ENGINEERING APPROACH TO CALIBRATE A CONCRETE MODEL FOR HIGH SPEED IMPACT APPLICATIONS

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ABSTRACT

This paper describes a study on the mechanical response of concrete under high-velocity impact. It encompasses both experiments and numerical simulations. The aim is to validate an approach for building a concrete numerical model sufficiently robust and accessible to be used for designing civil or defense infrastructures. A conventional concrete (35 MPa compressive strength) has been chosen to apply the method. Experimental tests are conducted to characterize the material in compression and to measure its residual strength during compaction. Impact tests of a kinetic energy projectile (KEP) with an ogive shape nose are also conducted at velocities ranging from 200 to 900 m/s to reproduce both subsonic and supersonic impact conditions. The effect of the concrete confinement is investigated by varying the thickness of a metal jacket surrounding the impacted specimen. Regarding the numerical model, a Holmquist–Johnson–Cook (HJC) for concrete has been calibrated from the measured data. Simulations of the impact perforation are conducted with the γ-SPH solver available in IMPETUS AFEA^{TM}. The numerical model has been able to reproduce the main damage in the concrete during the projectile penetration. Good correlation in terms of deceleration profile during penetration is obtained with the experiment. Moreover, the model is robust enough to reproduce the effects of the confinement variation in the projectile residual velocity. This methodology could be applied to other types of concrete materials subjected to various loadings such as near-field blast for example.

Keywords: concrete, KEP, impact, HJC, γ-SPH.

1 INTRODUCTION

Concrete is commonly used as building material for its good strength in compression and relatively low price. However, it shows brittle response in traction unless it is reinforced with metallic bars or fibers. Understanding concrete response facing warhead threats is important for both the design of strategic infrastructure protection and the prediction of warhead performances. From both perspectives, it is important to have access to a robust model that is able to reproduce the main phenomena during such terminal ballistic event. This knowledge also gets increasingly important as terrorisms attacks with improvised explosive devices (IEDs) need to be considered

Many studies related to concrete damage under dynamic events are available in the literature. For the defense industry, the main considered threats are blast and penetration. In general, blast involves a structural response of a wall. However, when the explosive is relatively close, it can lead to similar damage to impact for which the response is highly governed by the concrete damage mechanism and post-failure mechanical properties.

For the case of penetration, one such example is the impact of kinetic energy penetrator (KEP) on reinforced concrete structure. Fig. 1 describes three main steps that are encountered during such event. First, a craterization due to the compaction of the concrete is observed upfront of the projectile. Simultaneously, shock waves are propagating throughout the thickness of the wall. Then, the penetration process starts which is governed by the strength of confined damaged concrete. This step is characterized by the propagation of diffused damage and closing of voids due to compaction. Finally, fracture or spall may appear on the back side as the penetrator is reaching the end the wall. Step two may not be as prevalent if the concrete is not confined. Large crack appears sooner and the penetrator faces less

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resistance during its penetration. Therefore, the presence of reinforcement improves the response of the concrete under both traction and compression loadings as it withstands some of the loads and improves the level of confinement [2]. From these descriptions, the residual compression strength of damaged concrete is important to consider for any concrete.

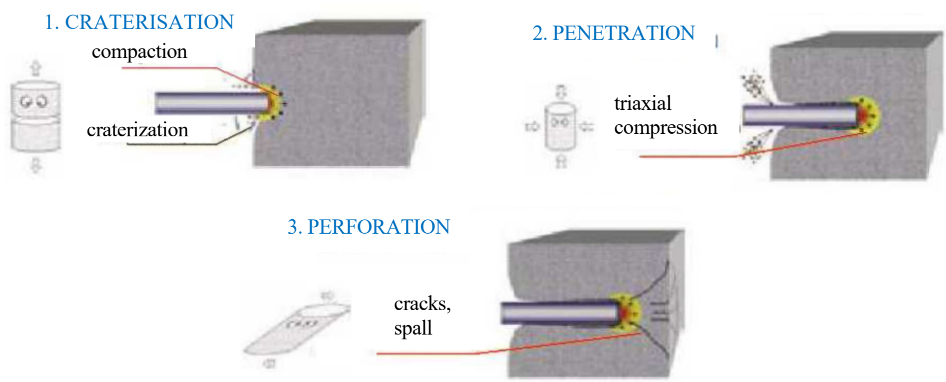


Figure 1: Description of concrete impact phenomena. *(Source: Reproduced from [1].)*

