DEVELOPMENT OF IMPACT RESISTANT UHPFRC

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Abstract

The development of ultra-high performance fibre reinforced concrete (UHPFRC) has recently received extensive attention from researchers. Various applications of UHPFRC have also been explored. This research is concerned with the resistance of UHPFRC under impact and rocket propelled grenade attacks. One interesting problem for UHPFRC is that its values of flexural tensile strength in the literature can be up to 35 MPa, obtained with the use of σ=My/I which assumes a linearly varying stress through the depth of the section. This equation is not applicable for UHPFRC which has a pseudo-hardening region after cracking. Therefore, the tensile stress-strain behaviour must be obtained from axial tensile tests and not flexural tests. A drop hammer test rig has been designed and fabricated to investigate the impact resistance of UHPFRC beams. The aim of the project was to quantify the improved resistance of UHPFRC under impact when compared to ordinary concrete and to investigate the possibility of accurately modelling its behaviour under both static and impact/dynamic loadings in the first instance and ultimately modelling the damage from rocket propelled grenades.

Résumé

Le développement du béton fibré à ultra-hautes performances (BFUP) a récemment suscité un grand intérêt chez les chercheurs. Différentes applications ont également été explorées. Cette recherche porte sur la résistance du BFUP à l'impact et aux attaques de grenades propulsées par fusées. Un problème intéressant pour le BFUP est que ses valeurs de résistance à la flexion et à la traction dans la littérature peuvent atteindre jusqu'à 35 MPa, au sens de la contrainte équivalente σ = My/l, ce qui suppose une contrainte qui varie linéairement sur la hauteur de la section. Cette équation n'est pas applicable pour le BFUP qui présente un régime pseudo-écrouissant après fissuration. Par conséquent, le comportement contrainte – déformation en traction doit être obtenu à partir d'essais de traction axiale et non pas d'essais de flexion. Une machine d'essai d'impact par masse tombante a été conçue et fabriquée pour étudier la résistance à l'impact des poutres en BFUP. Le but du projet était de quantifier la résistance améliorée du BFUP sous impact par rapport au béton ordinaire et d'étudier la possibilité de modéliser avec précision son comportement à la fois sous charges statiques et charges d'impact/dynamiques, puis de modéliser au final les dégâts causés par les grenades propulsées par fusées.

1. INTRODUCTION

Concretes with compressive strengths of 100 to 120MPa have been developed and are being used for the construction of structural elements [1, 2]. Concrete with compressive strength of 250-300 MPa can also be produced using different techniques such as:

• Compact granular matrix concretes (DSP) with high superplasticizer and silica fume content, also incorporating ultra-hard aggregate [3].

• Macro Defect Free (MDF) polymer pastes [4] which have very high strength (150MPa or more), in particular when mixed with aluminous cements [5].

A major problem of the cementitious matrices obtained with these various techniques is their low ductility. An answer to this was found with the incorporation of steel fibres. The Slurry Infiltrated Fibre Concrete (SIFCON) technique [6] involves filling the formwork with bulk fibres, and injecting a fluid mortar slurry. However, SIFCON has had only limited industrial applications because of the difficulties in placing it. Nonetheless, the above techniques have provided a basis for the development of a number of similar or derivative materials. One such group of materials is the ultra-high performance fibre reinforced concretes (UHPFRCs) which have been developed to improve the mechanical performance of cementitious materials, especially strength and ductility under tension [7]. Examples of commercial UHPFRCs are (a) Compact Reinforced Composites (CRC) developed by Aalborg Portland in Denmark, (b) BSI developed by Eiffage group in France, (c) Reactive Powder Concrete (RPC) developed by Bouygues in France, (d) Multi-Scale Fibre-Reinforced Concrete (MSFRC) developed by Laboratoire Central des Ponts et Chaussees in France, and (e) Ductal developed by Lafarge, Bouyges and Rhodia in France.

RPC appears to be a promising Material not only because of its enhanced ductility but also because the mixing and casting procedures are no different to existing procedures for normal and high strength concretes. RPC has, however, a substantial increase in cost over and above that of conventional and even high performance concrete and it is therefore appropriate to identify applications which fully utilize RPC's mechanical properties and performance characteristics. Research therefore needs to be conducted to develop, and facilitate commercialisation of, precast products which utilize many of the enhanced properties of RPC.

