Numerical simulation of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) under high velocity impact of deformable projectile

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ABSTRACT

This paper presents the numerical simulation of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) under high velocity impact of deformable projectile. The 3D finite element models for the target and deformable projectile are built in LS-DYNA. The Johnson Holmquist Concrete model is utilized to simulate the reaction of UHPFRC plate under the impact. The projectile is a small-mass flat-nose projectile with a diameter of 15 mm and a length of 50 mm, which is meshed with 8-node hexahedron solid elements, with the mesh size of about 3 mm. The target is an UHPFRC plate with a dimension of 300 × 300 × 50 mm, and it is meshed with 8-node hexahedron solid elements. The impact speed of the projectile is 1000 m/s. During the impact process, the variation of the velocity, acceleration, energy of the projectile and the UHPFRC plate are evaluated. The simulation results show that, compared to the normal concrete, the UHPFRC can effective reduce the crater and scabbing dimensions on the concrete plate. However, to avoid the perforation of the high speed projectile, the thickness of the UHPFRC plate should be prudently considered.

Keywords: Numerical simulation, Ultra-High Performance Fibre Reinforced Concrete (UHPFRC), high velocity impact, deformable projectile, LS-DYNA

INTRODUCTION

Ultra-high performance fibre reinforced concrete (UHPFRC) is the outcome of a demand that began in the 1930s to find means of improving the mechanical strength of concrete. The so-called ultra-high performance concretes (UHPC) result in high compressive strength values of 150 N/mm^2 and more [1]. To overcome their brittle failure mechanism and to improve the post-critical behavior, fibres (especially steel fibres) are added to the concrete mix [2]. The application of steel fibres gives UHPFRC much greater ductility compare to reinforced normal strength or normal weight concretes (Figure 1), which means the UHPFRC can absorb more energy compared to the normal concrete [3]. Hence, it can be predicted that UHPFRC is one of the potential candidates for producing impact resistant concrete. However, in the testing of impact resistance capacity of concrete, all the methods and apparatus cost a lot of resources and labours, which cause that the modeling of concrete under impact loading becomes more and more popular[4-6].

As commonly known, concrete has very complicated nonlinear behavior, which is difficult to be fully described for general stress conditions by a simple constitutive model. When concrete is subjected to extreme loads such as high velocity impact of missiles and fragments, the modeling of concrete can be further complicated due to rate effects, overloading and large deformations [7]. With the advancement in the computing power, it is now possible to perform numerical simulation for the response of concrete structures subjected to severe shock and impact loads, including the modeling of the loading sources if necessary. A number of commercial hydrocodes such as ABAQUS [8], AUTODYN [9] and LS-DYNA [10] are available for the general simulation of structural nonlinear dynamic responses. Especially the LS-DYNA, which perform perfect in simulating the physical projectile impact with different loading rates, is utilized frequently in recent years. For instance, Agardh [11] presented the simulations using LS-DYNA for the projectile perforation of a 60 mm thick fibre-reinforced concrete slab with a velocity of 1500 m/s. The material model used was Type 78 “Soil/Concrete” with erosion. The results were in fairly good agreement with test results, but more studies are necessary to assess the sensitivity of certain material parameters. Teng [12] employed hydrodynamic finite element code LS-DYNA to study the dynamic response of steel fibre reinforced concrete (SFRC) subject to impact loading. The elastic-plastic hydrodynamic material model was employed to model the non-linear softening behavior of SFRC. The results show that the proposed methodology is useful and efficient can be further developed for designing the protection of military structures, nuclear power plants and other facilities against high-velocity projectiles. Beppu [13] described the evaluation of the local damage of concrete plates by the impact of high-velocity rigid projectiles. Impact tests for concrete plates have been conducted by using the system to examine failure modes of the local damage of concrete plates. The damage or failure behavior has been discussed on the basis of the failure process captured by a high speed video camera and the strain histories obtained by strain gauges on the concrete plate. Numerical simulations have been also carried out in order to explain the mechanism of the local damage observed in the experiment. Li [14] investigated several widely used material models for plain concrete under dynamic loading, especially the Concrete Damage model and the Elastic-Plastic Hydrodynamic model to determine an appropriate material model for engineered cementitious composite (ECC) materials under dynamic loading. A material model which is appropriate to simulate the dynamic behavior of ECC materials is established based on the Concrete Damage model. The proposed material model is validated via numerical simulation of the impact process of a hybrid-fibre ECC slab struck by a high-velocity projectile. Nevertheless, it can be noticed that the numerical simulation of UHPFRC under high velocity impact of deformable projectile can seldom be found. This should be attributed to that the UHPFRC is still a type of advanced concrete, and most investigations on its characteristics are focus on the quasi-static testing.