This study focuses in building a concrete model dedicated to impact. The model should be good enough to be used for the defense industry applications and yet it should require a limited number of tests for its calibration. The Holmquist–Johnson–Cook concrete model (HJC) [3] available in IMPETUS AFEA™ corresponds to these criteria. A simplified characterization approach is proposed and tested with a conventional building type concrete. Regarding the discretization method, a meshless method is used to avoid difficulties related to element erosion.

This paper is divided into two parts. Firstly, a description of the modelling approach followed by the presentation of the characterization approach. And finally, the validation test is presented with the corresponding model and an analysis is proposed.

2 MODELLING

2.1 Concrete material model

Apart from the linear response, concrete models for impact simulation must have at least two other characteristics: a brittle response in traction and an important dependency of the compression strength on the confinement for both undamaged and damaged material. Material property can go from a simple elastic-brittle to very complex laws with damage and cracks propagation controls. For example, some of the interesting models for concrete are K&C [4] and RHT (Fig. 2) [5]. They both account for stress triaxiality, strain rates and residual strength when confined. The PRM model [6], [7] and the model proposed by Bazant et al. [8], [9] are even more complex candidates as they consider the propagation of cracks in the damaged material. Such models have been developed for multiple applications (blast, penetration, etc.) and therefore require a quite substantial efforts to be calibrated.

The HJC concrete model [3] has been introduced in 1993 to study the mechanical response of concrete under large deformation, high strain rate and high pressures. The concrete

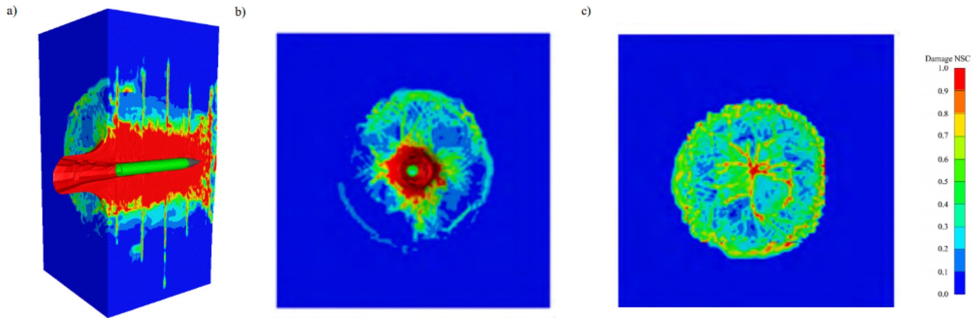


Figure 2: FE modelling damage after 3.9 ms impact of 420 m/s nose projectile on reinforced concrete using RHT model. *(Source: Reproduced from [2].)*

response is described in terms of two independent behaviors: compaction and strength (Fig. 3). The compaction behavior is characterized by three main regions:

- region I: region of linear response with a bulk modulus K_0,
- region II: it is a transition region during which voids are closed,
- region III: fully compacted material where the pressure is computed with K_1, K_2 and K_3.