The main applications of RPC have been a) Construction of prestressed structures without any steel reinforcement (e.g. the Sherbrooke Footbridge in Canada [8] and the construction of two raised sections of motorway close to the city of Valence in the Drome Region by the French Ministry of Transport and its Roads Department using BSI (another type of UHPFRC) [9]; and b) pipe products for the conveyance of water, sewage and other liquids under pressure or gravity flow provide an opportunity to utilize many of the enhanced properties of RPC [10].

Based on the mechanical properties of RPC it would also appear to be attractive for construction of security enclosures, such as safes, computer centres, nuclear waste containment vessels, and defence structures; applications that require high impact resistance. We were approached by Hamber Safes Ltd. (UK) to assist with: (a) determining guidelines for the production (selection of materials and mix proportions, and curing regimes) of RPCs and (b) investigating the impact load resistance of RPC in order to determine its suitability for use in the construction of security enclosures and more specifically safes. This paper presents some preliminary results of this research.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

Initial work aimed at developing a workable concrete mixture with compressive strengths of around 200MPa. Once this was achieved, sixteen variations of this mixture were cast to optimise/improve its mix proportions and mechanical properties.

2.1 Materials

Single batches of Portland cement and ground granulated blast furnace slag (GGBS) were used throughout. Silica fume in the un-densified form was initially used but for health and safety reasons this had to be changed to the slurry form for later test. The aggregate used was a silica sand with particle sizes less than 400μm (79% passing the 300μm sieve). The superplasticizer used was a polycarboxylate polymer based one. The fibres were 12mm in length and 0.16mm in diameter.

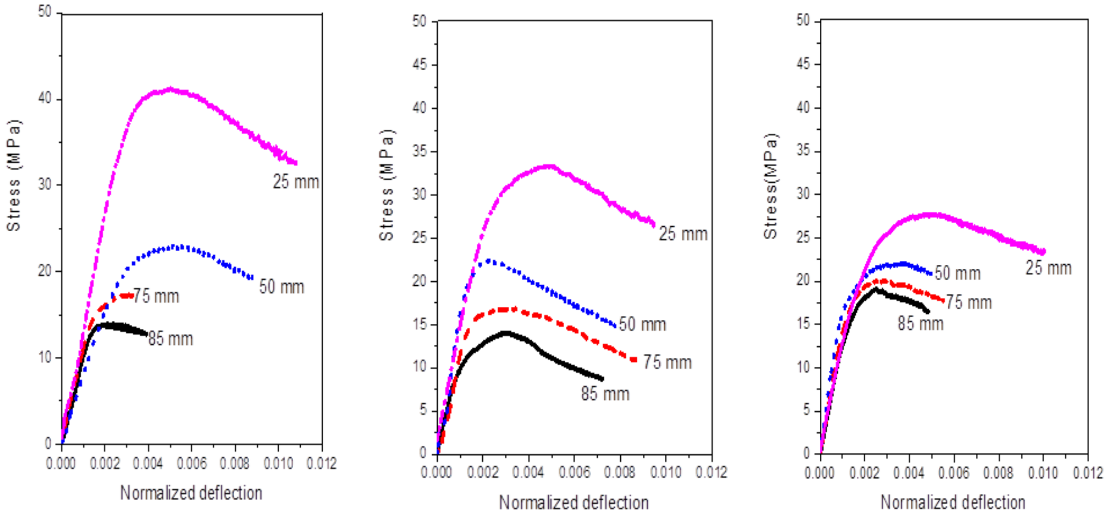
2.2 Mixing, Casting, Curing and Testing of Concrete Specimens

