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Low and High Velocity Impact Studies on Fabric Reinforced Concrete Panels

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Abstract: This paper presents the details of experimental and numerical investigations performed on fabric reinforced concrete (FABcrete) panels under impact loading. Experimental investigations have been carried out using drop weight impact on a square FABcrete panel to study the damage, failure mode and acceleration. The drop weight of 20 kg is used for the study and drop heights have been varied as 100mm, 200mm and 300mm. Numerical simulation of the drop weight impact tests on FABcrete panels have been carried out and observed that there is a good correlation between experimental and numerical predictions. It is observed that the FABcrete specimen with a volume fraction of 1% of fabric withstood an impact force of 50 kN. Further, a high velocity projectile impact on reinforced concrete (RC) slab strengthened with FABcrete has been carried out using nonlinear explicit transient dynamic analysis and observed that the computed penetration depth for RC slab strengthened with FABcrete is lesser compared to RC slab without strengthening, which proves the suitability of FABcrete as an impact resistant material.

Keywords: Fabric Reinforced Concrete; Impact Analysis, Drop weight, Panel, Glass Fabric, Finite Element Analysis, Concrete damage model, Contact algorithm, Nonlinear transient dynamic analysis.

1 Introduction

The concrete structures are highly susceptible to impact loading due to natural and artificial hazards. Incorporation of fibers in concrete improves its toughness, ductility, energy absorption capacity and reduces the rate of deformation. Experimental

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studies were conducted under low-velocity impact behaviour of fiber reinforced composites [Xu et al. (2004)]. It was noticed that when fabrics are used as reinforcement instead of fibers, it is possible to avoid complete fracture [Deju Zhu et al. (2009)]. Deju Zhu et al. (2009) studied the behaviour of AR-glass fabric developed by pultrusion production process under low velocity flexural impact. The specimen was subjected to three point bending condition using an instrumented drop weight impact system. Variation of impact load, deflection response, acceleration, and absorbed energy were studied. In plate specimen, the extent of cracking was observed to be dominated by matrix flexural cracks which ultimately redirect and convert to inter laminar shear cracks. It was predicted that the higher is the number of fabric layers, the higher will be the impact load carrying capacity and lower will be the absorbed energy level and displays less deflection. Padaki et al. (2010) studied in detail about the failure of textile composites under low velocity impact and observed that (i) the textile composites dissipate the imparted energy through several interacting damage modes than simple deformation (ii) the load-time and the energy-time histories compared with the fractographics and (iii) fiber breakage occurs prior to major damage. Johnson (2009) studied the behaviour of various hydrocode models like elastic damage mechanics model, elastic-plastic model and compared it with Textile reinforced concrete plate. Choong et al. (2011) investigated the impact damage behaviour of woven glass fiber reinforced polymer composite and used composite damage model for modeling the glass composite, but it could not accurately predict the complete failure as the model did not consider the shear effect.

Considering the importance of impact load with high velocity, there is lot of concern for concrete structures in civil and defense sectors. Sometimes the projectiles with high velocity, which vary broadly in their shapes and sizes, impact velocities, hardness, rigidities, impact attitude produce a wide spectrum of damage in the target. The interest in penetration, perforation and fragmentation of plain and RC targets arises from their use as barriers to protect civilian buildings and as bunkers to protect against impacts. Numerous studies were carried out in the last 15 years for the development and improvement of the macro-scale concrete models for high-velocity applications [Govindjee et al. (1995); Malvar et al. (1997); Govindjee et al. (1994); Malvar et al. (1994); Malvar et al. (1996); Hentz et al. (2004);Yonten et al. (2005)]. Various material models were proposed, from relatively simple to more sophisticated ones and their capabilities in describing the actual nonlinear behaviour of the material under different loading conditions. Besides, because of the general complexity of the models, the determination of the model parameters also plays an important role in the actual performance of these models. With the rapid developments of computational tools, computational mechanics and material constitutive models, the numerical simulation of local projectile impact effects becomes more reliable and economic. A number of commercial hydro codes such as AUTODYN (2001) and LS-DYNA (2003) are available for the general simulation of nonlinear dynamic responses. However, such simulations can produce reliable results for concrete structures, only if a material model capable of representing the essential mechanical processes of the material under varying stress and loading rate conditions is available. It is known that very high strain rates occur during impact or blast loads event as a large amount of energy is transmitted to the structure in a short duration; which will lead to severe damage to the concrete structures. A new composite material, which possesses high strength and high energy dissipation capacity is required to resist the impact/blast load. FABcrete is one type of textile reinforced concrete capable addressing such situation. In this direction, limited research was carried out on textile reinforced concrete [Ghani et al. (2007); Larbi et al. (2010); Brucker et al. (2006); Choong et al. (2011)].