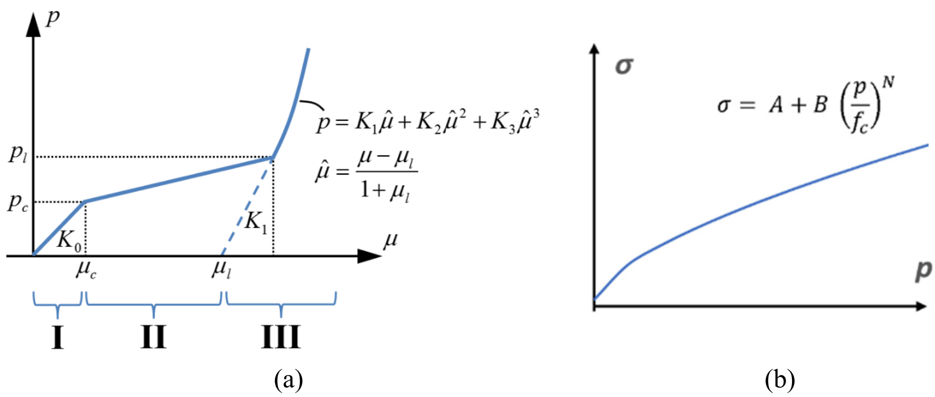


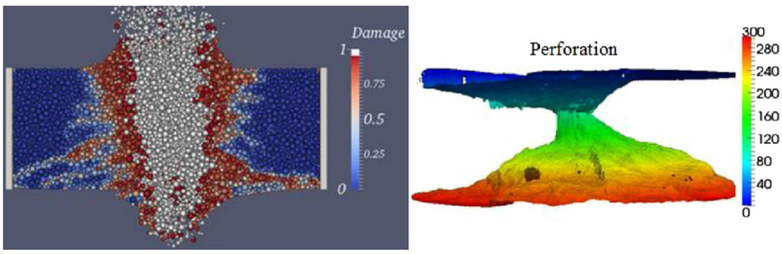
Figure 3: Description of the Holmquist–Johnson–Cook concrete model. (a) Pressure vs volume strain curve; and (b) Yielding curve represented in the equivalent stress vs pressure plane [3].

$$\sigma_y = f_c\left[A\,(1-D) + B\left(\frac{p}{f_c}\right)^N\right]\left[1 + C\ln\left(\frac{\dot{\epsilon}}{\dot{\epsilon_0}}\right)\right]. \tag{1}$$

The material strength is pressure sensitive. It is described by eqn (1) where A, B, N and fc (compressive strength) describe the quasi-static strength of the material. D is a damage variable that progresses during compaction and plastic strain and C is the strain rate sensitivity factor. It can be considered as a simple model in the concrete damage modelling community. Though, it accounts all the major concrete states encountered during a perforation. Another advantage is the availability of the HJC model in major commercial explicit dynamic solvers like LS-DYNA®, IMPETUS AFEATM, Abaqus Explicit®, Ansys Autodyn®.

2.2 Discretization

Most of the presented simulations use Lagrangian finite element with erosion. Some authors have tested meshless methods. For example, Antoniou et al. [10] adapted a discrete element model to simulate confined concrete under hard impact (Fig. 4). The model was able to reproduce some of the cratering damage. SPH is also another attractive meshless method thanks to its ability to handle large arbitrary deformation, though it suffers from instabilities like non-physical oscillation, tensile instabilities, particle clumping…. Questioning their accuracy damage and fragmentation modelling.



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(a) (b)

Figure 4: (a) DEM comparison of perforation crack pattern [10]; and (b) FE modelling damage after 3.9 ms impact of 420 m/s nose projectile on reinforced concrete using RHT model [2].

To achieve robust and consistent stabilization, a new meshless method called γ-SPH based on Arbitrary Lagrangian Eulerian (ALE) considerations is used. The idea is to combine and benefit from both Eulerian and Lagrangian movement descriptions. The formulation has been proven to be conservative, robust, stable and consistent. We refer to Collé et al. [11] for the detailed proof in the context of monophasic barotropic Euler equations (Fig. 5). These properties are validated on many academic test cases ranging from hydrodynamics to solid dynamics [11], [13]. By producing elastic waves free from spurious oscillations and by correcting the tensile instability, γ-SPH provides results in very good agreement with the analytical, experimental and reference numerical ones. It is not only able to handle material failure, but properly capture the strain localization process as well, a precursor to failure. Besides, fracture is now initiated on physical criterion and not numerical instabilities.

2.3 Simplified material characterization approach for the HJC model

As described in the introduction, concrete penetration is mainly characterized by large volume deformation and its high pressure. In the HJC model, the concrete is working in regions I and II. To investigate these areas, two types of characterization tests have been conducted: quasi-static compression tests for the compressive strength (f_c) (Fig. 6) and dynamic oedometric compression to recover the strength vs pressure curve. Both tests have

