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Performance of a shock tube facility for impact response of structures

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ABSTRACT

This paper presents a numerical approach to compute the performance of a double diaphragm shock tube facility for structural response investigations. To assess the influence of different sources of dissipation, including partial diaphragm opening and shock tube vibration, numerical simulations are carried out using several different finite element models of increasing complexity to compute shock tube performance. The numerical model accounting for tearing and partial opening of the diaphragms is the one that best reproduces the results of the experiment, thus indicating that the diaphragm non-ideal opening process is the most relevant cause of losses. Both the numerical and the experimental results agree in predicting shock tube efficiency in terms of intensity of the reflected shock of about 50–60% with respect to ideal, one-dimensional conditions.

1. Introduction

The response of critical civil and industrial infrastructure such as government structures, nuclear power plants, power stations, tunnels and shopping centers to shock and blast loading has become a topic of great interest. Terrorist attacks around the world and the resulting casualties and damage have highlighted the vulnerability of existing infrastructure to the highly impulsive nature of the blast loads. It is primarily government and military organizations that have developed blast resistant design guidelines and retrofit procedures, while the civil engineering community has not traditionally been involved in blast engineering research. The methods currently adopted in blast-resistant design are largely based on empirical observations of live explosive tests [1–11].

Experimental activities are particularly relevant in this field not only for validating computational methods, but also because of the limited amount of existing experimental blast data. Experimental investigation of structures or structural components has traditionally been performed through live explosive testing, but the use of explosives remains very limited due to its dangerous and expensive nature. An alternative technique for creating impulse loading on portions of a structure involves use of shock tubes; they offer an opportunity to impose on the specimen surface the loading history typical of blast waves due to explosions. As reported, for example, in [12], the use of shock tubes to create impulsive loading scenarios has several advantages over the use of explosives, such as safety, cost and repeatability of experiments, though it also has some limitations, mainly related to the size of the structural members tested.

There has been considerable interest in research into blast simulation methods since the 1960s, at which time a research symposium titled “Military Applications of Blast Simulation” was formed for the sole purpose of designing blast simulators to produce the specially tailored waveforms representative of nuclear blasts [13,14]. By the mid-1980s, with the aim of measuring blast loads from nuclear explosions on full-sized military equipment such as tanks, small aircraft and helicopters, several large air-blast simulators had been built in various countries as part of a well-financed defense effort as, for example, the facility described in [15]. The use of shock tubes to simulate blast loading on structures is not new, and this technique was developed to reproduce blast waves nearly identical to those obtained in live explosive tests [16,17]. The literature reports experimental observations for material blast testing covering concrete specimens [18,19], steel plates [20], reinforced masonry walls [21] and polymeric materials [22]. In recent years, new shock tube facilities have been developed for structural applications [12,23–25] and the response of composite materials, including glass-reinforced polymers, 3-D woven composites [23,26] and fiber-reinforced concrete materials [27], has been investigated.

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The importance of shock tube facilities in blast engineering is thus apparent. However, this growing interest in shock tube development has not been matched by studies of shock tube efficiency. In fact, the design of a shock tube facility for blast engineering applications involves many challenges, mainly due to the difficulty of predicting the pressure history against the specimen, which, together with the impulse and the duration of the positive phase, is the most important parameter in order to correctly load the specimen.

Pressure loads are strongly influenced by several parameters, such as tube geometry (boundary layer effect), tube wall response and the diaphragm opening process. Note that the diaphragm opening process is difficult to assess using an analytical approach. Previous studies have investigated tube wall deformation when subjected to internal shock waves [28–33], the mutual interaction between the shock wave and the structure [34,35], the boundary layer effect on the shock wave [36–40] and the influence of incomplete diaphragm opening on shock wave formation [41–46], including the structural dynamics and the diaphragm failure mechanism [47,48].

This paper presents a numerical approach based on finite element (FE) models used to predict the performance of a facility recently developed in Italy [25]. The efficiency of the device is evaluated taking several sources of dissipation into account. Due to the fact that the shock tube under study is intended for structural applications, shock tube performance is evaluated here in terms of the peak value of the pressure at the end-wall position. In the following, with a slight misuse of technical terms, we refer to the reflection of the impinging shock wave as “reflected pressure”, to distinguish it from the “incident pressure” measured before the arrival of the shock wave, in accordance with standard practice in describing shock tube flows for blast engineering.

This paper is intended to provide guidelines to researchers for designing effective shock-tube facilities for structural engineering applications. The authors wish to share the methods they devised in order to verify the experimental apparatus developed at the Politecnico di Milano.