In the present investigation, experimental and numerical investigations have been carried out on fabric reinforced concrete (FABcrete) panels under low and high impact loading.

2 Fabric reinforced concrete (FABcrete)

The material ingredients used in FABcrete consists of a cementitious matrix and an alkali resistant glass fabric. Fabric is introduced to increase the toughness, to improve the energy absorption capacity under impact and to obtain a finer crack pattern.

2.1 Cementitious binder

The effectiveness of fabrics can be utilized to maximum extent by embedding it in inorganic binder for obtaining composite action. The fine grained binder systems used as matrix for fabric reinforced elements meets the required mechanical properties of composite and durability of the fabric reinforcement. Typically they show highly flowable consistencies which offer full penetration of fabrics. These special properties are achieved by using a small grain size, high binder content and adding different pozzolanic additives. This leads to a more homogeneous and finer structure compared to ordinary concrete. Fine grained cementitious matrix consists of ordinary Portland cement, fly ash, silica fume, water and silica based very fine filler of size less than 0.6mm and superplasticizer to achieve required workability. The average compressive strength for the above mentioned mix is expected to be in the range of 40 to 50MPa.

2.2 Glass Fabric

An alkali resistant glass fabric consisting of a perpendicular set of yarns (warp and weft) woven at the junction points is used in the investigation. The fabric has a weight of 110 g/m^{2}. The mesh size of the fabric is 10mmx10mm and the tensile strength of 29 kN/m in warp and weft direction. A typical representation of the fabric is given in Figure 1.

Figure 1: AR Glass Fabric

3 Low Velocity Impact on FABcrete panel

In order to assess the behaviour of FABcrete under low velocity impact, experimental investigations using drop weight impact have been carried out on a square FABcrete panel of size 350x350x15mm as shown in Figure 2. A volume fraction of 1% of the AR-glass fabric has been provided in the slab with 11 layers of fabric in 15mm thick slab specimen.

Figure 2: Square FABcrete Panels

3.1 Pre-stressing the Specimen

The glass-fabric used as reinforcement has a wavy nature and to make use of the full potential of the fabric as soon as the matrix cracks, a pre-stressing force is applied while casting the specimen. Pre-stressing mechanism used for the study is a steel plate having angles with bolts at the edges of the mould as shown in Figure 3. After placing the required amount of glass fabric, bolts are tightened to pre-stress the fabric.

