Materials and Design 155 (2018) 451–462

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Experimental analysis of an attenuation method for Hydrodynamic Ram effects

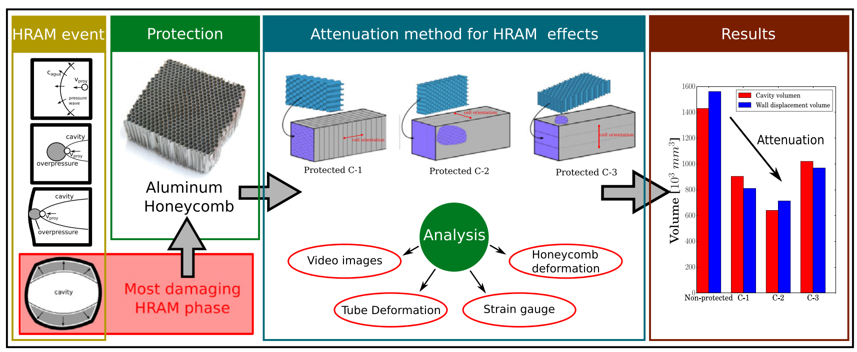
J.A. Artero-Guerrero*, D. Varas, J. Pernas-Sánchez, J. López-Puente

Department of Continuum Mechanics and Structural Analysis, University Carlos III of Madrid, Avda. de la Universidad, 30, Leganés 28911, Madrid, Spain

HIGHLIGHTS

- HRAM damaging effects on aluminum tubes has decreased up to a 54% using aluminum honeycomb as attenuation method.
- The greatest attenuation is achieved using the cell orientation in which the cells wrap the cavity as it evolves.
- For the best configuration, in which the cells wrap the cavity, the dominant failure mechanisms cell wall buckling which lead to a higher resistance.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 March 2018
Received in revised form 8 June 2018
Accepted 10 June 2018
Available online 12 June 2018

Keywords:
Hydrodynamic Ram
Attenuation method
Fluid-structure interaction
Fluid-filled tank
High velocity impact
Experimental test

ABSTRACT

The Hydrodynamic Ram (HRAM) phenomenon occurs when an object with a high-kinetic energy impacts against a fluid-filled structure, which could induce important damages. An attenuation technique would be of great interest for structures which could be subjected to impact. In this work, honeycomb panels are used to fill the entire space inside the structure in such a way that they are able to alleviate the loading onto it. Experimental tests were carried out varying aluminium honeycomb cells orientation, to determine the configuration that mitigates more efficiently the effects of HRAM comparing the results with a non-protected structure. The experimental tests were analysed using a high speed video camera, strain gauges, residual displacement of the structure walls and the deformation of the honeycomb panels. It is shown that for all the configurations, the honeycomb is able to reduce the plastic deformation of the structure. The honeycomb allows to reduce the cavity expansion in the fluid, which is the most dangerous phenomenon in the studied cases. The best configuration is able to diminish up to 54% the residual expanded volume in the structure walls, and hence considerably attenuating the HRAM effect on the structure.

1. Introduction

The Hydrodynamic Ram (HRAM) phenomenon occurs when an object with high kinetic energy penetrates a fluid-filled container. The object, while travels through the fluid, transfers part of its energy to it, and consequently to the surrounding structure. Hence the walls of a fluid-filled structure, subjected to an impact load, have to withstand higher energy levels than the same structure without fluid. Therefore it is important to take into account the presence of fluid inside a structure because it is responsible for increasing the risk of a catastrophic failure [1]. Thus, the HRAM phenomenon is considered one of the most important factors in aircraft vulnerability [2,3]. Fuel tanks can be impacted by different kind of fragments and in different situations. Different impactors such as hail [4,5], bird [6] or tyre

* Corresponding author.
E-mail address: jartero@ing.uc3m.es (J.A. Artero-Guerrero).

https://doi.org/10.1016/j.matdes.2018.06.020
0264-1275/© 2018 Published by Elsevier Ltd.

fragments [7] could impact fuel tanks with enough kinetic energy to generate the HRAM phenomenon causing a catastrophic failure, as happened in the accident of the Concorde [8]. Also, the accidental explosion of an engine can generate a number of fragments that impact at high velocity against the wing fuel tanks [9] producing the HRAM effects as happened in Qantas A-380 accident [10]. The commercial aircraft industry is greatly concerned about this type of Uncontained Engine Rotor Failure (UERF) events. But the HRAM phenomenon is not a unique issue in the aerospace industry, also it is important and should be taken into account in the industrial sector, where a structure containing fluid (vessel, tanker truck, etc.) can be hit at high velocity [11-13]. This case can be particularly dangerous if the fluid inside the container is a hazardous material.

The first researches concerning the HRAM were carried out by military agencies in the 70s. It's not until the 90's when academic institutions had studied this phenomenon, applied to commercial aircraft. The HRAM has been analysed experimentally [1,14-16], numerically [17-21] and with analytical models [22]. An extensive review regarding the studies performed can be found in the experimental and numerical works of D. Varas et al. [1,17]. Additionally to these works, the authors of the present research have published several articles concerning the study of this phenomenon in metallic and composite tubes filled with water [18,23-25].