The materials were weighed and placed in a 0.01 m^3 or 0.02 m^3 capacity horizontal pan mixer in the order of: silica sand, cement and GGBS. The materials were first dry mixed and then the silica fume in slurry form and the water and superplasticizer, previously mixed together, were added to the rotating drum. When fibres were used, they were added slowly to the rotating drum after the rest of the materials had been properly mixed and the concrete had a "wet" appearance. The concrete was mixed for 5 minutes and then cast into (a) 100 mm steel cube moulds for compression tests, and (b) either 25, 50 75 and 100 x 100 x 500 mm steel prism moulds for flexural strength. All the specimens were then compacted on a vibrating table and subsequently covered with a damp hessian and a polythene sheet. They were demoulded at 1-day, or as soon as the concrete had set, and placed either in a curing tank whose temperature was set at 90 °C or wrapped in wet hessian and polythene sheet and placed in an oven at 90 °C. The majority of these were subsequently tested for compressive strength at 7, 14 and 28-days.

3. MATERIAL TEST RESULTS AND DISCUSSION

Figure 1 shows the flexural stress derived from $\sigma = My/I$ in three point bending test of prisms. The method assumes that the stress distribution is linearly distributed through the thickness of the section up to failure, meaning that the material is linear elastic brittle. Figure 1 shows a clear 'size effect' in terms of both the span and the thickness. The calculated flexural stress is much higher for a thinner specimen with smaller span compared with a thicker specimen with a larger span. However, this is not the true material property because the material is nonlinear in tension.

Assuming a tri-linear stress-crack width behaviour for UHPFRC, the load-displacement curve as well as the stress distribution at the mid span of a notched three point bending prism specimen can be obtained as in Figure 2 following Olesen's fictitious crack model analysis (10). It clearly shows that the stress distribution on the section is nonlinear after the peak load is reached, and the position of the neutral axis moves upwards as the deformation increases. It is therefore important that direct axial tensile tests are conducted to determine the true tensile constitutive relationship for UHPFRC that can be used in finite element analysis software.



a) Span = 250 mm b) Span = 350 mm Span = 450 mm

Figure 1: Flexural stress vs normalised mid-span displacement curves

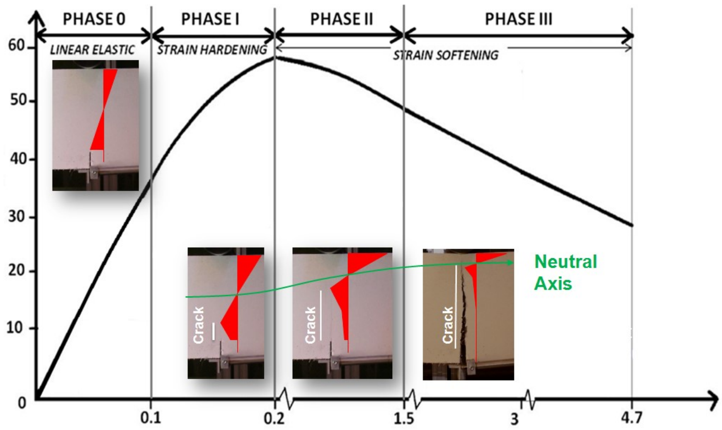


Figure 2: Typical load displacement curve obtained from fictitious crack model fracture analysis

A range of different test set-ups have been explored at Queen's University Belfast, attempting to optimise the direct axial tensile test of UHPFRC specimens. The tensile stress obtained from these tests varied from 8 to 13 MPa, depending on the magnitude of eccentricities experienced in the test. Figure 3 shows one such test where significant eccentricities were experienced. Further research is required to optimise the direct tensile test so the eccentricities are minimised and the true tensile constitutive parameters are determined with high accuracy.

4. FINITE ELEMENT MODELLING OF UHPFRC BEAMS UNDER IMPACT

4.1 Simulation using ABAQUS

The finite element analysis package Abaqus has been developing a four stage approach for the modelling of extreme failure modes. The first two stages are the same as traditional nonlinear material analysis, namely elastic behaviour followed by a plastic analysis. This is then followed by a progressive damage stage and finally there is option for material removal. The progressive damage model is distinctly different from the concrete damage model in Abaqus and is much better suited for extreme impacts.