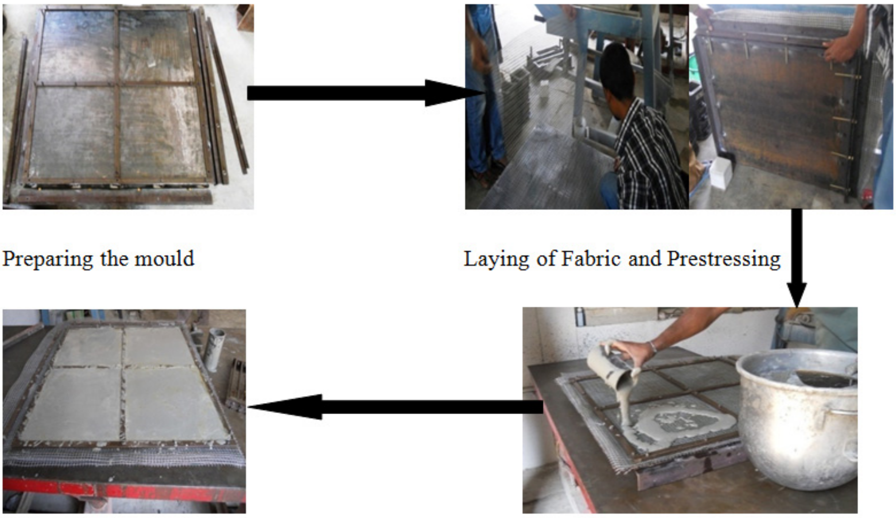
Figure 3: Fabric Pre Stressing

3.2 Preparation of specimens

As a first step, 11 fabric layers which form a volume fraction of 1%, are placed one after the other, as shown in Figure 4. Secondly, they are pre stressed by means of fastening the nut and bolt arrangements placed at equal spacing on both longitudinal and transverse directions, as shown in Figure 4. Finally, the cementitious matrix is poured and vibrated to get a properly compacted Fabric Reinforced Concrete Panel and finishing is done at the end.

3.3 Drop weight Impact system

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 5, is made to impact from a predetermined height using a pulley and rope arrangement, made to pass through the tubular structure attached over the supporting frame as shown in Figure 6, 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 7.



Preparing the mould

Laying of Fabric and Prestressing

Finishing of slab

Pouring of FABmix

Figure 4: Casting of FABcrete slab

Drop weight impact loading is applied by freely dropping the impact mass from the different heights of 100 mm, 200 mm and 300 mm. The crack / failure patterns were observed for each drop height. The contact force history during impact was measured using a load cell with a range of 710kN and sensitivity of 0.16 μV/volt/kg, located on the top of the impact **tup** and acceleration time history is recorded using an accelerometer of capacity $\pm$ 2000g mounted on the top of the specimen. The accelerometer and the load cell are connected to a data acquisition system to obtain force and velocity data and it was in accordance with the minimum instrumentation requirements, of test Method Specified in ASTM: D7136. The minimum sampling rate is 100 kHz and the storage capacity is more than 1000 points.

3.4 Results

Impact damage / failure pattern and contact force histories are recorded for each drop height. As depicted in Figure 8, a circular impression of the impact tup approximately 10 mm in radius is observed for a drop height of 100 mm, since impact velocity is very low. Figure 9 shows a circular crater of approximately 6 mm in depth occurred due to 200 mm impact but there is no damage in the area vicinity to the point of contact of impact tup, ie. 20mm. The impact force – time history graph is shown in Figure 12 and it can be observed that the peak force is about 55kN.

Figure 5: Drop mass 20 kg

Figure 6: Drop weight testing frame

Figure 7: FABcrete panel with C clamps

Finally, for the drop height of 300 mm complete penetration of impact tup occurred leading to protrusion of fibers on the rear face exactly below the point of impact as

Figure 8: impression – 100 mm drop

Figure 9: small crater – 200 mm drop

Figure 10: Protrusion of fibers on rear side - 300 mm drop

Figure 11: crater front side – 300 mm drop

shown in Figure 10. On the front face, an irregular crater with approximate width of 45 mm and length of 35mm occurred and the maximum damage diameter is observed along the diagonal which is approximately 47 mm as shown in Figure 11. The impact force – time history graph is shown in Figure 13 and it can be noted that the peak force is about 78kN.

4 Numerical Simulation of Drop Weight Impact Test

The drop weight impact tests on FABcrete specimen have been simulated through commercially available three-dimensional nonlinear dynamic finite element code, LS-DYNA. Both the steel impactor and FABcrete have been modeled with 8-node solid elements. FABcrete is modeled as three layers, namely; top and bottom layer of bilinear kinematic hardening material (cementitious matrix) and the middle layer of linear isotropic material (AR-Glass fabric). The drop weight hammer made of steel is modeled as rigid material. The impact mass and the impact tup (Figure 14) is also represented as rigid material.

