Low velocity impact behaviour of ultra high strength concrete panels

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Abstract. This paper presents the results of an investigation carried out on Ultra High Strength Concrete (UHSC) panels subjected to low velocity projectile impact to assess impact resistance. UHSC panel of size 350×350 mm and thickness 15 mm is studied under drop weight impact loading for three different pre-determined drop heights ranging from 100 mm to 300 mm. The response of UHSC panel in terms of acceleration vs time is obtained experimentally. Numerical model has been developed to simulate the impact behaviour of UHSC panel. The Brittle cracking model is used to simulate the behaviour of UHSC panel under impact loading and to perform parametric studies by varying the volume fraction of steel fibres.

Keywords. Ultra high strength concrete; panel; drop weight test; impact analysis; ABAQUS.

1. Introduction

Ultra high strength concrete is a special type of concrete which is characterized by a low water-binder ratio, high quality pozzolanic material, and without any coarse aggregates. Addition of steel fibres significantly improves the mechanical characteristics of concrete including tensile, flexural, fatigue and impact strengths. Additionally, inclusion of steel fibres reduces the brittleness of concrete and alters the mode of failure. Understanding of the impact resistance of concrete and especially of high strength concrete is very limited. Also there is no standardized test technique for testing concrete under impact. Zhang *et al* (2010) studied the characteristics of a drop weight impact machine that has been specifically designed for studying the dynamic behaviour of structural concrete samples. It was observed that the impact force is used to maintain the balance with the inertia force and only a small portion of impact is used to deform and

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fracture. High strength concrete absorbs more energy under impact and it is a load rate-sensitivity material. Many researchers have used different impact machines, specimen configurations, and instrumentations and also adopted different analysis schemes (Farnam *et al* 2010; Ghouse *et al* 2011; Gayarre *et al* 2009; Wang *et al* 2011; Gopinath *et al* 2012; Abbas *et al* 2004; Xu *et al* 2004; Georgin & Reynouard 2003; Habel & Gaurvran 2006; Zineddin & Krauthammer 2007; Jiang & Mirza 1988). Ong *et al* (1999) investigated fibre concrete slabs subjected to low velocity projectile impact to assess impact resistance. The main variables of the study were type of fibre and volume fraction of fibres. The types of fibres chosen were polyolefin, polyvinyl alcohol and steel. The volume fraction of fibres examined were 0%, 1% and 2%. A total of 10 square slabs of size 1 m and 50 mm thickness were cast and tested. Test results indicated that hooked-end steel fibre concrete slabs have better cracking and energy absorption characteristics than slabs reinforced with other fibre types. Slabs reinforced with polyvinyl alcohol fibres exhibited higher fracture energy values compared to slabs reinforced with polyolefin fibres. Elavenil & Samuel Knight (2012) investigated the dynamic behaviour of steel fibre reinforced concrete plates under impact loading with respect to displacement, velocity and acceleration. In the drop weight test, eighteen plate specimens were tested with three different thicknesses of 20, 25 and 30 mm and with three different steel fibre contents of 0.5, 0.75 and 1%. Displacement versus time, velocity versus time and acceleration versus time behaviour for all the plates tested were studied. It was found that when the aspect ratio of fibres is 50 and 75, there is a marginal increase in energy absorption for change in fibre content from 0.5 to 0.75%. There is a steep increase in energy absorption for a steel fibre content of 1% when the aspect ratio of fibre is 100.

This paper consists of two parts: experimental program and numerical simulation. In the first part, drop weight impact test is carried out on six UHSC panels with 2% of steel fibres. The set-up is made in accordance with the ASTM D7136/D7136M – 07. In the second part, numerical simulations of impact tests are comprehensively discussed and compared with the corresponding test data. The ABAQUS explicit finite element code is utilized to analyse the impact resistance of UHSC panels under low velocity drop weight impacts.

2. Experimental program

2.1 Materials and mix proportion

The materials used in the preparation of test specimens are ordinary Portland cement of grade 53 conforming to IS : 12269 – 1987, Sand Grade I (0.6–2.36 mm) and Grade III (0.075–0.15 mm), Silica fume, Quartz powder and steel fibre of diameter 0.4 mm and length 13 mm. Table 1 defines the matrix mix proportion used for all samples (Prem *et al* 2012).