Figure 3: Direct tensile test

However, the option of including the damage with element removal is only offered with only selected plasticity models. The approach was developed with ductile metals and carbon fibre composite materials in mind. Nevertheless, it has been demonstrated to be valuable for modelling the high speed impact of ceramic based materials. This has been achieved through the combination of the Drucker-Prager plastic model and a progressive damage failure model for ductile metals.

4.2 The Drucker-Prager plastic model

The Drucker-Prager model is chosen for modelling the behaviour of UHPFRC. There is a simple relationship between the compressive and tensile strengths of the concrete and the friction angle φ and the cohesion c of the Mohr Coulomb plasticity model:

$$\sin\phi = \frac{f_c - f_t}{f_c + f_t} \quad \text{and} \quad c = \frac{f_c\left(1-\sin\phi\right)}{2\cos\phi} = \frac{1}{2}\sqrt{f_c f_t} \tag{1}$$

Further to this Abaqus suggests a relation between the Mohr Coulomb parameters φ and c and the Drucker-Prager parameters of friction angle of β and cohesion d for associated flow as:

$$\tan\beta = \frac{\sqrt{3}\sin\phi}{\sqrt{1+\frac{1}{3}\sin^2\phi}} \quad \text{and} \quad \frac{d}{c} = \frac{\sqrt{3}\cos\phi}{\sqrt{1+\frac{1}{3}\sin^2\phi}} \tag{2}$$

In this study the UHPRFC is assumed to have a compressive strength f_c = 150 MPa and a tensile strength f_t = 10 MPa. Using Equation (1) above, the equivalent Mohr Coulomb parameter are derived as $\varphi = 61°$ and c=19.3 MPa. Substituting these into Equation (2) gives the equivalent Drucker-Prager parameters $\beta = 53.5°$ and d=14.5 MPa.

4.3 The progressive damage model

The progressive damage model defines the damage initiation criteria. Two causes leading to fracture in ductile materials have been identified as ductile fracture due to nucleation, growth and coalescence of voids, and shear fracture due to shear band localization. The ductility criterion is defined as a function of the stress triaxiality and plastic strain rate, while the shear criterion is defined as a function of shear stress ratio and plastic strain rate. Both criteria are satisfied when the equivalent plastic strain exceeds the criteria.

The damage evolution starts once an initiation criterion is satisfied. The damage takes the form of softening of the yield stress and the degradation of the elasticity. The degree of damage is represented by a damage parameter D ranging from 0 for no damage to 1 for full damage. A damage evolution law defines a relationship between D and the equivalent plastic displacement or the fracture energy G_f. The equivalent plastic strain is not used here as it tends to be mesh dependent. The equivalent plastic displacement is related to the equivalent plastic strain through the effective length for the element.

Finally, element removal occurs at a specified degree of damage. If 90% damage is specified, then the element is removed when D reaches 0.9. This value was adopted here.

In this study, the ductility criterion without any dependence on the triaxiality or strain rate was adopted for the damage initiation criterion, i.e. damage initiating occurs when the equivalent plastic strain reaches the specified strain. This is the same as adopting the strain criterion when there is no dependence on the shear stress ratio or strain rate. It has been found that adopting strain values in the range of 0.01 to 0.0001 does not influence the results much and a value of 0.001 was adopted here. For the progressive damage an exponential softening with an energy fracture value of 15 N/mm was used.

4.4 Explicit dynamic analysis

The explicit dynamic analysis was adopted to simulate the high speed transient dynamic impact. Care must be taken when choosing some characteristic values of the explicit method. The method is conditionally stable and the time step must be below a specified value which is a function of the wave speed in the material and smallest element size in the model. The time step could be easily of the order of one millionth of a second which translates into a very large number of increments in an analysis. The explicit method does not require to solve the systems of stiffness equations at every increment, a simple update is all that is required. This makes the explicit method a viable alternative to the implicit method as the reduced computation per increment counteracts the much larger number of increments needed. Nevertheless, in most cases the explicit method does take significantly longer than the implicit method. The big advantage of the explicit method is that it does not suffer from convergence problems as it does not need to solve equations.