The drop mass is with blunt nosed impact head with diameter of 20 mm, shank length l_1 –50 mm, nose edge length l_2 - 10 mm, a load cell with a diameter of 120

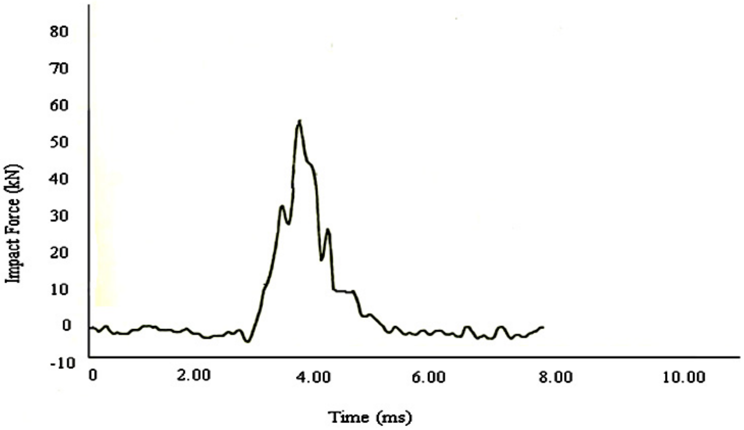


Figure 12: impact force – time graph - 200 mm drop

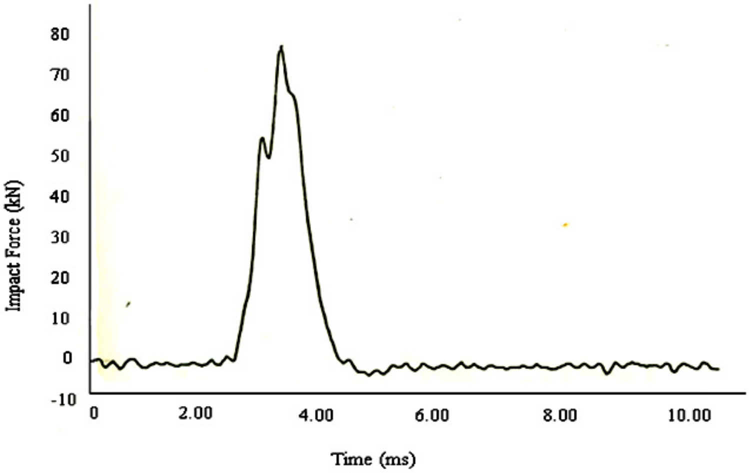


Figure 13: impact force- time – 300 mm

mm and 150 mm length is attached to a impact mass of 150mm diameter and 250 mm length.

4.1 Results

The deformation pattern of FABcrete panel subjected to drop weight impact loading for 200 mm and 300 mm drop is compared with the corresponding experimental observations are shown in Figures 15 and 16.

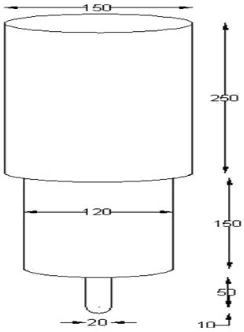
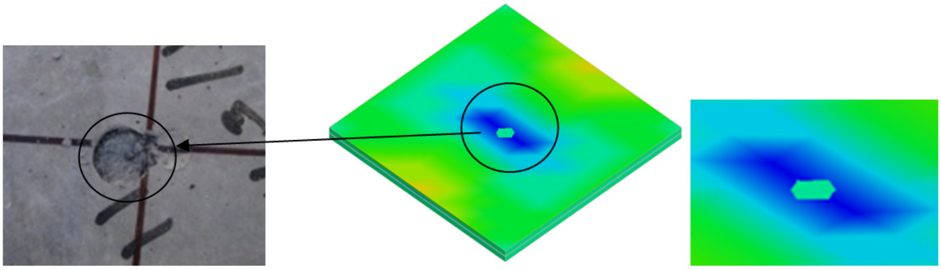
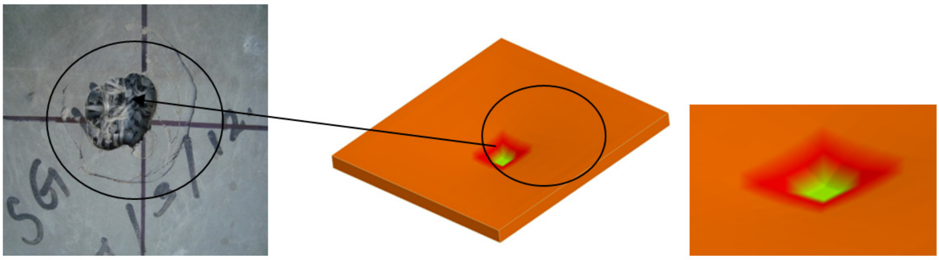