Hence, the objective of this study is to simulate the process of UHPFRC under high velocity impact of deformable projectile. The variation of velocity, acceleration and energy of the concrete plate and the projectile are also analysed.

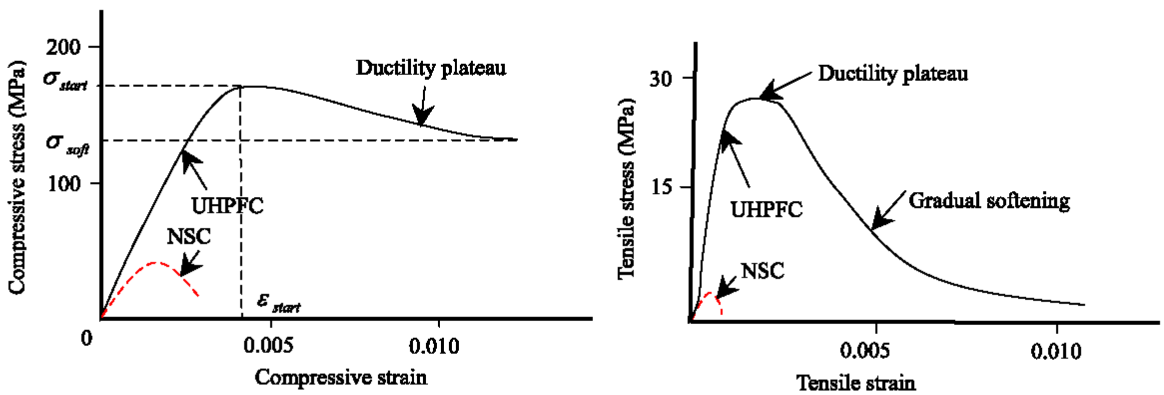


Figure 1. Mechanical properties of conventional concrete and UHPFC under compressive load (left) and tensile load (right) [3]

METHODOLOGY

Johnson-Holmsquist Concrete model

To fully describe the concrete's dynamic effect within the impact procedure, several concrete models have been implemented in LS-DYNA [10]. In this paper, the Johnson-Holmsquist Concrete model is chosen to describe the reaction of UHPFRC plate under the high velocity impact. The equivalent strength of material is expressed as a function of the pressure, strain rate and damage:

$$\sigma^* = \left[A(1-D) + BP^{*N}\right] \cdot \left[1 + C \ln \dot{\varepsilon}^*\right]$$

where P* denotes the normalized pressure, shown as $P^* = P / f_c^{'}$; P denotes presure; $f_c^{'}$ denotes the quasi-static uniaxial compressive strength; $\dot{\varepsilon}^*$ denotes the dimensionless strain rate, given by $\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0$; $\dot{\varepsilon}$

represents the actual strain rate; $\dot{\varepsilon}_0$ represents the reference strain rate; D ($0 \le D \le 1$) denotes the damage parameter. Additionally A, B, N, and C denote the material parameters.

The model accumulates damage both from equivalent plastic strain and plastic volumetric strain, and is expressed as:

$$D = \sum \frac{\Delta\varepsilon_p + \Delta\mu_p}{\varepsilon_p^f + \mu_p^f}$$

Here, $\Delta\varepsilon_p$ and $\Delta\mu_p$ represent the equivalent plastic strain increment and plastic volumetric strain increment, respectively, during one cycle integral computation. $(\varepsilon_p^f + \mu_p^f)$ represents the plastic strain to fracture under a constant pressure, which can be expressed as follows:

$$\varepsilon_p^f + \mu_p^f = D_1\left(P^* + T^*\right)^{D_2}$$

where D_1 and D_2 represent damage constants, and $T^* = T / f_c^{'}$ is the normalized largest tensile strength (T represents the maximum tensile stress).

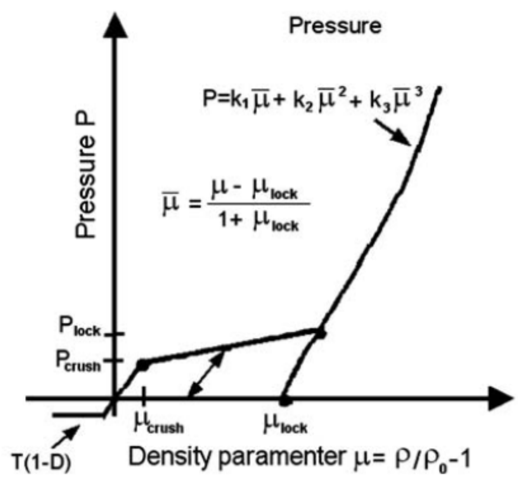


Figure 2. The relationship between hydrostatic pressure and material volumetric strain [15]

The equation of state (EOS) of this model describes the relationship between hydrostatic pressure and volume. The loading and unloading process of concrete can be divided into three response regions (Figure 2). The first zone is the linear elastic zone, where the material is elastic state. The elastic bulk modulus is given by $k = P_{crush} / \mu_{crush}$, where P_{crush} and μ_{crush} represent the pressure and volumetric strain arising in a uniaxial compression test. Within the elastic zone, the loading and unloading equation of state is given by:

$$P = K\mu$$

where $\mu = \rho / \rho_0 - 1$, ρ denotes the current density, and ρ_0 denotes the reference density.

