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Prediction of the perforation of targets impacted by deformable projectiles

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A B S T R A C T

This paper proposes a simple formulation for the impact analysis of a deformable projectile on reinforced concrete targets. This approach assumes the presence of soft strikers and rigid targets. Based on an energy balance, it aims to predict a perforation limit for different targets under soft impacts. The procedure employed is validated by means of tests performed on a rigid target (pendulum test) and reinforced concrete slabs. The article discusses various estimations of the crushing force of projectiles, as derived from experimental results and numerical approaches. The efficiency of simplified approaches is highlighted from an engineering point of view. The limit between soft and hard impacts is also analyzed according to a recent criterion. Moreover, the paper proposes validating the approach using experimental tests with both perforating and non-perforating impact tests on nine slabs.

1. Introduction

The study of the mechanical response to loads generated by impacts is key to the analysis of structural vulnerability. Depending on the striker's strength, the phenomenon involved and therefore the target response may differ. Most of the existing empirical formulae used to predict perforation are proposed for the case of hard impacts on either reinforced concrete (RC) barriers [1,2] or metal targets, e.g. Ref. [3]. Few approaches are available to assess the possible perforation of a barrier subjected to a soft impact. In the case of an aircraft impact, Riera [4] considered the projectile as a two-body system: a crushed pipe with no velocity in contact with the structure, and a tube. The resulting contact force however still needs to be applied to a numerical model of the barrier in order to predict the perforation. CEB and Baroth et al. [5,6] proposed analytical formulae of ballistic velocities in the case of a soft missile impact on reinforced concrete targets. Baroth et al. [6] based their study on a collection of experimental data, as presented in Ref. [7]. Their findings highlight that the application ranges of most perforation formulae [1] must be considered with caution since such ranges often depend on the compressive strength of concrete after 28 days (f_{c28}), whereas various experimental results [8–10] demonstrate that concrete under high confinement becomes insensitive to f_{c28}.

The present work develops a simple analytical formulation of perforation models in the case of soft impacts. This formulation, based on an energy balance, yields a model aimed at predicting a perforation limit for different targets under soft impacts. This paper also discusses various estimations of the crushing force of projectiles, through reliance on experimental results and different numerical approaches. The limit between soft and hard impacts is also analyzed using the criterion developed by Koechlin [11].

Section 2 recalls and develops the formulation proposed in Ref. [6] and moreover specifies the crushing force calculations. This set of formulation and calculations are then applied to the experimental results of a pendulum test (Section 3). From the initial formulation, simple formulae are also deduced in order to predict the ballistic velocity limit and perforation limit in the case of a soft impact on reinforced concrete targets (Section 4). Lastly, Section 5 proposes a validation of the approach through an experimental campaign on both perforating and non-perforating impact tests [7].

2. Prediction of perforation in the case of soft impact

The first subsection (2.1) recalls and develops the premise proposed in Ref. [6]. It is complemented by potential calculations of the crushing force generated by the deformable projectile (subsection 2).

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2.1. The energy balance of a soft impact process

Let's consider a target of mass, M_T, under the impact of a projectile of mass M_P, total length L and diameter d. The projectile is assumed to be rigid over a length L_H. Let's begin by decomposing the impact process into three stages (see Fig. 1), with a distinction made between soft and hard impacts [12].

2.1.1. Stages of the impact process

During Stage 0, i.e. before the impact has occurred, the initial projectile velocity and kinetic energy are respectively denoted V_0 and E_{P0}.

Stage 1 corresponds to the soft part of the impact (crushed length $u < L - L_H$). The energy dissipated during the crushing phase, which lasts Δt, is defined as the mechanical work W_P done by the time-dependent crushing force $F_p(t)$ through the crushed length u_P of the projectile. The motion of the impacted target is characterized by: displacement u_T, velocity $\dot{u}_T$, acceleration $\ddot{u}_T$, and mechanical work W_T. At the end of Stage 1, i.e. after the crushing, the velocity and kinetic energy of the projectile are respectively denoted V_1 ($<V_0$) and E_{P1}. In Stage 2, the impact becomes hard (if the velocity is high enough). During perforation, the failure energy of the target E_F is dissipated. The projectile velocity and kinetic energy are now respectively denoted V_2 and E_{P2}. The velocity of the target V_T reaches its maximum value.