Figure 14: Drop mass



(a) Experimental **(b) Numerical** **Zoomed view**

Figure 15: Deformation pattern of fabcrete panel for 200 mm drop height

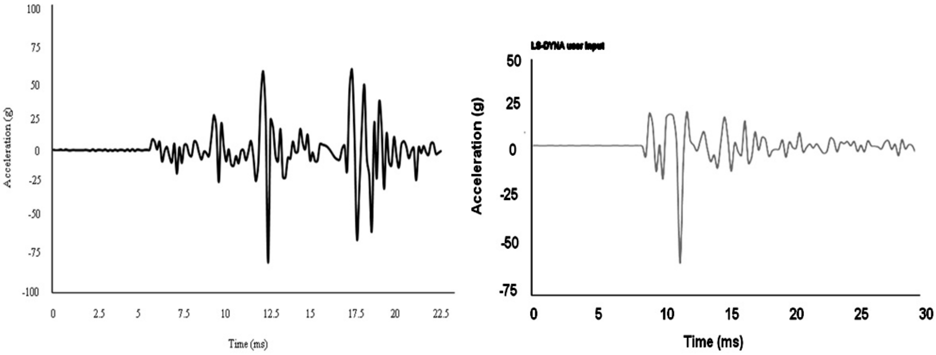


(a) Experimental **(b) Numerical** **Zoomed view**

Figure 16: Deformation pattern of fabcrete panel for 300 mm drop height

4.1.1 Acceleration

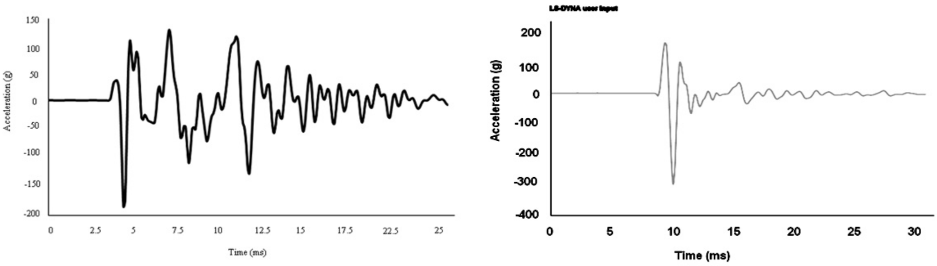
Figure 17 shows the acceleration history of FABcrete panel obtained experimentally as well as numerically for 100 mm drop height. The peak value of acceleration for experimental value is 57.5 g which occurred during the 12.5th ms of impact and that for numerical simulation is 38 g which also occurred during the same time period.



(a) Experimental (b) numerical

Figure 17: Acceleration vs Time

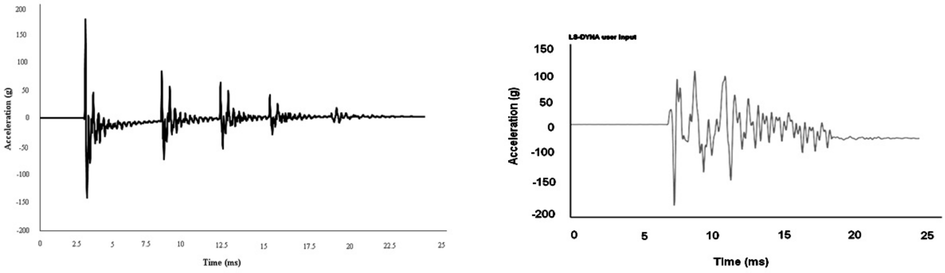
In Figure 18, the variation of acceleration with time for the duration from 0 to 25 ms obtained experimentally and numerically are represented. It can be observed that the peak value is 180 g occurred at 10^{th} ms for experimental result and it is 150 g occurred at 7.5^{th} ms for numerical result. The percentage difference is about 27%.