The second zone arises at $P_{crush} < P < P_{lock}$, where the material is in the plastic transition state. In this area, the concrete interior voids gradually reduce in size as the pressure and plastic volumetric strain increase. The unloading curve is solved by the difference from the adjacent regions.

The third area defines the relationship for fully dense material. The concrete has no air voids. The relationship between pressure and the volumetric strain is given by:

$$P = K_1 \bar{\mu} + K_2 \bar{\mu}^2 + K_3 \bar{\mu}^3$$

where K_1, K_2, K_3 are constants and $\bar{\mu} = \dfrac{\mu - \mu_{lock}}{1 + \mu_{lock}}$ (μ_{lock} is the locking volumetric strain).

Numerical simulation of perforation of concrete slabs

In this study, the perforation of concrete plate under deformable projectile impact is analysed. The 3D finite element models for the target and deformable projectile are built in LS-DYNA (as shown in Figure 3). The projectile is a small-mass flat-nose projectile with a diameter of 15 mm and a length of 50 mm, which is meshed with 8-node hexahedron solid elements, with the mesh size of about 3 mm. The target is a square concrete plate with a dimension of 300 × 300 × 50 mm, and it is meshed with 8-node hexahedron solid elements. The angle between the projectile impact direction and the normal direction of the plate is 10°. The velocity of the deformable projectile is 1000 m/s. The material model for UHPFRC plate and projectile are Johnson-Holmsquist Concrete model and Johnson-Cook model, respectively. The material parameters for the UHPFRC are shown in Table 1.

Table 1. Material parameters of UHPFRC

Density (kg/m^3)	Shear modulus (MPa)	Strength constants							
		A	B	N	C	f_c' (MPa)	f_t (MPa)	S_{max}	$\overset{*}{\varepsilon}$ (s^{-1})
2550	33200	0.79	1.60	0.61	0.007	156	8.4	12.5	1.0

Damage constants

D1	D2	$(\varepsilon_p^f + \mu_p^f)$
0.05	1.0	0.01

EOS constant

P_{crush} (MPa)	μ_{crush}	K_1 (GPa)	K_2 (GPa)	K_3 (GPa)	P_{lock} (MPa)	μ_{lock}
19	0.0001	8.5	17.1	20.8	850	0.1

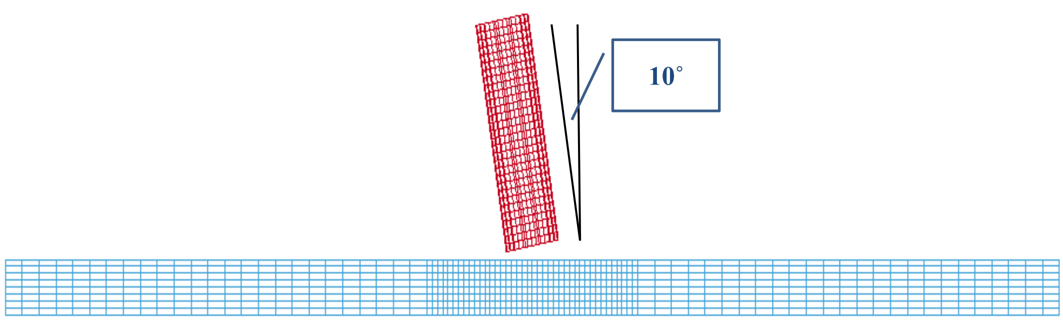


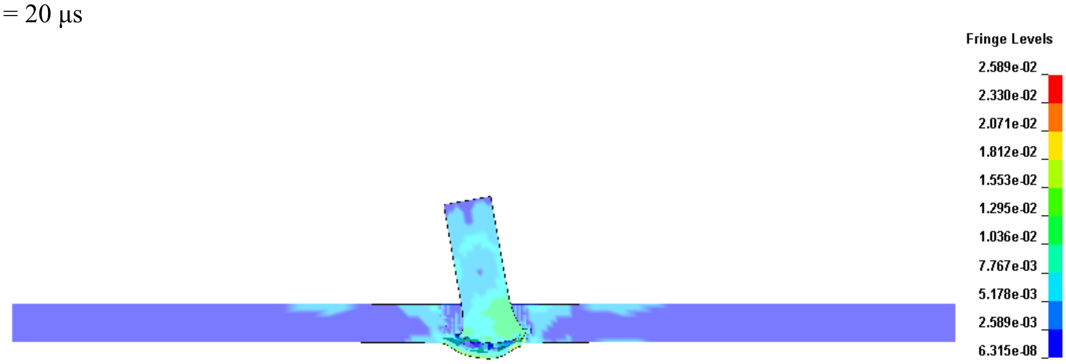
Figure 3. 3D finite element models for the target and deformable projectile (after meshing)