Table 1. Mix proportion.

Mix	Cement	Silica fume	Quartz powder	Sand Grade I	Sand Grade III	Steel fibre (% of binder)	Water	Sp % (Binder)
Ratio	1	0.25	0.40	0.71	0.30	2.0	0.22	3.25
Quantity (Kg/m ³)	768.78	192.19	307.51	600.40	245.25	153.72	169.10	25.55*

*litres/m³

2.2 Specimen preparation, casting and curing

A pan type mixer (Eirich mixer of 300 kg capacity) was used to mix the UHSC mixture. The advantage of the mixer is its ability to rotate the mixing drum and the blades simultaneously at the same time, to provide a uniform blending. The dry binder powder was poured in the mixing pan and dry mixing was done at slow speed of 10 minutes. Around 30% of the water and the super plasticizer were added and the level of mixing was increased to medium, which was continued for another 10 minutes, again 50% of the water and SP were added to inhibit homogeneity in the mix at high speed for 10 minutes. The steel fibres were added to the mix manually through the open slit available at the top of the drum. Finally, remaining 20% of the SP and water were added and the drum was rotated at a very high speed for 10 minutes.

After mixing, the fresh concrete was transferred into steel moulds (which were previously oiled) in three layers and compacted for 30 seconds each using a vibrating table shown in figure 1. The aim of vibrating the filled moulds is to properly compact the materials, to make sure that the fibres are distributed without segregation. The specimens were given a proper finishing ensuring uniformity and perfect appearance. The specimens were demoulded after a time interval of 24 h. The samples after demoulding were kept in water for 7 days after which they were exposed to hot air curing at 200°C for 2 days. After the hot air regime, the samples were then continued with water curing till the period of testing.

2.3 Mechanical properties

Compression test on UHSC was carried out on cubic specimens of size 70 mm. The strength was recorded at 7, 14 and 28 days. The average reading of the tested cubes was represented as the strength at the respective age as shown in table 2.

The split tensile test was carried on cylindrical specimens of 100 mm diameter and 200 mm height at the age of 28 days. Five cylinders were tested and the mean value of the recorded data is reported (table 3).

3. Drop weight impact test

The test set-up consists of a supporting frame on which the specimen is placed, an impact mass of 20 kg with 20 mm diameter impact set-up as shown in figure 2, is made to impact from a

Figure 1. Specimen preparation. (a) Pouring of UHSC into moulds; (b) Hardened UHSC before demoulding.

Table 2. Compression test results.

Day of testing	Force (kN)	Strength (MPa)
7 th day	795.61	162.37
14 th day	915.52	186.84
28 th day	934.61	190.74

Table 3. Split tensile test results.

Force (kN)	Split tensile strength (MPa)
717.55	22.84
730.13	23.24
710.57	22.61
736.90	23.45
725.86	23.10
Average value =	23.05

pre-determined height using a pulley and rope arrangement which is being made to pass through the tubular structure attached over the supporting frame as shown in figure 3, in order to guide the free fall of impact mass. The specimen was hinged over the supporting frame by means of fastening C-clamps over the corners as shown in figure 4. This set-up is made in accordance with the ASTM D7136/D7136M – 07.

Drop weight impact loading is applied by freely dropping the impact mass from different heights of 100, 200 and 300 mm. The acceleration time history is recorded using an accelerometer mounted on the top of the specimen which is further connected to a Data Acquisition

Figure 2. Drop mass 20 kg.

Figure 3. Drop weight testing frame.

Figure 4. Test specimen.

System which is capable of recording velocity data and it was in accordance with the Minimum Instrumentation Requirements, of Test Method D3763.

4. Test results

The impact test was conducted and the results were recorded. Impact damage/failure pattern were recorded for each drop height. No impression occurred for a drop height of 100 mm. No patterns were observed even when the load cell was dropped for the second and the third time. All the three test specimens showed the same results. Similar results were obtained for the 200 mm drop. Finally, under the drop height of 300 mm in the first trial there was a slight impression which got deeper in trial two. And in the third trial, the load cell punched fully into the panel. The responses for typical panel for all drop height is shown in figure 5.