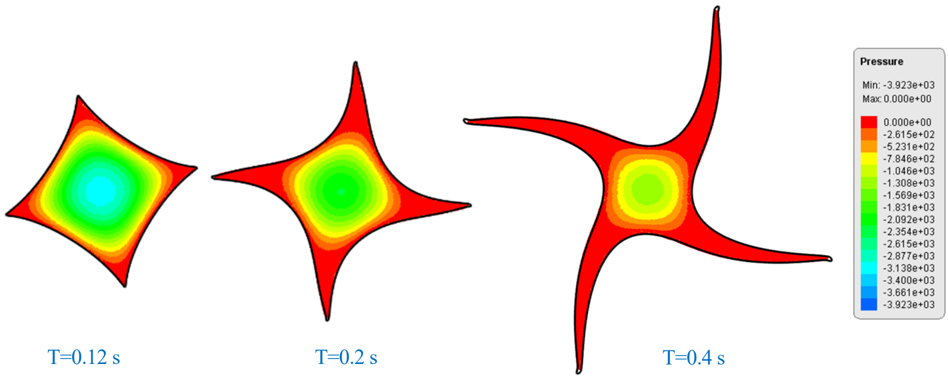

Figure 5: Simulation of barotropic flows: comparison γ-SPH (in color) and finite element solutions (black border) [12].

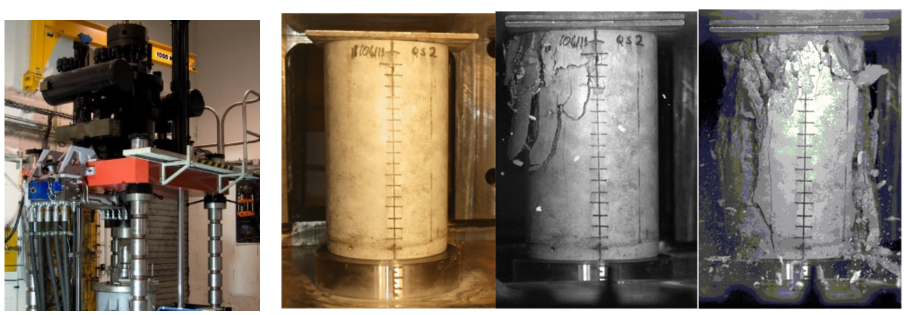

Figure 6: Compression test. (a) JUPITER dynamic press; and (b) Specimen tested in compression.

been conducted with the dynamic press JUPITER (Fig. 6(a)). It has an available volume of 1 m^3 for the specimen which makes it suitable for testing materials with important representative volume element like concrete and geomaterials [14]. The maximum load is 200 kdaN. Depending on the configuration, the press reachable strain rates ranges from 0.1 s^{-1} to 50 s^{-1}. During the test, the displacement of the top plateau is measured with an optoelectronic sensor and the loading force is recorded by a sensor placed on the lower plateau. A preloading of a few kilonewton is applied before the test to catch up any clearances between the plateau and the specimen.

Cylindrical specimens (Ø100 × L200 mm^2) are used for the quasi-static compression test. The measured compression strength is between 35 and 40 MPa. Regarding the oedometric tests, the concrete specimen (Ø75 × L100 mm^2) is confined by a metal jacket as presented in Fig. 7. Apart from the measurement of compression force and displacement, strain gages are used to record the circumferential deformation of the jacket. The analysis of all three curves enables to compute the two main input curves of the model: pressure vs volume strain and the equivalent stress vs pressure (Fig. 8). It should be noted that this last curve is different

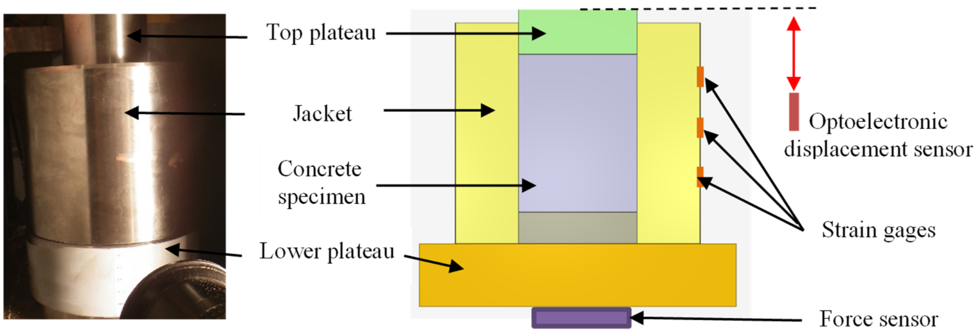

Figure 7: Oedometric test configuration with JUPITER press.