EXPERIMENTAL RESULTS AND DISCUSSION

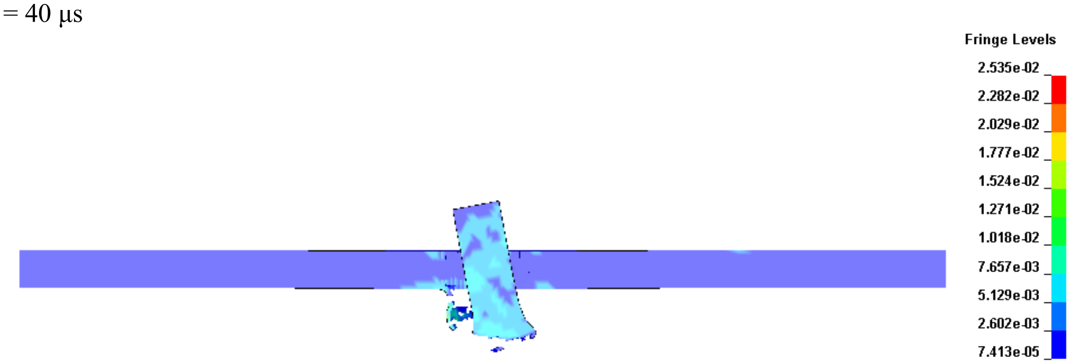
Impact process simulation

The stress distribution of the UHPFRC plate and the deformable projectile during the impact process are shown in Figure 4 and 5. It can be seen that the deformable projectile is still embedded in the UHPFRC plate at 20 μs, and the stress around the projectile head and the crater are larger than the other place. Moreover, due to the influence of steel fibre and the good combination between fibres and concrete matrix, the rear face of the UHPFRC plate obviously deform during the impact process (Figure 4a), which can effectively absorb the impact energy and reduce the velocity of the projectile. However, due to the relatively small thickness (30 mm) of the concrete plate and the high velocity (1000 m/s) of the projectile, the UHPFRC is perforated by the deformable projectile. During the perforation process, the deformation of the projectile head can also be noticed. This simulation results are similar as that illustrated in [12], in which the elastic-plastic hydrodynamic material model is employed to model the non-linear softening behavior of steel fibre reinforced concrete (SFRC). Nevertheless, it can be found that the crater and scabbing dimensions of the UHPFRC plate are smaller than that of SFRC. This should be attributed to the large steel fibre amount and the perfect combination between fibres and concrete matrix of UHPFRC.