4.5 Contact analysis

UHPRFC specimens are to be tested using a drop hammer test, which involves the contact between the steel projectile and the UHPFRC specimen. As in some tests the impact will be severe enough for the specimen to incur significant damage or breakup, the progressive damage material model with element removal is needed to simulate this. The contact is usually defined to occur between two surfaces, but in this study one of the surfaces will no longer exist as the material breaks up. The answer to this is to define the contact surface of the specimen to consist of not only the external surface but also the internal surfaces between the elements making up the mesh. As element are removed and a surface disappears, new surfaces are exposed to act as the contact surfaces.

4.6 The drop hammer test model

A drop hammer apparatus has been developed to test impact resistance of UHPRFC and an Abaqus finite element model of the apparatus has been built as shown in Figure 4. The test set has been designed to resist vertical movement at the supports by allowing rotation of the specimen. A summary of the parameters used in the model are given in Table 1.

Table 1: UHPFRC material properties

Material Property	**Value**
E Young's Modules	40 GPa
ν Poisson's ratio	0.2
ρ Density	2.4×10^{-9} Tonnes/mm^3
β Friction angle	53.5
d Cohesion	14.5 MPa
ε_D Damage initiation plastic strain	0.001
G_f Fracture energy	15 N/mm

The impact was modelled by applying an initial velocity to the bullet. The results of three impacts with increasing velocity are given in Figures 5 to 7. The velocities of the three models were 5 m/s, 10 m/s and 25 m/s. They have been selected to represent increasing levels of damage occurring to the specimen. The bullet has been removed from the figures to allow the damage to be more easily seen. The contour plots given in Figures 5-7 show the value of the damage parameter D.

The parameters used in the reported analysis have been based on representative values for the material obtained from expermental tests undertaken on the material. However they are only meant as prelimary estimates. An extensive experimental test programme is currently underway. The programme consists of beam specimens containing various percentages of steel fibre reinforcement which are being tested using the drop hammer at increasing heights until failure (Table 2). The results from the drop hammer tests and the material properties determined from static tests will be used to undertake the calibration and validation of the finite element model.

Table 2: Experimental test programme

Concrete Type	**Impact Height (m)**	**Impact Weight (kg)**
Normal Strength Concrete	0.2, 0.4, 0.6, 0.8, 1.0	10, 40
UHPC	0.2, 0.4, 0.6, 0.8, 1.0	10, 40
UHPFRC (0.5%, 1.5%, 2.5%)	0.2, 0.4, 0.6, 0.8, 1.0	10, 40

