



Comparative numerical and experimental study of projectile impact on reinforced concrete



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ABSTRACT

Concrete structures in military areas are subject to projectile impact both as a result of direct fire and in the form of splinters from explosives. These structures may be damaged, resulting in partial loss of integrity, but must leave the objects or individuals within them unharmed to the largest extent possible. The degree of damage depends on a variety of factors relating to the projectile, including its mass, geometry, impact velocity, trajectory and material properties. A number of controllable factors also relate to the characteristics of the concrete structure itself and the reinforcing material used to produce barriers. In order to analyse the structural response and optimize design parameters, various dynamics simulations have been performed in this work relating to projectile impact on concrete structures. To correctly model the impact, both non-linear material response and progressive finite element erosion have been taken into account. The numerical results have been discussed and compared with experimental results for three different impact scenarios, with good alignment achieved in terms of both penetration depth and crater size. This correspondence also demonstrated the pertinence of a specific material model, the Riedel-Hiermaier-Thoma (RHT) model within the LS Dyna FEM software package, in guiding and interpreting physical experiments in the case of impulsive projectile loading and penetration of concrete. The alignment between experiments and simulations also confirmed the robustness of the material model, specifically selected for this particular application.

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1. Introduction

Concrete is the most widely used artificial material in world [1], with an estimated 7.5 billion cubic meters produced every year, equivalent to one cubic meter for every inhabitant of the Earth [2]. Despite its widespread and common use, concrete continues to represent a highly valid choice for non-civilian applications such as military shelters and casemates due to its combination of resistance, functionality and low cost [3,4]. Its suitability and diffusion in military applications is sufficiently great that a number of important technological developments have recently been introduced to optimize construction methods for improved strength in interfacial transition zones (ITZ) [5]. Prediction of material and structural response is equally as important in unconventional applications such as military shelters. Specifically, recent studies have sought to

verify the level of security provided to occupants in concrete structures in the case of explosions [6] and impact from projectiles such as missiles [7] and other ballistic objects [8]. The experimental verification of concrete structural response to these types of loads is problematic and expensive due to both the requirement to create complex structures, complete with foundations, reinforcement and protective barriers [9], as well as difficulties in performing and measuring the experiment itself [10–12]. The latter is due to the complexity of reproducing loads that are representative of those expected in the field, requiring unique environments such as shooting ranges and the handling of high-calibre firearms or explosives such as mines or grenades, which present potential risks to those carrying out the experiments [3].

To bypass these problems and directly determine the response of concrete in unconventional applications, numerical simulations exploiting the Finite Element Method (FEM) have yielded important results in recent years (as in Ref. [13]). To provide realistic outcomes that accurately reflect real-world scenarios, the constitutive model of concrete must be improved to reproduce even the most elementary phenomena. Anisotropic elastic degradation,

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hysteretic unloading loops, un-associated plastic flow, and unstable and post-failure behaviour are just some of the aspects that must be accounted for to correctly model concrete subject to ballistic impact [14]. Developments in FEM such as improvements in material constitutive models and large increases in computer calculation speed have led to the possibility of reproducing complex real-world situations with good accuracy. The equations currently employed for this type of simulation derive from experimental data, with well-established methods for establishing parameters such as impact crater diameter [15,16]. Both 2D and 3D FEM simulations have been proposed for penetration of projectiles into reinforced concrete structures [17], including useful guidelines for optimization of parallel calculations for modern computer hardware. Despite these important developments in calculation power and complexity, there is considerable room for improvement in providing univocal, accurate results.

Extensive analyses have recently been performed assessing the validity of empirical formulae, analytical models and simulation techniques for impact loading [18]. It has been found that mathematical functions relating to projectile penetration resistance such as stiffness play an important role in correctly modelling the problem, with robust formulations present in the literature [19]. It is also necessary to take into account both deformation and possible fracture of the projectile during impact, for which various modelling strategies have recently been proposed that consider progressive projectile deformation [20]. Such details may seem excessive when considering practical results; however, a number of studies have demonstrated that they have a non-trivial influence on the precision of simulation outcomes and prediction accuracy. For example, it has been shown that incorrect material modelling can produce significant deviations between simulation and experimental results in terms of the burst effect and erosion [4]. It has furthermore been shown that, despite using correct process parameters and mathematic representations, an incorrect choice of time step can lead to poor interpretation of wave propagation mechanisms during impact and fragmentation of concrete [21].