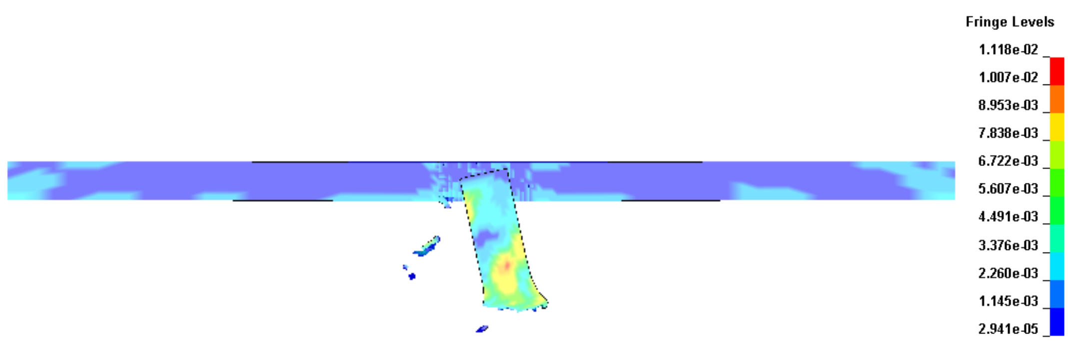
a) t = 20 μs



b) t = 40 μs



c) t = 60 μs



d) t = 80 μs

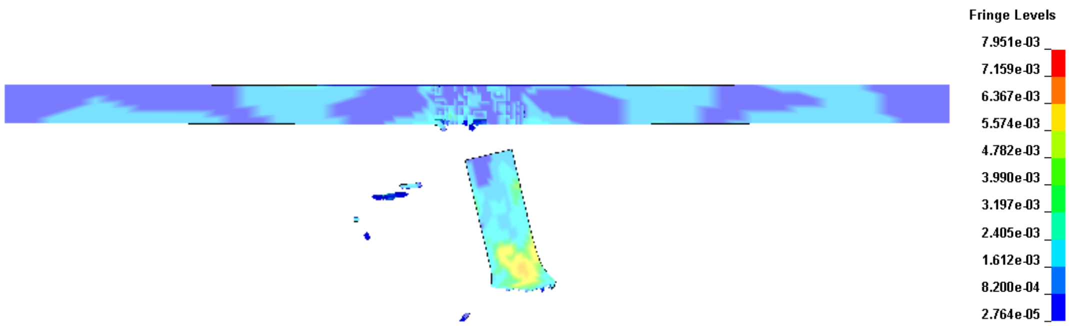
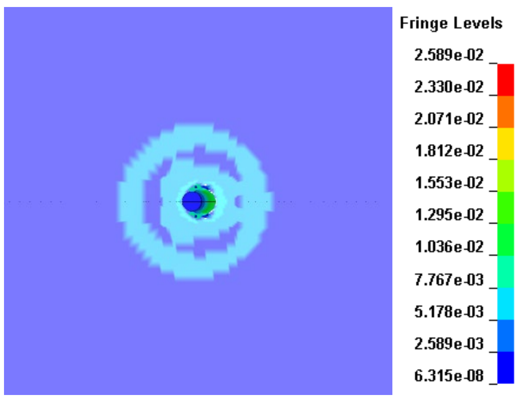
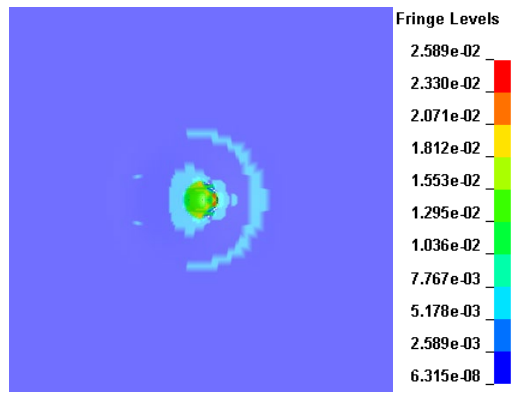


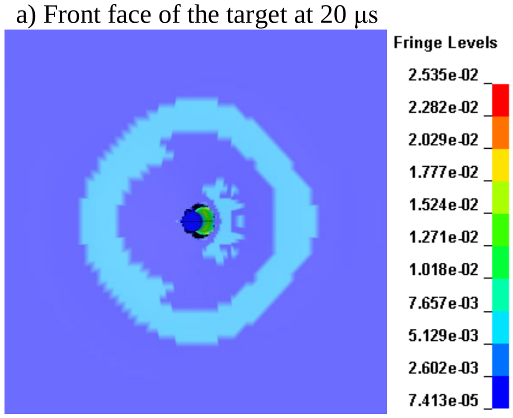
Figure 4. Stress distribution of the UHPFRC plate and projectile during the impact process



