International Journal of Impact Engineering 86 (2015) 145–156

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Air blast resistance of full-scale slabs with different compositions: Numerical modeling and field validation

R. Castedo [a,*], P. Segarra [a], A. Alañon [b], L.M. Lopez [a], A.P. Santos [a], J.A. Sanchidrian [a]

[a] E.T.S.I. Minas y Energía, Universidad Politécnica de Madrid, Ríos Rosas, 21, 28003 Madrid, Spain
[b] Departamento de Construcción y Agronomía, Universidad de Salamanca, C/ Hornos Caleros n° 50, 05003 Ávila, Spain

ARTICLE INFO

Article history:
Received 7 February 2015
Received in revised form
4 August 2015
Accepted 5 August 2015
Available online 11 August 2015

Keywords:
Blast test
Scaled distance
Damage mechanism
Full-scale slabs
Peak overpressure

ABSTRACT

This paper investigates the advantages and accuracy of a finite element simulation of a blast loaded full-scale slab by validating the results with the corresponding field tests. For this modeling, a 3D pure Lagrangian approach using LS-DYNA with appropriate blast load routine (CONWEP), material models and suitable boundary conditions is developed. Eight full-scale slabs were cast and tested. Three standard reinforced concrete slabs with the explosive at a scaled distance of 0.79 m/kg$^{1/3}$ were used to calibrate the numerical model. Two normal reinforced concrete (RC) slabs with the explosive charges located at scaled distances of 0.41 and 0.20 m/kg$^{1/3}$, and three more with different constructive solutions, such as fiber reinforced concrete (steel and polypropylene fibers) or reinforced concrete protected with a steel sheet at the center of the slab, aim to study the sensitivity of the model to these changes. Field data obtained with accelerometers and pressure transducers are compared with results obtained from the numerical modeling for the calibration tests. For the others, the results from numerical model match those from field blast tests in terms of damage pattern and percentage of surface damage. The model is sensitive to the effect of scaled distance (explosive at lower scaled distance produced higher surface damage and different fracture patterns) and to different construction patterns. Reinforced concrete slabs with steel or polypropylene fibers had better blast resistance under tensile stress (bottom part of the slabs) than simple reinforced concrete. The slab with the steel sheet on top had higher surface damage on both faces than the others for the same scaled distance.

1. Introduction

Reinforced concrete is one of the principal building materials in engineered structures like airports, transport stations, bridges and buildings, for many reasons such as price, weathering and fire resistance, formability and good compressive strength. However, recent terrorist attacks using improvised explosive devices in New York (2001), Madrid (2004), Stockholm (2010), Moscow (2011) and Boston (2013) show great vulnerability of these structures to this kind of threat.

Attacks over vulnerable structures can cause a large number of casualties especially when they collapse. Consequently, it is of great importance to investigate and improve the response of concrete structures to blast loading. To enhance the blast performance of these materials, two main procedures have been widely used. The first, consist on adding steel [1–3], carbon [4,5] or polypropylene [6,7] fibers as an internal reinforcement to get a fiber reinforced concrete (FRC). These materials have been used in FRC to achieve a variety of property enhancements, including: tensile strength, cracks number of smaller size, impact and concrete spalling resistance, among others. Another method to reduce the damage of concrete structures is by protecting them with external elements like aluminum foam [8–10] or steel sheets [11]. As any technique used is not an absolute solution and there is always an associated high cost, finite elements simulations have been widely used to better understand the influence of the blast load and the resulting dynamic structural response in detail [12], so that the level of damage of new as well as existing structures can be assessed with a reasonable accuracy. These modeling tools must be, however, calibrated and validated with experimental data [13].

Over the last decade, the investigation of the effects of blast and ballistic loadings on structures has been an area of active research

* Corresponding author. E.T.S.I. Minas y Energía, Universidad Politécnica de Madrid, Ríos Rosas, 21, 28003 Madrid, Spain. Tel.: (+34) 91 336 6454; Fax: (+34) 91 336 6948.
E-mail address: ricardo.castedo@upm.es (R. Castedo).

http://dx.doi.org/10.1016/j.ijimpeng.2015.08.004
0734-743X/

in different fields [6,14,15]. It was found that, except for some rare experiments [6,8,16], blast resistance tests are normally performed on small scale specimens of less than 2 m in each dimension [1,2,17–19]. This is because full-scale tests are expensive, complex to handle and difficult to monitor in terms of physical parameters that characterize the blast event and the specimen response. Due to these limitations, the charges used are also scaled and their dimensions became smaller than the charges that can be potentially used by terrorists. Furthermore as the structure response to blast loading is governed by many factors, including charge mass and standoff distance, structure size and orientation, proximity of the target to other structures or to significant land features, misleading conclusions may be drawn when small-scale tests are extrapolated to full-size specimens [11].