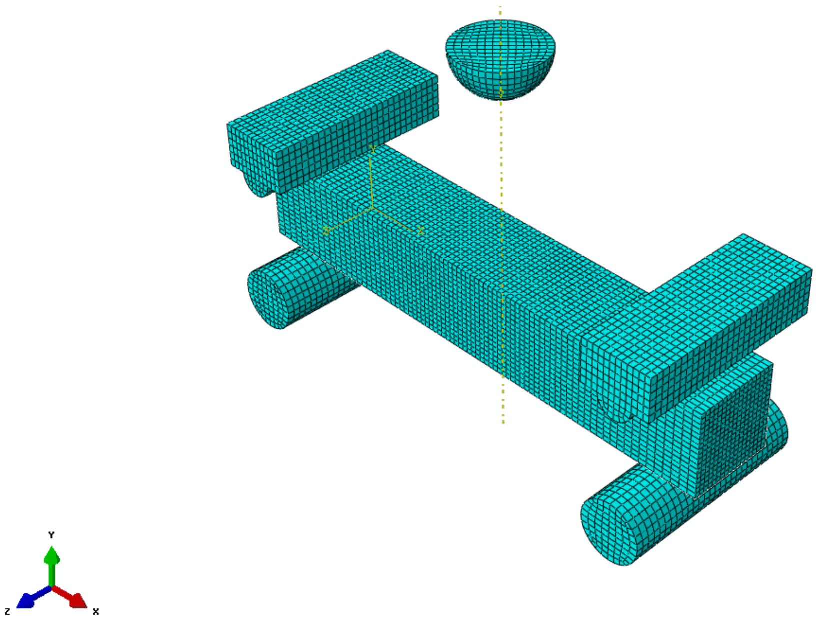


Figure 4: FE mesh of a drop hammer tester

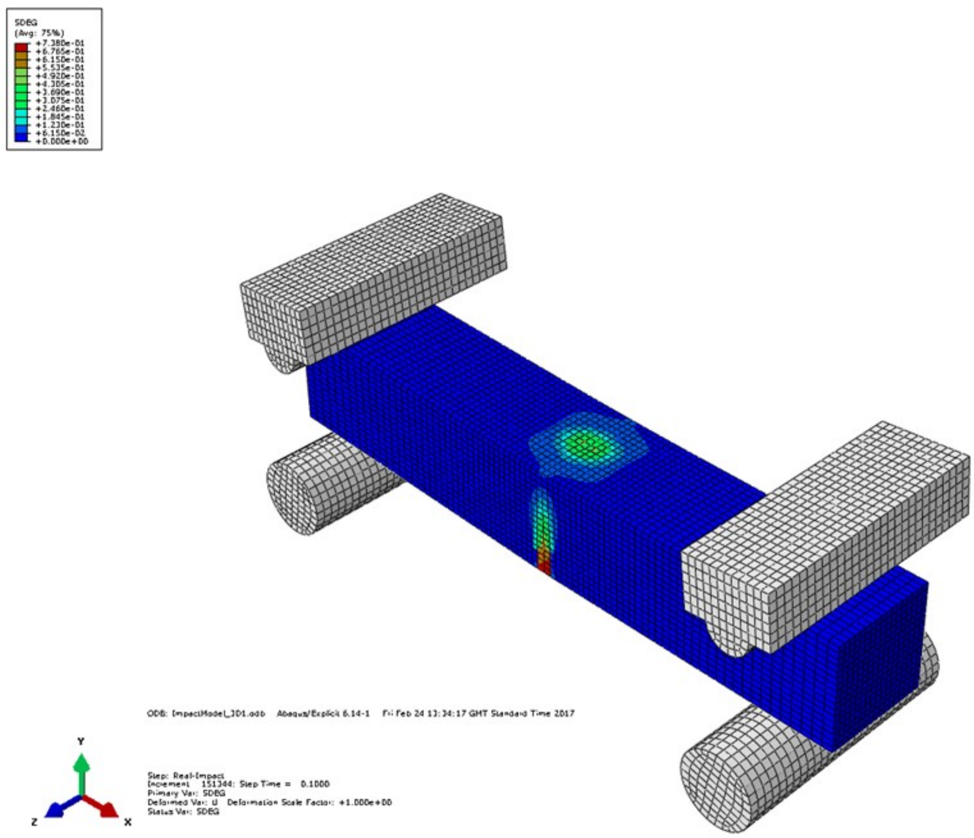


Figure 5: Damage of UHPFRC specimen under impact with a bullet velocity = 5 m/s

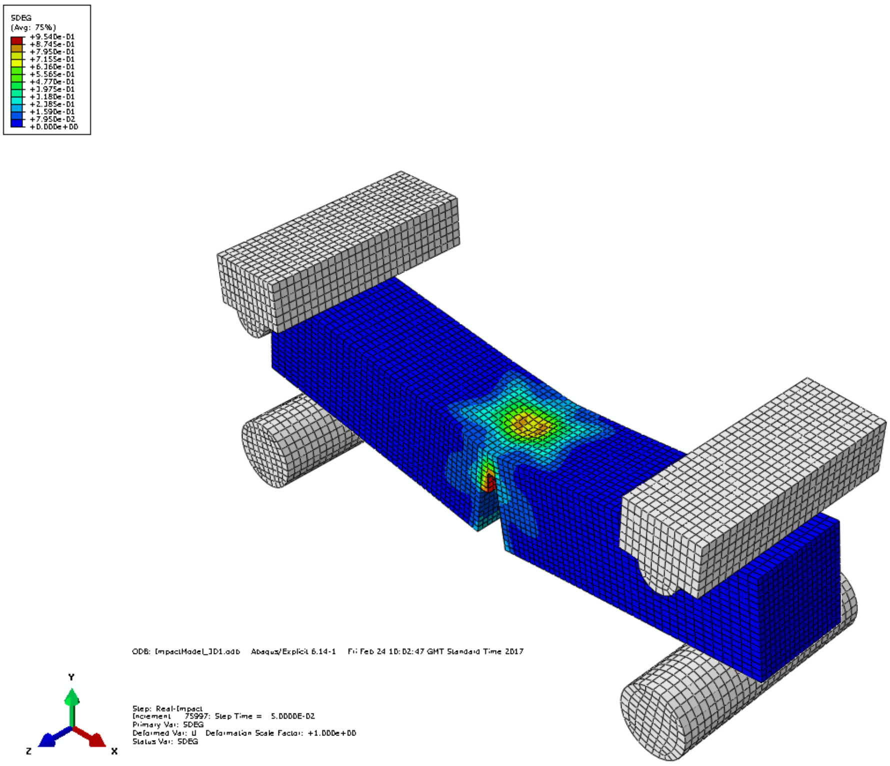


Figure 6: Damage of UHPFRC specimen under impact with a bullet velocity = 10 m/s

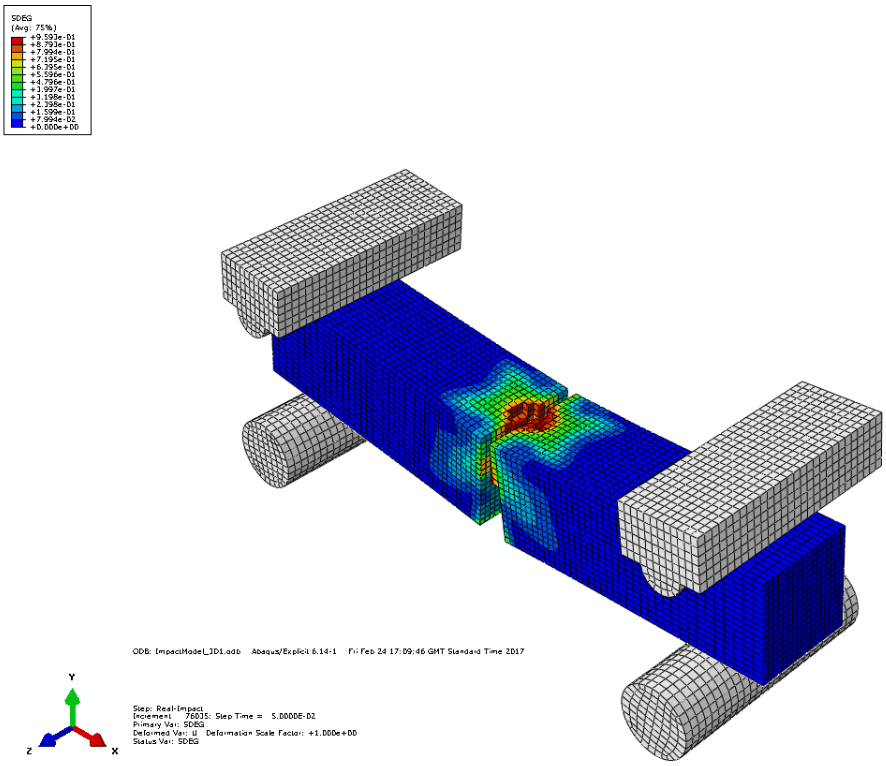


Figure 7: Damage of UHPFRC specimen under impact with a bullet velocity = 25 m/s

5. CONCLUSIONS

This paper has reported some recent studies at Queen's University Belfast on UHPFRC mix design, material tests and drop hammer tests. The test results have shown that the material experiences strong 'size effect' if the tensile strength is derived from $\sigma = My/I$ in bending test of prism specimens. However, this is not necessarily correct as it is based on the assumption that the stress distribution on the cross-section is linearly distributed and this incorrect as the material is nonlinear in tension. A finite element model has been developed to simulate the drop hammer test. Preliminary results from finite element simulation are promising. It is hoped that these will be developed further to enable the modelling of damage to the concrete from the molten metal jet of rocket propelled grenades.

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