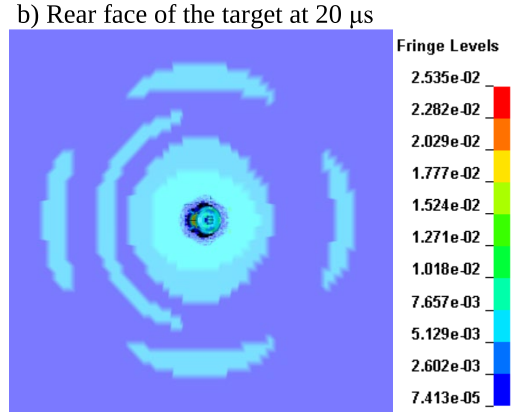
a) Front face of the target at 20 μs



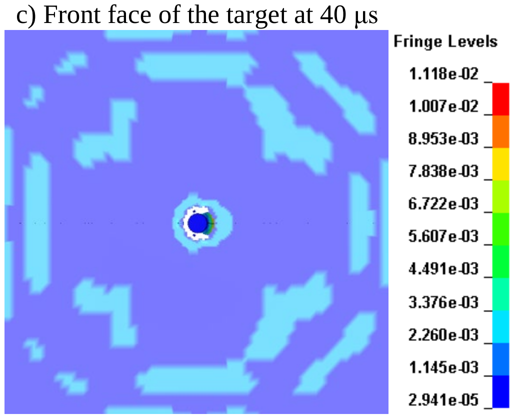
b) Rear face of the target at 20 μs



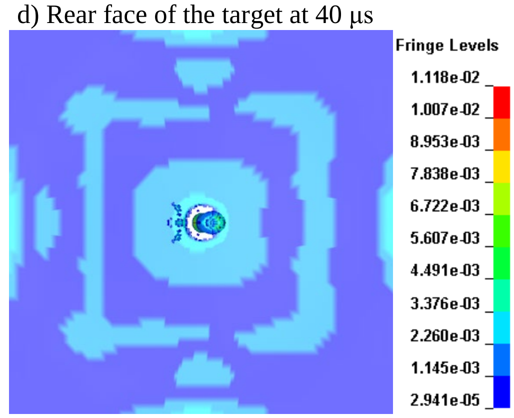
c) Front face of the target at 40 μs



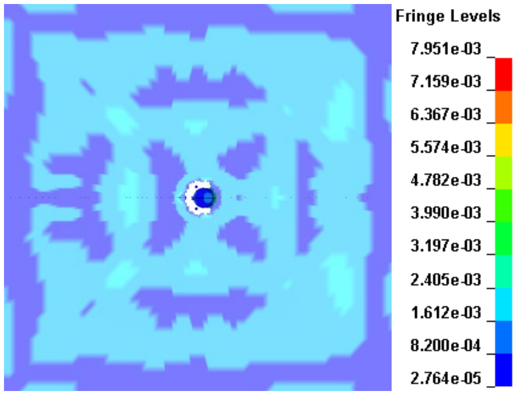
d) Rear face of the target at 40 μs



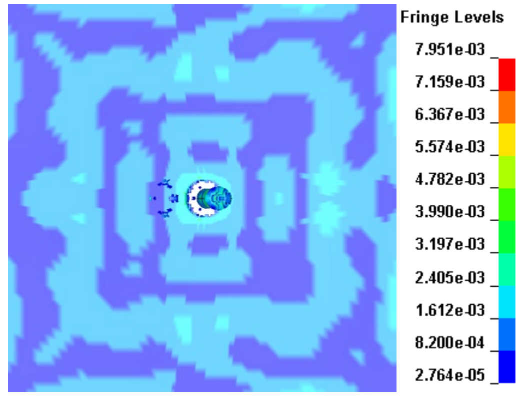
e) Front face of the target at 60 μs



f) Rear face of the target at 60 μs



g) Front face of the target at 80 μs



h) Rear face of the target at 80 μs

Figure 5. Stress distribution on the front and rear face of the target at different time

Velocity and acceleration analysis

To evaluate the velocity and acceleration of the projectile and concrete plate during the impact process, some points on the models are chosen ramdomly, as shown in Figure 6. The variation of resultant velocity and acceleration of these points with time are illustrated in Figure 7 to 10. As can be seen that the original velocity of the projectile is 1000m/s, which reduce to around 930 m/s after the perforation (Figure 7). From Figure 8, it can be noticed that the acceleration of the projectile obviously flucturate at the beginning of the impact (before 20 μs). Then, after the UHPFRC is perfoated, the acceleration of the projectile is close to zero. Moreover, Figure 9 show the resultant velocity of the chosen points on the concrete target during the impact. It is obvious that the residule velocity of the point (31167) is much higher than the other two points, which means this concrete part (represented by the point 31167) is seperated with the concrete matrix by the external impact, and the final velocity of the seperated concrete part is around 440 m/s. Additionally, the effect of the impact on the points (31062 and 31258) is not significant, which can be found in Figure 9 and 10. Hence, this further demostrate that the UHPFRC can significantly reduce the crater and scabbing dimension on the concrete plate. However, to definitely avoid the perforation of the high speed projectile, the thickness of the UHPFRC plate should be prudently considered.

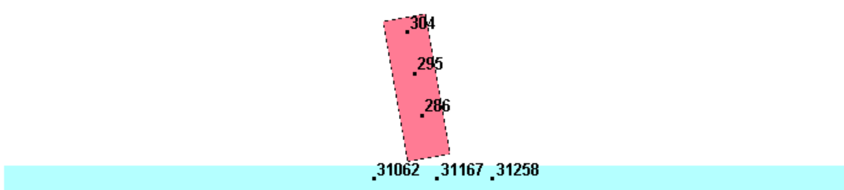


Figure 6. Chosen points of the concrete target and projectile

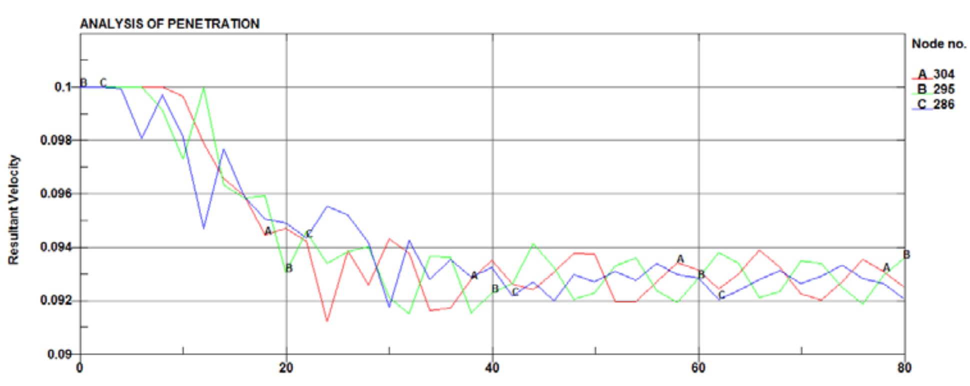


Figure 7. Resultant velocity of the chosen points on the projectile (velocity unit: 10 km/s)