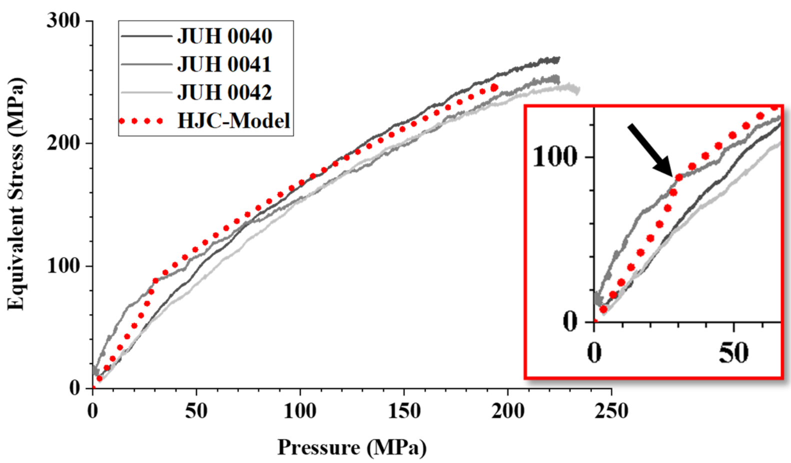

Figure 8: Equivalent stress vs pressure computed from oedometric tests and the calibrated HJC model curve obtained from the simulation of the test.

from the limit state curve obtained generally through multiple triaxial tests with various loading paths. The equivalent strength obtained from an oedometric test is below the limit state strength. However, from a practical point, it is relatively easier to conduct oedometric tests rather than multiple triaxial tests. Moreover, the oedometric test can be realized at an intermediate or high strain rates regimes.

Experimental curves of equivalent stress vs pressure from three different tests, presented in Fig. 8 show a good repeatability. Then, a fitted HJC model was used to simulate the oedometric compression test above. A simulation of the test is conducted using parameters from the fitted curves. For the simulation, displacement of the lower plateau is constrained and the experimentally measured displacement is applied to the upper plateau. The curve compared with the experimental data in Fig. 8 is obtained from an element in the center of the specimen. The slope discontinuity observed in the beginning of the numerical curve appears at the crushing limit "p_c" of the concrete. This discontinuity is also slightly observed in the experimental curves, though the phenomenon might be smoothed by the inertia of the dynamic press (not reproduced in the model).

3 IMPACT TESTS

3.1 Impact configuration and modelling

The presented impact test can be considered as an intermediate validation test for the model. It helps also to investigate the dynamic interaction between the projectile and the concrete material as this aspect has not been investigated before. It consisted of a down scaled Kinetic Energy Penetrator (KEP) with an ogive nose shape impacting a confined cylindrical concrete specimen (Ø100 mm × 200 mm^2). The concrete is confined by a 5 mm thick metal jacket. To limit the sources of uncertainties, specimens for both characterization and impact tests are made from the same batch of concrete. The KEP is made in high strength 35CrMo15 grade steel and it weighs 520 g. The impact velocity is 396 m/s for the presented test. A high-speed camera records the test from a side view. The test is conducted with a two-stage gas gun in a confinement chamber (Fig. 9).

(a) (b) (c)

Figure 9: (a) Two-stage launcher; (b) Containment chamber; and (c) Target specimen configuration inside the chamber.

For the simulation of the impact, the numerical model has integrated all the parts surrounding the concrete specimen as presented in Fig. 10. The concrete is represented with γ-SPH and the remaining parts are modelled with finite elements. A contact interaction is defined between the γ-SPH and the finite elements. There are 1.5 million γ-SPH particles in the model. The KEP is represented with a non-deformable material, its sabot is not geometrically represented in the numerical model. Only the mass of the sabot is considered by modifying the KEP material density.

3.2 Model results analysis

This section begins with a detailed description of the results of a reference case (Fig. 11) conducted at a striking velocity of 396 m/s. As observed in Fig. 11(a), the front side of the specimen is completely damaged. Some concrete has been ejected from the jacket. The specimen is not completely perforated and the KEP is stuck inside. The depth of the penetration of the projectile is 160 mm. On the front side of the target, external diameter of the jacket has increased from 110 to 115 mm.