2. Experimental apparatus

The primary purpose of the shock tube facility studied in this paper is investigation of the structural response of a circular plate resting on soil when subjected to a shock wave [25]. Investigation of the underground tunnel lining under blast and fire conditions represents the general framework in which the present shock tube was conceived. The innovative features of the shock tube are a suitable end-chamber designed to investigate soil–structure interaction and burner equipment to heat concrete specimens in order to study to what extent thermal damage can affect the transmitted and reflected pressure wave as well as the structural response.

A detailed description of the shock tube facility with emphasis placed on the principles that have driven the experimental design choices may be found in [25]; only the features of interest are summarized in the following description.

A schematic layout of the shock tube device in the assembled configuration ready to test a specimen is shown in Fig. 1a. Four chambers, movable on a linear guide system, are shown in Fig. 1a: (a) the driver section, (b) the buffer or diaphragm section, (c) the driven section, and (d) the specimen/soil section. The total length of the shock tube is 14.9 m.

The buffer chamber is located between the driver and driven chambers and two diaphragms are placed in it. The three chambers have a circular cross-section with an internal diameter of 481 mm. The gas used in the experiments is helium for the driver and buffer chambers, while the driven gas is air under ambient conditions.

The driver and driven chambers have a length of 2.35 m and 10.5 m, respectively, with a 13.5 mm thick wall, while the buffer chamber has a length of 260 mm. The external diameter of the buffer chamber is 857 mm, equal to the maximum diameter of the flange welded on the driver and driven extremities. The buffer chamber is separated from the driver and driven chambers by two scored steel diaphragms; a gasket is placed on each side of the diaphragms to guarantee seal during the experiments. When the twenty screws are tightened with an impact torque wrench, each edge of the buffer, driver and driven sections bites into the diaphragms, guaranteeing an effective seal between the different shock tube chambers.

One innovative feature of the shock tube is the specimen/soil chamber, which is 1.8 m long and 13.5 mm thick and has an inner diameter of 583 mm. The specimen/soil section can be connected to the driven section through an ad hoc flange welded at one of its extremities; a blind flange closes the other end of the chamber. The chamber contains a circular slab specimen continuously supported on the soil. Further details of the specimen/soil chamber may be found in [25].

In the present paper, the performance of the shock tube is not evaluated in the full configuration normally adopted during structural tests (Fig. 1a), but instead the specimen/soil chamber is substituted with a blind end flange (Fig. 1b). In this case, the blind end flange is connected to the end flange of the driven chamber and reproduces the ideal situation of a rigid end. In this way the source of dissipation given by the finite specimen/soil axial stiffness on the performance of the shock tube equipment does not need to be modeled.

2.1. Firing mechanism

Either a single or a double diaphragm mode can be adopted for each test run. In double diaphragm mode, which is the test procedure adopted in this study, the buffer chamber is filled with a gas at a pressure approximately equal to the average of the driver (p_4) and driven (p_1) gas pressure. When the gases reach the assigned pressure levels in both chambers, the gas in the buffer chamber is vented, allowing it to return to atmospheric pressure. At that instant, the differential pressure between the driver and the buffer sections exceeds the rupture pressure of the corresponding diaphragm, and the first diaphragm opens. As a consequence, when the pressure wave arrives at the second diaphragm's interface, the second diaphragm fails and the firing mechanism is completely activated.

As mentioned above, no breaking devices are used to force the diaphragms open. Diaphragms are in fact designed to break under a given pressure difference. All diaphragms used in this study are made of S235 JR structural steel in accordance with [49]. This choice of material was motivated by the fact that steel can guarantee a burst pressure in the range of interest with a small thickness. In addition, S235 JR steel is easily available and inexpensive. The diaphragms are of a circular shape with a diameter of 697 mm, and are obtained by laser cutting from hot rolled plates. On one surface of the diaphragm, two grooves are scored through a milling machine. The two grooves are inclined at 90° with respect to each other and cross the center of the diaphragm.

In this study, two different types of diaphragms with a thickness of 2 mm are used; they differ in score depth, which was equal to 1.3 and 0.8 mm, respectively. The two diaphragm types correspond to increasing levels of burst pressure and were used for the two different pressure combinations inside the driver and buffer chambers, as described in the following section.

2.2. Instrumentation and test program

In order to study shock tube performance, an appropriate set of instruments is applied to the tube. A set of three ICP (Integrated