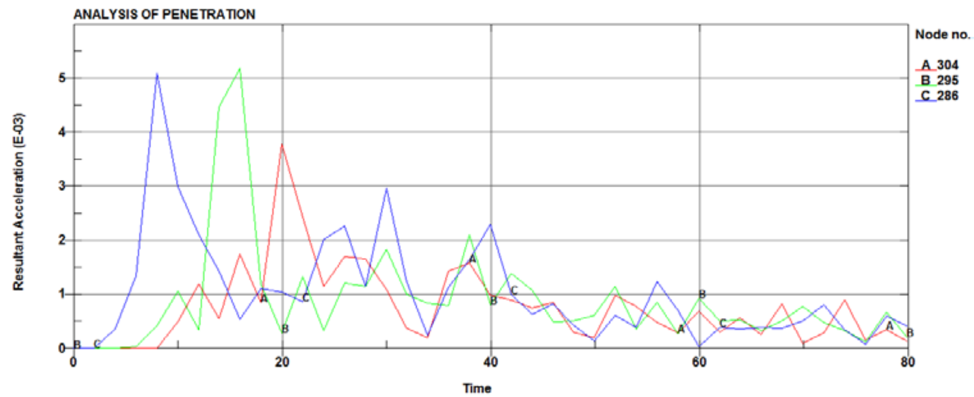


Figure 8. Resultant acceleration of the chosen points on the projectile (acceleration unit: cm/μs^2)

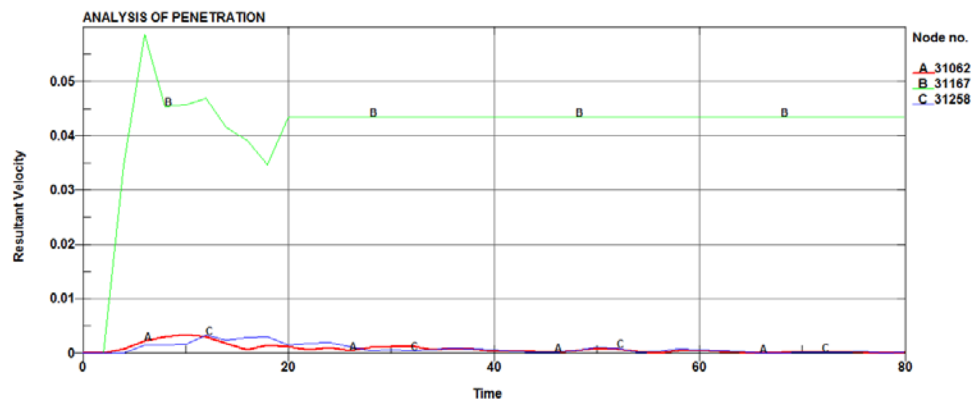


Figure 9. Resultant velocity of the chosen points on the concrete target (velocity unit: 10 km/s)

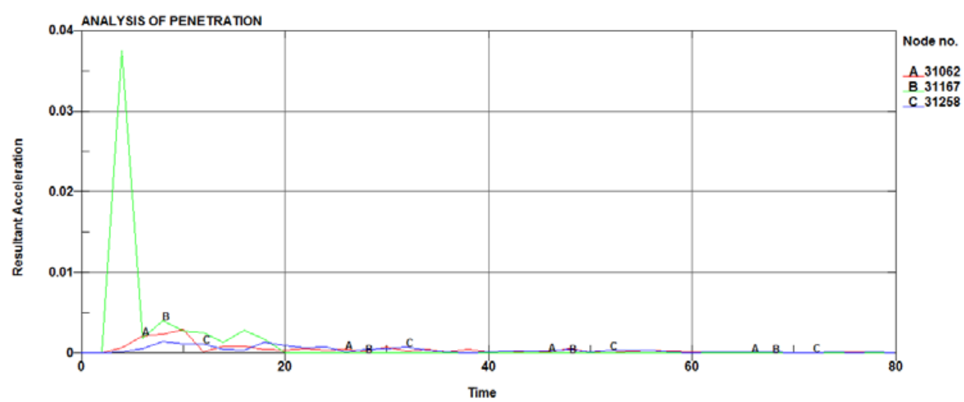


Figure 10. Resultant acceleration of the chosen points on the concrete target (acceleration unit: cm/μs^2)

Energy analysis

The variation of the kinetic energy of the projectile and the total energy with time are shown in Figure 11 and 12. Note that the kinetic energy of the projectile clearly decrease when the impat happens. This should be attributed to the energy absorbtion capacity of the UHPFRC plate. After 40 μs, the kinetic energy of the projectile is almost constant, which imply that the projectile has already passed through the UHPFRC plate after 40 μs. Furthermore, from the results of the total energy, it can be found that the final total energy is a little bit larger than that of kinetic energy of the projectile. This should be owned to the kinetic energy of the spalling concrete part (as shown in Fig 4 and 9).