A number of commercial hydrocodes such as AUTODYN [20] and LS-DYNA [21] are available for modeling structural nonlinear dynamic responses. Particularly in LS-DYNA different numerical techniques, mainly pure Lagrangian [4,22–24] and arbitrary Lagrangian–Eulerian (ALE) [17,18,25,26] are available to analyze the structural response to blast loading [21]. A pure Lagrangian formulation in combination with a simplified blast load description based on CONWEP [27] provide blast pressure time histories. An ALE formulation combined with a fluid–structure interaction assuming that the material flows through the fixed mesh is also used for that purpose. Both formulations provide accurate results, but ALE approach requires increased computational effort compared to the pure Lagrangian specially for full-scale slab model [13]. Although, there is a significant advancement of numerical modeling of blast tests on structures, the effects of different modeling settings on the results are rarely reported making necessary more numerical studies to understand the complexity of dynamic response of reinforced concrete structures [23].

In this work, a 3D LS-DYNA model, with Lagrangian mesh and CONWEP blast load description, is developed to simulate the structural behavior of full-scale reinforced concrete slabs under blast loading. The numerical results, obtained with two different models for concrete, are validated from experimental data in three field tests in which a standard reinforced concrete slab was blasted under the same conditions. Five more tests in which either the scaled distance of the explosive charge to the specimen or the slab characteristics are varied (steel sheet protection or the addition of steel or polypropylene fibers) to investigate the sensitivity of the model in terms of the resulting damage. As in other works [4], the extent of surface damage on each face has been used to assess the performance of numerical modeling in comparison with the tests. In the field, surface damage is defined as the ratio of spalled area to initial surface area, while in numerical modeling it is the ratio of the number of elements eroded (spalling) and detached from the surface to the number of total elements on the initial surface.

2. Test description and instrumentation

Eight full-scale reinforced concrete slabs were tested under different combinations of explosive mass and standoff distances, at the Technological Institute of “La Marañosa” (Spain) from 2010 to 2014.

The test set-up is shown in Fig. 1 and summarized in Table 1. Six slabs, identified as S1–S6, were built with conventional reinforced concrete. A steel sheet (S-275 JR) of dimensions 1.5 × 1.46 m and 10 mm thick was located at the center of the span of slab S6, on the side facing the blast charge (Figs. 1 and 2). The steel sheet was fixed to the concrete using a two-component epoxy resin, ensuring a rigid bond. Two more slabs were built with fiber reinforced concrete, steel fibers were used in specimen S7 and polypropylene ones in S8. The slabs were 4.40 × 1.46 m with a thickness of 0.15 m. They were bolted to two concrete blocks with steel sheet cover of 2 × 1.2 m and 0.95 m height placed 4 m away each other, see the layout in Fig. 1. The reinforced meshing was constructed with a

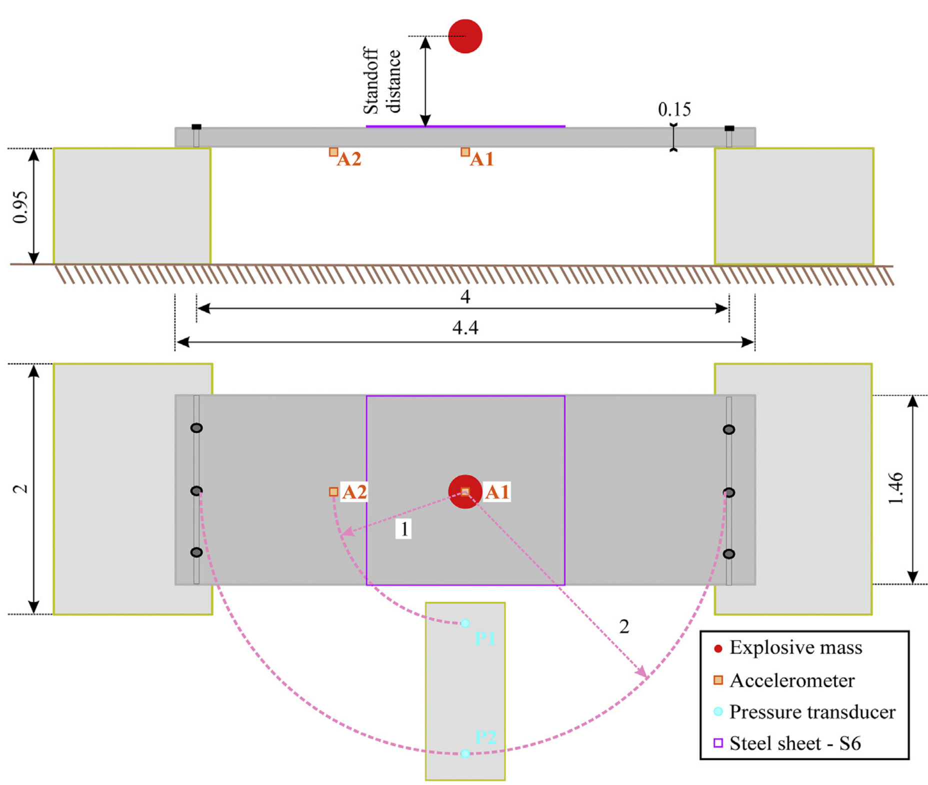

Fig. 1. General blast test set-up. Measurement devices locations in slabs S1, S2 and S3, and steel sheet used in slab S6 (units: m).