Regarding the simulation results, the proposed model has reproduced similar projectile penetration (165 mm). The graph in Fig. 11(b) shows the projectile velocity during the

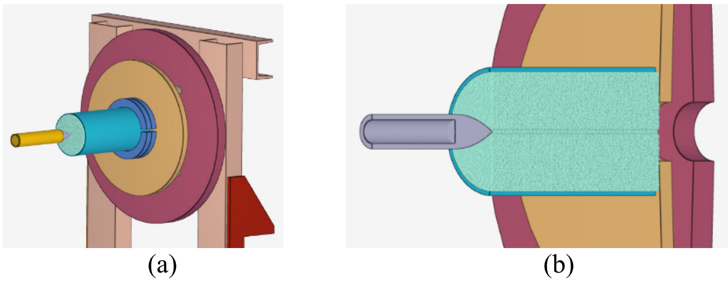

Figure 10: Isometric view of the numerical model. (a) Large view; and (b) Detail at the KEP and target interaction.

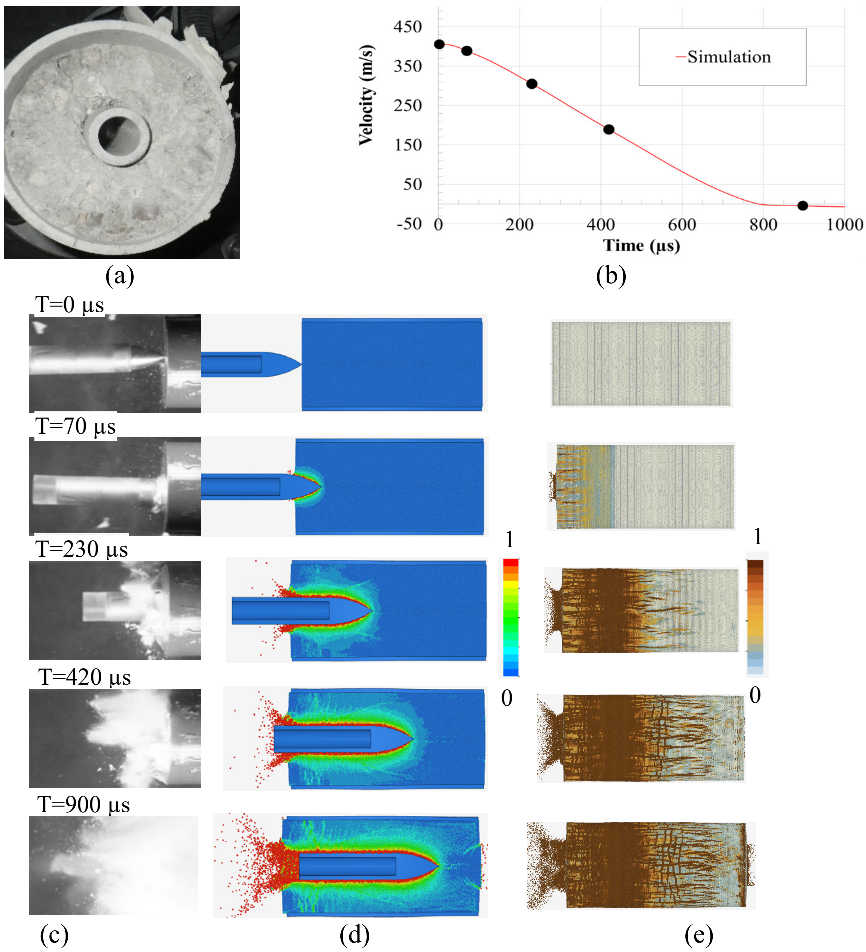

Figure 11: Comparison of test with simulation. (a) Photography of the impacted specimen; (b) Simulated velocity vs Time profile of the penetrator; (c) Images from high speed camera; (d) Simulated concrete internal strain; and (e) Simulated concrete external damage.

perforation with the points corresponding to the states of the images below. Large deformation is observed around the penetrator due to concrete compaction followed by some radial cracks near the front side of the specimen (Fig. 11(d)). The pressure level of concrete in front of the KEP ranges from 150 to 200 MPa during penetration. On the surface of the concrete specimen, the damage state is characterized by diffuse failure on the front side and fewer large cracks on the right side (Fig. 11(e)). Lack of confinement in the back side inside of the specimen induces shear crack propagation leading to the formation of a spall-like fragment. Some plastic deformation of the jacket is also observed leading to an increase of its diameter of 112.5 mm compared to 115 mm (experimental value).

