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Structural design and analysis of an impact resisting structure for volcanic shelters

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Abstract

This paper describes the conceptual design, the engineering process and the implementation of an impact resisting structure for volcanic shelter. Basically, the designed shelter consists of two homologous reinforced concrete shells, interconnected by suitable flexible and highly dissipative devices, which absorb and dissipate the impact energy. The shelter has been purposely designed to resist, without damage, an impact with a 150 kg mass rock, colliding with the surface of the external shell at approximately 62 m/s. The characteristics of the shelter and the process followed in its design and implementation are illustrated. Particular attention is addressed to the mechanical behaviour of the impact absorbing devices. The numerical modelling of the impact phenomenon and of the shelter structure is illustrated. Finally, the results of accurate non-linear dynamic simulation analyses for safety verifications are discussed.

Keywords: Impact loading; Impact absorbing devices; Dynamic response; Stromboli volcano; Pyroclastic eruptions

1. Introduction

The dynamic stable response of shell structures subjected to impact loading is a topic of structural impact engineering [1]. Shells are extensively used in many engineering applications, for storage (e.g. tanks), transportation (e.g. pipelines) and protection purposes (e.g. shields). Impact loading includes ballistic impacts, blast loadings, jet impacts, projectile penetration, structural crashing, etc. A few years ago, Corbett et al. presented a comprehensive review of the experimental and numerical studies on the dynamic response of plates and shells caused by ballistic impacts [2]. Most of these studies focused attention on the penetration and perforation processes involved in the impact of thin metallic thickness by rigid projectiles.

Concrete is a material that is suitable for impact protection, when weight and space are not limited. The failure mechanisms of concrete structures depend on the amount and type of steel reinforcement. Concrete tends to be less sensitive to impact conditions, determined by projectile shape, impact velocity, and projectile mass, than steel structures [3]. As a consequence, it can be used with greater confidence when the impact conditions are not well known in advance. Important examples of applications that rely upon the impact resistance of concrete can be found in the military and nuclear industries, in which the walls of certain structures must withstand impacts with missiles, etc. [4,5].

The impact of rigid projectiles on slightly reinforced (or plain) concrete targets can produce different levels of damage, which can be identified in surface cracking, spalling, penetration, scabbing and perforation, while increasing impact velocity. These phenomena have been extensively investigated in the past, for both civil and military applications [6–11].

In this paper an impact-resisting structure for volcanic shelter is presented. It basically consists of two independent reinforced concrete (R/C) shells, interconnected by suitable devices, which absorb and dissipate most of the impact energy. As a result, the external shell withstands possible impacting rocks without significant damage, while the internal shell (where people are protected) is practically not affected by the impact.

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Two different levels of impact have been considered in the design of the shelter. The protection against the first level, relevant to highly probable low energy impacts, relies upon the visco-elastic behaviour of rubber-based devices, thus resulting in no permanent deformation of the shelter after the event. The second level, referring to very high-energy impacts occurring with very low probabilities, exploits the plastic behaviour of suitably shaped steel devices. Such impacts result in permanent deformation, which, however, do not compromise the correct structural performance to further first-level impacts.

The dynamic response of the shelter to the most challenging impact is studied with a two-step analysis. The first step is aimed at evaluating the impact loading under the simplifying hypothesis of elastic impact [12]. The second step is aimed at evaluating the response of the shelter when subjected to the impact loading and is carried out through non-linear step-by-step dynamic analyses on an accurate finite element model of the shelter.

2. Performance requirements and characteristics of the shelter

Several monitoring, research and tourist activities are often carried out in the area of an active volcano. Depending on the character of the volcanic eruption, the operators and the visitors can be subjected to high risk, due to the short warning time available to get rapidly away from the dangerous area. This is the case of the pyroclastic eruptions of the Stromboli Volcano in Italy, near Sicily (see Fig. 1) [13,14]. The only possibility to protect human lives is, in this case, to provide shelters placed in strategic sites that can be reached in a few seconds by people nearby. Obviously a shelter must have the capability to resist the impact of falling rocks, whose size and velocity can result in very high impact energy. With this scope, the Italian Department of Civil Protection asked the University of Basilicata to make theoretical and experimental studies finalised at designing and engineering a volcanic shelter to be installed on the Stromboli Volcano.

Designing a volcanic shelter is a challenging task, not only for the high structural and dynamic performances required, but also because of several other design conditions, related to transportation and assembling operations in areas only reached by helicopter, durability in an aggressive environment, and low visual impact in a protected landscape.

According to the main scope of the shelter, which is to protect human lives in case of pyroclastic eruptions, and to the other aforesaid prerequisites, the shelter was designed to satisfy the following requirements:

(1) capability of resisting, without significant damage, an impact with a 0.5 m diameter rock (approximately 150 kg mass), coming from 400 m distance, after reaching a maximum height of 100 m;
(2) sliding and overturning stability of the structure as a whole;
(3) modularity of the structure, whose single parts weigh no more than 50 kN, in order to allow their transfer by sky-crane helicopter from the base camp to the volcano slope;
(4) quick in situ assembling of the different parts of the shelter;

Fig. 1. Location of the Stromboli Volcano in the southern Tyrrhenian sea.

(5) resistance to aggressive chemical agents (e.g. CO_2, SO_2, H_2S), due to volcano emissions;
(6) low ambient aesthetic impact;
(7) protection from atmospheric discharges.

The basic assumption (1) is based on the observation of the pyroclastic eruptions of the Stromboli Volcano and on the location of the shelter with respect to the volcano craters.

A shield structure, consisting of two homologous cylindrical R/C shells, interconnected by suitable flexible and highly dissipative devices, has been conceived to satisfy the aforesaid requirements. The protection from falling rocks is obtained by exploiting the mechanical behaviour of the devices, with possible minor damage in the external shell (e.g. hairline cracking or minor spalling of concrete cover) limited to the impact area. The cylindrical shape of the shells derives from the need to minimise the impact surface of the structure.

The need to limit the external overall dimensions of the shelter, in relation with its visual impact, required a good balance between flexibility and energy dissipation capability of the devices, resulting from an optimisation carried out in the preliminary design stage.

Due to the adverse environmental conditions, any moving mechanical device was excluded, so that only devices whose functioning is associated to deformations of materials, like rubber and steel, have been considered.

Fig. 2 shows all the structural elements, impact-absorbing devices and non-structural parts and their assembling. The overall dimensions of the shelter (foundation included) are 4.16 m in the longitudinal direction (x-direction of Fig. 2), 2.46 m in the transverse direction (y-direction), 3.25 m in the vertical direction (z-direction). The clean height off-ground in the rear part is 1 m, as shown in Fig. 3, due to the partial embedment of the shelter in the earth from behind, in order to reduce the visual impact. The clean internal dimensions of the shelter are about 3 m length, 1 m width and 1.8 m height, so that at least 10 people can be safely arranged inside in case of danger.

The structure of the shelter is made of five components (see Figs. 2 and 4):

(1) one external R/C 180 mm thick shell, equipped with two lateral 10 mm thick steel plates;
(2) four impact-absorbing devices (two each side), based on rubber and damping material, sandwiched between the steel