5. Numerical investigations

The drop weight impact tests on ultra high strength concrete (UHSC) were simulated through commercially available three-dimensional nonlinear dynamic finite element code, ABAQUS. Both the steel impactor and ultra high strength concrete (UHSC) have been modelled with 8-node solid elements.

5.1 Details of the drop weight

The impact mass along with the load cell and the impact tup is modelled as a rigid material as shown in figure 6. The drop weight hammer made of steel is modelled as a rigid material as the deformation in the impactor is not expected. The Young's modulus of 210 GPa and Poisson's ratio of 0.2 was given as input in the modelling.

The drop mass is with hemispherical nose with impact head of diameter of 20 mm, shank length $l_1 - 2$ in 50 mm, nose edge length l_2 of 10 mm. The load cell is with a diameter of 120 mm and 150 mm length and is attached to a impact mass of 150 mm diameter and 250 mm length.

Figure 5. Responses of panel. (a) 100 mm drop; (b) 200 mm drop; (c) 300 mm drop.

Figure 6. Drop mass geometry details (all dimensions are in mm).

5.2 Details of the target

The development of the FE model (figure 7) for the low velocity impact simulations in ABAQUS involves the modelling of the composite material and the modelling of the impactor with adequate contact definitions. The UHSC composite material is modelled as a plain concrete slab in which the fibres are oriented randomly. Only half of the panel is modelled due to symmetry.

The mesh size used for analysis is 35×35 mm. The target is meshed using solid 8 noded elements of type C3D8R. Each node has 3 degrees of freedom. The target is hinged at the bottom surface. The impact is defined using general contact algorithm where the top surface of the panel is defined as the master surface and the impactor as the slave surface. Brittle cracking model

Figure 7. FE model of the UHSC panel.

is defined by giving the elasto-plastic behaviour of the material and the direct cracking failure strain is given as input under brittle failure option.

5.3 Results

In this part, the experimental and numerical results are compared. The acceleration-time graph found experimentally and numerically for 100 mm drop height is shown in figure 8. The maximum peak value of acceleration for experimental value is 29.45 mm/sec^2 which occurred during the 26.84^{th} ms of impact and that for numerical simulation is 21.34 mm/sec^2 .

In figure 9, the acceleration-time graph found experimentally and numerically for 200 mm drop height are shown and it can be observed that the experimental result gave a maximum peak acceleration of 29.45 mm/sec^2 at 26.74 ms and the numerical result gave a peak acceleration of 22.97 mm/sec^2 .

Figure 8. Acceleration-time for 100 mm drop height.

Figure 9. Acceleration-time for 200 mm drop height.

In figure 10, the variation of acceleration with time found experimentally and numerically is represented for 300 mm drop. It is observed that the peak value is 30.12 mm/sec^2 occurred at 16.52^{th} ms for experimental result and it is 24.83 mm/sec^2 for numerical solution. As per Oliver Martin (2010), brittle cracking model assumes that the compressive behaviour of concrete is always linear elastic, which does not resemble reality and is a limitation of the model. It is most accurate in applications where the brittle behaviour dominates such that the assumption of the material is always linear elastic in compression is adequate. This is not really the case for missile impact analysis where the reinforced concrete slab experiences the plastic behaviour predominantly. In the present numerical study, up to a velocity of 1.98 m/s it is observed that the brittle cracking model can be employed for analysis. But for a velocity of 2.42 m/s , the experimental and numerical graphs do not coincide completely.

Figure 10. Acceleration-time for 300 mm drop height.

6. Conclusions

Drop weight impact analysis has been conducted to find the ability of UHSC to resist impact loads. For UHSC panels having 2% of steel fibres, the 20 kg drop mass allowed to impact the panel at 100 mm drop height did not show any change for three consecutive drops for all three specimens. Similar observations were made for 200 mm drop height for all three specimens. In the case of 300 mm drop height, the first drop created a slight impression which became deeper in the second drop. In the third and final drop, the impact tup completely penetrated into the panel. The variation of acceleration with time for various drop heights were studied experimentally and numerically and both the studies gave similar results. Parametric studies were conducted by varying the volume fraction of fibres to 0.5% and 1%. The total energy values for 100, 200 and 300 mm drop heights were obtained from the Finite Element models.

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