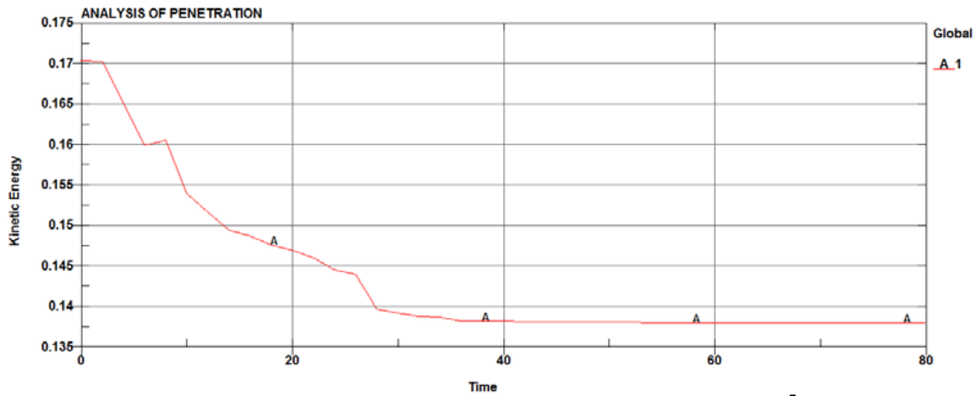


Figure 11. Kinetic energy of the projectile (energy unit: 10^5 J)

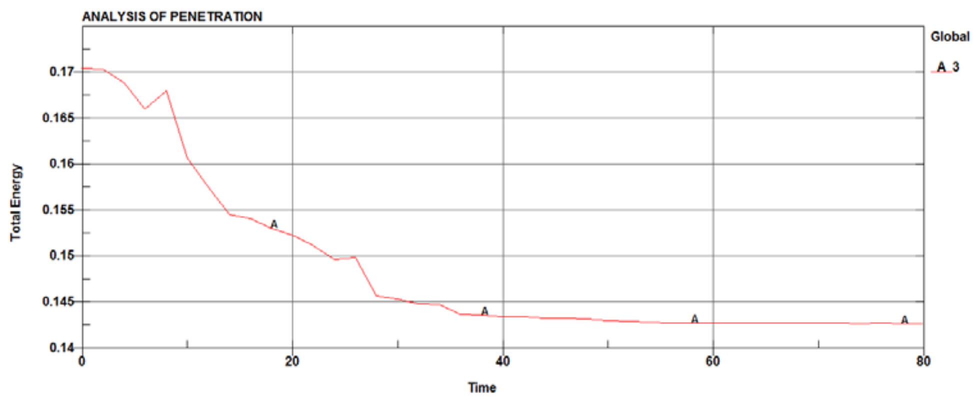


Figure 12. Total energy of the concrete plate and the projectile (energy unit: 10^5 J)

CONCLUSIONS

This paper presents the numerical simulation of the Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) under high velocity impact of deformable projectile. The Johnson Holmquist Concrete model (implemented in LS-DYNA) is utilized to simulate the reaction of UHPFRC plate. The 3D finite element models for the target and deformable projectile are built in LS-DYNA. From the results addressed in this paper the following conclusions are drawn:

- Johnson Holmquist Concrete model can be successfully utilized to simulate the process of UHPFRC under high velocity impact of deformable projectile.

- Compared to the normal concrete or normal steel fibre reinforced concrete, UHPFRC can effectively reduce the crater and scabbing dimensions on the concrete plate.

- To definitely avoid the perforation of the high speed projectile, the thickness of the UHPFRC is quite important and should be prudently considered.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the following sponsors of the Building Materials research group at TU Eindhoven: Rijkswaterstaat Centre for Infrastructure, Graniet-Import Benelux, Kijlstra Betonmortel, Struyk Verwo, Attero, Enci, Provincie Overijssel, Rijkswaterstaat Directie Zeeland, A&G Maasvlakte, BTE, Alvon Bouwsystemen, V.d. Bosch Beton, Selor, Twee "R" Recycling, GMB, Schenk

Concrete Consultancy, Geochem Research, Icopal, BN International, APP All Remove, Consensor, Eltomation, Knauf Gips, Hess ACC Systems, Kronos and Joma (in chronological order of joining).

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