Previous studies have shown that the HRAM phenomenon consists of four main stages: shock, drag, cavity and exit [1,15,17,18]. Each stage contributes to the structural damage through a different mechanism and to a different extent. In addition, depending on the particular circumstances (dimensions of the structure, material and kinetic energy of the object that impacts...), the importance of each stage varies. Shock phase is usually described as one of the main cause of failure for large containers [14] or in the case of low-strength impactors. However when the size of the cavity is similar to the size of the tube, cavity stage becomes the main cause of deformation and failure of the tank.

The conclusions obtained from the previous works are the basis to propose improvements in the vulnerability of fluid-filled tanks subjected to the HRAM phenomenon. It has to be remarked that the works in which HRAM attenuation methods have been proposed are very scarce. In 1983 A. Copland [26] evaluated the ability of different inerting agents to attenuate HRAM in armoured vehicles. Two different containers were impacted by 12.7 mm AP bullets and 11.9 mm steel spheres. The results indicate that the destructive effects of HRAM may be enhanced by the addition of the inerting agent called "Explosafe" to liquid containing cells, while the addition of the foam studied delayed the pressure pulse and reduced its value contributing to attenuate the effects of HRAM. Other passive fuel tank inerting systems can be found in the work of S. McCormick et al. [27] where a review about both fuel tank fillers and systems which surround the fuel tanks is presented. The work is focused on the capability of different systems to suppress fire in and from ground combat vehicle fuel tanks. D. Townsend et al. [28] used two different techniques in order to reduce the shock pressure waves which are generated in HRAM: thin air-filled baffles introduced inside the fuel tank and bubbling air through the fluid. These two techniques consist of introducing low impedance solutions and hence disrupt or disperse the shock wave produced in the fluid by the projectile impact. The mitigation effect for both techniques reaches approximately 50% of reduction in the pressure wave in some region of the fuel tank, and therefore it decreases the damage induced in the structure. Another work that proposed an attenuation technique is the one developed by Peter J. Disimile et al. [29]. In this case, the mitigation of shock waves using wedged bars placed inside the water filled tank has been also analysed. These elements are specially designed to reduce the shock pressure wave by the destructive interference between the original pressure wave and its reflections. It is shown that the proposed technique allows reducing the pressure measured in the sensors inside the fuel tank up to 60%. These two works successfully reduced the shock pressure wave and therefore the damage induced in the structure. However, as it was said previously, depending on the studied impact conditions and the structure characteristics in which the HRAM is generated, the shock pressure wave may not be the most damaging stage.

The cavity expansion can be considered as the major cause of deformation and failure in the tanks in which the size of the cavity generated inside the tank is similar to the size of the mentioned tank [24,25]. These cases could occur in high velocity impacts of metallic fragments against small range aircrafts or fighters. Therefore, in this work an attenuation method focused in the reduction of the cavity expansion is proposed, instead of the reduction of pressure waves. In this case, a honeycomb structure is placed inside the fluid filled tank, so that when the cavity grows inside the tank, the honeycomb structure gets deformed plastically, absorbing part of the energy transferred into the fluid. The high energy absorption to density ratio of honeycomb or lattices structures is well known [30-34], consequently, it is expected that the structure protected with honeycomb will be subjected to a less damaging loading case. As it is well known honeycomb low density will not counteract with the effort in reducing the weight on aircraft structures. The different orientation possibilities, in which the honeycomb structure can be placed inside the tank, are analysed in order to obtain the best configuration to attenuate the HRAM effects on the structure when it is impacted perpendicularly.

2. Experimental description of the problem

2.1. Experimental set-up

In this work, an experimental set-up has been used to carry out the tests in which the performance of the HRAM attenuation method proposed is analysed. Fig. 1 shows a sketch of the experimental devices used to accomplish and register adequately the tests. All the experimental tests were done at the University Carlos III of Madrid Impact Laboratory.

The structure analysed is a 6063-T5 aluminium tube (150 *mm* × 150 *mm* × 750 *mm* and 3 *mm* thickness) that has been filled with fluid to study the HRAM effects. According to the recommendations of the Advisory Group for Aerospace Research and Development (AGARD) [2,3] no fuel was used in any of the experimental tests due to the risk of fire; replacing it with water. The tubes are closed by two PMMA windows (30 *mm* thick) allowing the recording of the impact process. Four steel bars joint the PMMA and the tube without pre-stressing it; therefore it is needed to use a sealant in the contact between the tube and the PMMA to assure the water tightness of the tube. This set-up

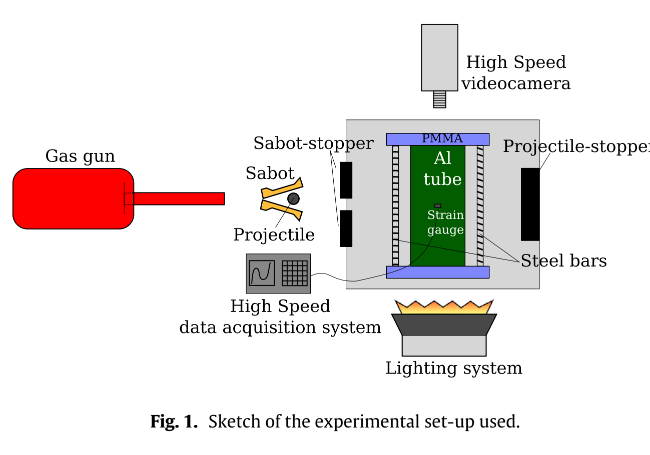


Fig. 1. Sketch of the experimental set-up used.