Many other impact tests have been simulated to evaluate the ability of the model to predict the perforation of the specimen. Fig. 12 compares the measured residual velocity vs striking velocity with the model prediction. Tests have been conducted for striking velocity between 280 and 900 m/s. Experimental critical velocity is between 400 and 550 m/s and the model gives a critical velocity of 490 m/s. The model is also showing very good correlation at higher striking velocity. Another interesting case is the impact of the specimen with thinner jacket (2 mm) for which the simulated residual velocity is coherent with the test. All these highlight the quality of the model and the effectiveness of the approach. The major mechanical phenomena have been considered in the material law and the robustness of the discretization has helped in building such good quality model. As erosion is not needed, the contact between the KEP and the concrete and the concrete confinement are well reproduced all along the penetration process.

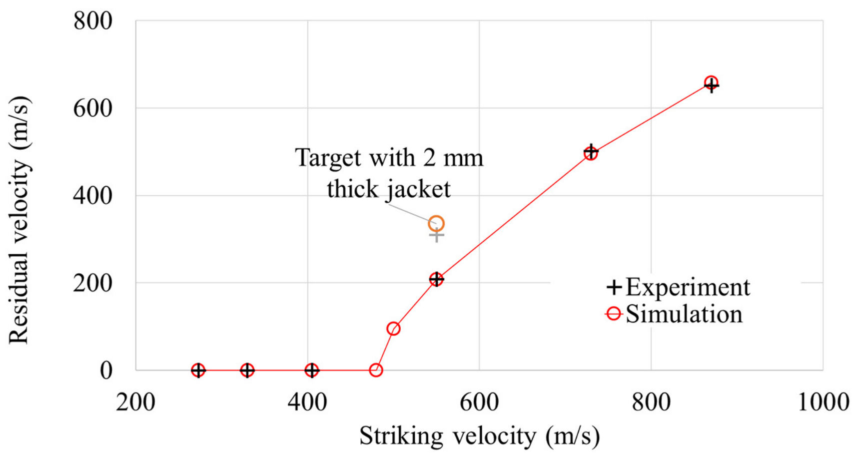

Figure 12: Comparison of experiment and model residual velocity vs striking velocity.

4 CONCLUSION

This paper has presented an approach for the characterization of concrete under impact for building a Holmquist–Johnson–Cook model. HJC is chosen for its relative simplicity and reduced number of parameters. The goal was to develop a relatively robust numerical tool that requires a limited number of tests for it to be applicable in an industrial context. The proposed calibration method uses data from quasi-static compression and oedometric tests to fit the parameters of the material model. Then, an impact configuration test at a reduced scale is proposed to verify and/or improve the response of the model. Furthermore, a robust meshless method (γ-SPH) is used to limits the influence of meshing choice and erosion. The use of such discretization is important because it improves the modelling of projectile/target contact interaction. The concrete confinement is also better reproduced since no element is deleted during the KEP penetration.

First simulations give very good results in terms of penetrator/concrete interaction. Projectile depth of penetration is reproduced by the model as well as the concrete damage. A good balance between model complexity and prediction capability has been reached.

Simulation of impact tests realized at a velocity ranging from 200 to 900 m/s give good correlation in terms of residual velocity. The prediction for a less confined configuration is also coherent with the test. Such model opens the door for simulations of more realistic configuration like concrete with reinforcement. The characterization approach could also be adapted to consider the specific tensile behavior of such concrete materials. The results of such simulation could then be used for improving the performance of KEP or the strength of a wall structure. Information regarding the level of deceleration can be of interest for the design of intelligent systems that include electronics and/or fuzes for KEP filled with explosive. For this particular purpose, it could be very interesting to acquire data from an embedded recording system inside the impactor to monitor its deceleration signature.

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