacity ratio was estimated as 0.63. This confirms that the RC roof system was in safe conditions at the time of collapse and the latter was generated by the masonry failure under eccentric compression.

As remarked above, more information on material strength would have been derived from simple compression tests on residual masonry walls. Nevertheless, it is underlined that the collapsed wall was made of small stones and mortar with small binder fraction and poor consistency. It is also emphasised that mortar weakening due to rainwater erosion induced a gradual reduction in cohesion of masonry, hence increasing the wall vulnerability. This is confirmed by the observed damage shown in Figure 8. This forensic investigation allowed the author to assess that the mortar of the collapsed wall even lost its integrity under hand pressures.

The very low capacity of the masonry walls under study was confirmed by spontaneous and gradual collapse of other walls in the archaeological site of Pompeii, basically subjected to their own weight. Therefore, the potential collapse of walls subjected to loads greater than masonry self-weight (e.g. those produced by heavy RC roofs) would have been even more simple to expect.

4 Conclusions

The work presented in this paper is a rather unique case-study in Forensic Engineering because the investigation was carried out on archaeological elements with high international importance. Special care was paid to any operation on site because of the cultural value of the structure being investigated, avoiding further damage to the archaeological heritage. The high importance of this investigation is related on one hand to the chance to evaluate the safety level of goods located in the archaeological site of Pompeii, and on the other hand to the capability of highlighting the issue of structural conservation of archaeological goods. This can prevent from similar accidents in the future, avoiding invaluable cultural losses and danger conditions for people.

The forensic investigation revealed that the maintenance of the archaeological site should be committed not only to restorers, archaeologists, architects and historians, but also to structural engineers with high experience in the field of structural failures. Actually, local cultural heritage offices often neglect, or even ignore, structural issues of constructions, resulting in a high risk for the integrity of sites and human life. This case-study gives evidence of the need for licensed forensic engineers in Italy, in order to correctly assess the causes of failures and their responsibilities.

The author of this paper publicly expressed his opinion that the numerous spontaneous collapses occurred several times in the archaeological site of Pompeii should have induced the local cultural heritage office to carry out a comprehensive structural assessment of all ancient constructions located there. That work should be assigned to structural engineers with high experience in the field of masonry constructions and structural failures. As a matter of fact, it seems paradoxical and useless to recover and restore archaeological goods without ensuring them an appropriate level of structural
safety. This could be made, for instance, by stipulating agreements with technical departments of universities, such as Federico II in Naples, which have significant skills in the field of engineering structures, masonry constructions and structural failures.

References