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Short communication

A study on the effects of an explosion in the Pantheon of Rome

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ABSTRACT

The response of an emblematic monumental structure, the Pantheon in Rome, to an internal blast is addressed. The analysis is a coupled solid-fluid numerical simulation done using JWL equation for the simulation of the blast event and considering the pre-existent cracks in the dome as well as the material nonlinearities of low-tensile strength concrete aggregates. We identify two main phenomena; a focalization of shock waves inside dome-vaulted like structures due to their tendency to concentrate the blast energy and the role played by the pre-existent cracks in the evolution of the structural damage.

1. Introduction

We propose in this paper a study on the structural effects of an explosion in the Pantheon in Rome. Highly representative monuments are unfortunately too often the objective of violences and iconoclastic destructions. Well-known examples are the Parthenon in 1687, the Cathedral of Reims in 1914, the Buddha statues of Bamyan in 2001 and the more recent destructions at Palmyra in 2015 and 2016.

Research on the effects of an explosion on monumental architectures are hence interesting for assessing the potential effects of a blast onto such kind of structures and also for helping in the design of reinforcements or any other possible passive protection device.

This domain is still almost unexplored; in fact, the most part of papers concerning the effects of an explosion on a civil structure regard modern reinforced concrete or steel structures with simple geometries, normally squared buildings [36,32,23,10].

This is not the case of monumental structures that have often a complex geometry, sometimes very articulated, which renders the assessment of the blast loads strongly case dependent and affects the type of simulation. This point is tackled in Section 3, where a short account of the state of the art for what concerns the simulation of blast loads is given and, on its base, the choice of the method used for the case of Pantheon is justified.

On the other hand, monumental structures are either masonry-like or timber structures, or both of them at the same time. In particular, monuments constituted by masonry-like materials have a structural response strongly affected by the no-tension behavior of the material. This is a key point, considered in Section 4.

A particular attention must hence be paid to the procedure to be used for numerical simulations, that must account, on one hand, for the hypervelocity of the phenomenon and, on the other hand, for the peculiar constitutive law of the material, that must be able to describe the non-linear phenomenon of damage, i.e. of cracks propagating into the body of the structure as a consequence of the blast actions. Considerations about the procedure used for the numerical simulations are given in Section 5 and the results are presented in Section 6.

In Section 2, the object of this study, the Pantheon in Rome, is presented.

2. The Pantheon in Rome

The Pantheon in Rome (Fig. 1), one of the most admired and studied monuments ever, was built upon the rests of previous temples by the Emperor Hadrian, since A.D. 118 to about 128, or later, perhaps until 140, under Emperor Antoninus Pius, and probably it is the joint work of Hadrian and of the Nabatean great architect Apollodorus of Damascus (see [28]).

The main body of the Pantheon, the so-called *Rotonda*, is composed by a cylinder whose inscribed sphere is coincident, for its upper part, with the dome, while its bottom touches the ground, Fig. 2. The coffering is sculpted in the intrados of the dome offering a high aesthetic value, but also reducing the dome's weight.

With a diameter of 43.30 m, according to the measurements of de Fine Licht, [20,29], or of 150 Roman feet, i.e. 44.55 m, according to Wilson-Jones, [50,7], the Pantheon's dome is, still today, the largest dome in the world, apart the modern realizations in reinforced

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Fig. 1. The Pantheon of Rome (from [35]).

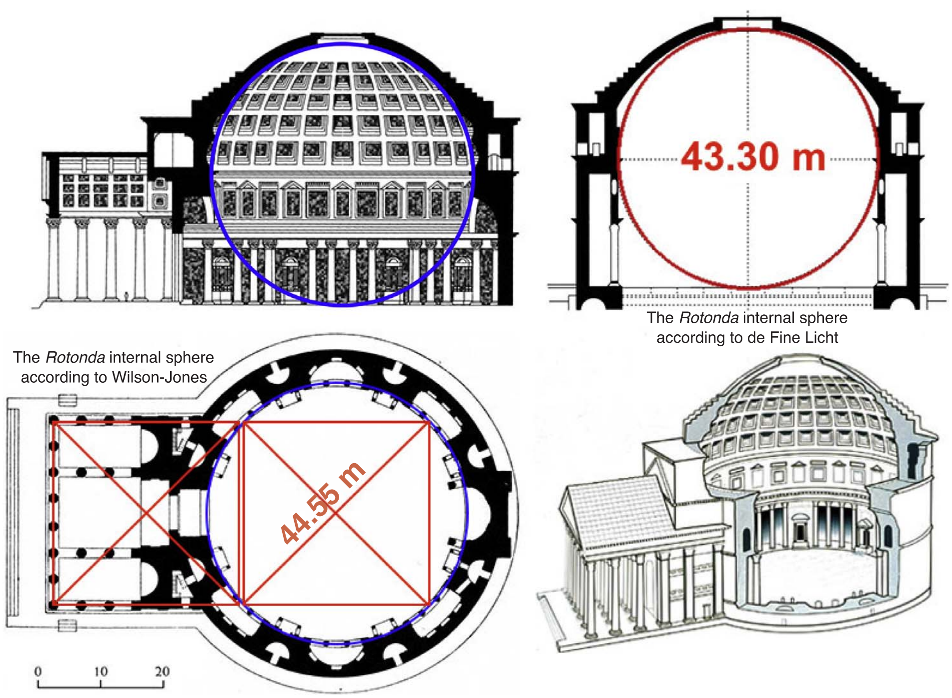

Fig. 2. Scheme and dimensions of the Pantheon (from [35]).

concrete. In fact, it is larger than the dome of Saint Peter in Vatican, whose diameter is 42 m, and also of the octagonal dome of F. Brunelleschi, in Santa Maria del Fiore at Florence, whose base is circumscribed to a circle of 41.57 m diameter, [8]. However, unlike these two famous domes, and also of other ones, made by bricks, the Pantheon's one is made of concrete, a technique already mastered by Apollodorus in other previous works (e.g. the vault of the Great Hall in the Trajan's markets in Rome, see [33,34]).

If the intrados of the dome is sculpted by a coffering, the external lowest part of the dome is modeled by stepped rings, whose function has been the object of different investigations, see Fig. 2. In an early application of finite element analysis to Roman structures, Mark and Hutchinson [30,29] used a simplified two-dimensional model of the Rotonda, exploiting the axial symmetry of the structure. According to this study, and contrary to what commonly thought, the step-rings do not contrast the hoop tension in the lowest part of the dome, because actually the dome is spread of cracks that have an almost meridional direction and stop at a latitude of approximately 57°, where the hoop stress begins to be compressive.

The distribution of these cracks, Fig. 3, was detailed in 1934 by A. Terenzio, the Superintendent of the Monuments of Latium, who had carried on a series of inspections on the dome of the *Rotonda* after that some fragments had fallen down, [41].

We cannot establish here what is the true origin of these cracks, but certainly they are to be modeled to have a more realistic response of the structure to gravity and blast loads. In fact, on one hand, the cracks undoubtedly change the stress regime of the *Rotonda*, on the other hand, they considerably affect the response of the structure to a blast by a special local mechanism, as we will see in Section 6.2.