The first documented study of impact resistance of concrete barriers goes back to the mid-1700s [18]. Experimental works relating to projectile impact on concrete have been performed with elevated attention to detail due to important ramifications for personal and public safety. Particular importance has been placed on defence, nuclear energy [22] and civil security [23], including anti-terrorism measures [16] and many other applications. Unfortunately, public access to studies in these fields is relatively limited due to the sensitive nature of results. While a number of works have presented the results of broad experimental campaigns in terms of firearms, ammunition, barrels and other aspects [3,24], there are insufficient data as yet to correctly calibrate simulations. As a result, several authors continue to state that there is currently insufficient information to correctly model projectile impact on concrete [18]. A review of results from ten different experimental studies highlighted the effects of several test parameters on the dynamic response of concrete [25], evaluated in terms of measured strength values for the material. The results highlighted the fact that small changes in impact dynamics lead to very different material responses, which must be reflected in simulation outcomes. As a consequence of this elevated sensitivity, relatively small errors in modelling can lead to significant deviations between simulated and experimental results.

Noting the above mentioned considerations, it is necessary to continue the development of numerical models for impact dynamics and validate their results with controlled experiments. The objective of this study is to provide a framework for the simulation of ballistic impact on reinforced concrete structures. A number of different codes, models, conditions and calculation parameters

have been analysed and compared so as to highlight theoretical considerations and provide useful, practical guidelines for the simulation of projectile impact based on preliminary experimental results obtained by the authors in a previous work [26]. Simulation accuracy has then been validated against reliable experimental data for ballistic impact tests on reinforced concrete structures, obtained by an independent research group [27] for three different types of firearm in order to cover a wide range of impact scenarios.

The RHT model is a macro-scale material representation that incorporates features necessary for the correct description of the dynamic strength of concrete at strain rates and pressures relevant to the study of impact. A complete description of this model has been presented [28], including details regarding its effectiveness in correctly modelling real situations. In brief, the model couples a material equation of state accounting for porous compaction of concrete with the RHT strength model containing three limiting surfaces in stress space that consider pressure, triaxiality and strain rate. The three surfaces describe, respectively, the elastic limit, failure strength and residual shear strength of damaged concrete under confined conditions [29].

Over the last decade, numerous applications appeared in publications which deal with dynamic load cases such as projectile penetration, contact detonation, internal and external blast loading. In any case, the correct selection of the material model remains a critical aspect.

For instance in Ref. [30] four conventional damage plasticity models for concrete, including RHT, are compared. All models use very similar elastic and inelastic computational procedures, but developed different formulations for dealing with the non-linear elasticity. Moreover, all these models employ the same three strength surfaces (yield surface, limit surface and residual surface as detailed), but slight differences are seen in mathematical expressions defining the profiles of these strength surfaces. As main result of the assessment, it is possible to report that all models rely heavily on well tuned parameters to reproduce observed material response. At the same time, it is also highlighted that many benchmarks were performed to provide information for the RHT model's basic parameters without providing sufficient data to accurately capture the response at various strain rates.

For instance [29], demonstrated that the correct application of the RHT model requires a set of suitable model parameters without which reliable results cannot be expected and complex procedures for their precise determination has to be considered. In that research, in particular, a C40 concrete was investigated while material data cannot be simply adopted in the case of different concrete.

Finally, it is noteworthy that the standard RHT model, when implemented in different codes falls short in representing the concrete behaviour under the dynamic compression and tension loading.

This research moves in the direction of fostering a conscious utilisation of the RHT model providing a new experimental validation, but also technical information and remarks for a better applicability on real cases.

2. Experimental data

Results for ballistic impact tests with 9 mm Luger, 0.357 Magnum and 7.62 Reflex Lead-core firearms at a firing distance of 25 m have been reported in the literature [3,26,27]. The firearms in question represent three classes of weapon: a semi-automatic pistol, a pistol and a rifle, respectively. All projectiles were full metal jacket (FMJ) type with characteristics as given in Table 1. The mechanical properties given in Table 2, corresponding to AISI-SAE 4340, were considered for the purposes of simulation in the present work.

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