2.1.2. Energy balance during the perforation process

During Stage 1, the initial kinetic energy E_{P0} of the projectile is reduced to the kinetic energy E_{P1} after crushing of the deformable part of the projectile. The energy balance during the crushing process can be summarized by noting:

$$E_{P0} - E_{P1} = W_P + W_T \tag{2.1}$$

where E_{P0} and E_{P1} depend on the initial velocity V_0 and velocity V_1, in assuming the weight loss is insignificant during crushing, thus neglecting damage in the target throughout the phase:

$$E_{pi} = M_p V_i^2 \Big/ 2, \quad i = 1, 2\ldots \tag{2.2}$$

The energy dissipated during the crushing phase, which lasts Δt, is defined by the mechanical work W_P done by the time-dependent crushing force $F_p(t)$ through the crushed length u of the projectile. Considering that the projectile can be modeled as a one-dimensional nonlinear spring, this mechanical work is written as:

$$W_P = \int_0^{\Delta t} F_p(t)\dot{u}_P(t)dt \tag{2.3}$$

where $\dot{u}_P(t)$ is the velocity of the projectile.

The mechanical work W_T relative to the motion of the target, whose mass is assumed constant, is expressed as follows:

$$W_T = M_T \int_0^{\Delta t} \ddot{u}_T(t)\dot{u}_T(t)dt \tag{2.4}$$

where $\ddot{u}_T(t)$ is the acceleration and $\dot{u}_T(t)$ the velocity of the impacted target.

At Stage 2, the initial kinetic energy E_{P1} of the projectile is reduced to the kinetic energy E_{P2} after perforation of the target by the crushed projectile:

$$E_{P0} - E_{P2} = W_P + W_T + E_F \tag{2.5}$$

E_F is the failure energy of the target, i.e. the energy dissipated during the perforation process. In the case of impact on a metal target, E_F can be found, for instance, in Ref. [3]. In the case of impact on a concrete target, E_F can be defined, according to the energy balance, such that

$$E_F = \frac{M_P\left(V_0^2 - V_2^2\right)}{2} - W_P - W_T - E_T \tag{2.6}$$

One difficulty encountered when using this approach is to estimate both the crushing force F_P of the projectile and the work W_P of this force over the crushed length. The following section will develop this point further. Afterwards, a pendulum test will be studied, with emphasis on estimating the crushing work of the projectile W_P and the crushing force F_P.

2.2. Crushing force for a deformable projectile

The well-known Riera Model may be used to estimate the force $F_P(t)$ [4], bearing in mind that this model is not explicit, nor does it take into account the strain velocity effect and cylindrical projectile

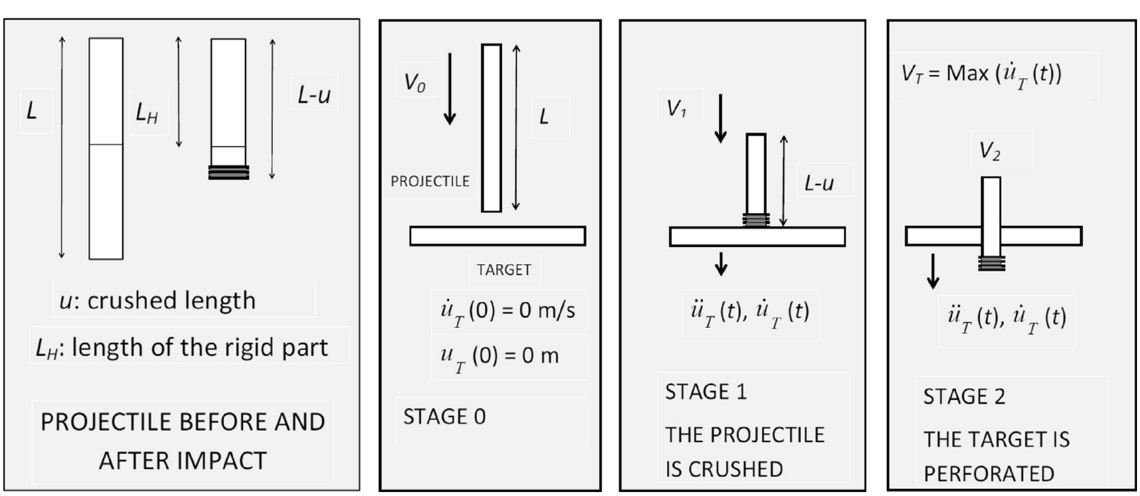

Fig. 1. Stages of the impact of a deformable projectile on a rigid target.