(a) Experimental (b) Numerical

Figure 18: Acceleration vs Time

Figure 19 shows the acceleration-time history obtained experimentally and numerically for 300 mm drop height and it can be observed that the experimental result indicated a peak acceleration of 175 g occurred at 3.5 ms and the numerical result indicated a peak acceleration of 115 g at 7.5 ms.



(a) Experimental (b) Numerical

Figure 19: Acceleration vs Time

5 High velocity Impact Analysis

High velocity impact analysis has been carried out by investigating the behaviour of RC slab strengthened with FABcrete. The material models for concrete-like materials generally share in common some basic features of brittle materials such as pressure hardening, strain hardening and strain rate dependency. However, for simplicity, some models adopt highly restrictive assumptions; consequently, their applicability is limited to a certain class of problems. In cases, where the loading environment of the material is very complex and cannot be pre-defined, more robust material models that are capable of describing the varying concrete material behavior under different loading conditions are desired. It is observed from the literature [Ramachandra Murthy et al. (2008)] that concrete damaged model is widely employed for representation of non-linear behaviour of concrete.

5.1 Concrete damage model for impact analysis

The material models for concrete-like materials generally share in common some basic features of brittle materials such as pressure hardening, strain hardening and strain rate dependency. However, for simplicity, some models adopt highly restrictive assumptions; consequently, their applicability is limited to a certain class of problems. In cases, where the loading environment of the material is very complex and cannot be pre-defined, more robust material models that are capable of describing the varying concrete material behavior under different loading conditions are desired. Concrete damage model was used by Rama chandra Murthy et al. (2012) for simulating the impact behaviour of reinforced concrete panels. The concrete damage model uses three independent strength surfaces, namely, an initial yield surface, a maximum failure surface and a residual surface, with consideration of all the three stress invariants (I1, J2 and J3). The strength surfaces are uniformly expressed as:

$$\Delta\sigma = \sqrt{3J_2} = f(p, J_2, J_3) \tag{1}$$

where $\Delta\sigma$ and p denote, respectively, the principal stress difference and pressure, and

$$f(p, J_2, J_3) = \Delta\sigma^c * r' \tag{2}$$

where $\Delta\sigma^c$ represents the compressive meridian andr' can be calculated by using the formula given below

$$r' = \frac{r}{r_c} = \frac{2(1-\psi^2)\cos\theta + (2\psi - 1)\sqrt{4(1-\psi^2)\cos^2\theta + 5\psi^2 - 4\psi}}{4(1-\psi^2)\cos^2\theta + (1-2\psi)^2} \tag{3}$$

where $\psi = r_t/r_c$(refer to Fig. 2). The Lode angle θ is a function of the second and third deviatoric stress invariant and can be obtained by either of the following two equations:

$$\cos\theta = \frac{\sqrt{3}}{2}\frac{s_1}{\sqrt{J_2}} \; or \; \cos 3\theta = \frac{3\sqrt{3}}{2}\frac{J_3}{J_2^{3/2}} \tag{4}$$

The compressive meridians of the initial yield surface$\Delta\sigma_y^c$, the maximum failure surface $\Delta\sigma_m^c$ and the residual surface $\Delta\sigma_r^c$ are defined independently as:

$$\Delta\sigma_y^c = a_{0y} + \frac{p}{a_{1y} + a_{2y}p} \tag{5}$$

$$\Delta\sigma_m^c = a_0 + \frac{p}{a_1 + a_2 p} \tag{6}$$

$$\Delta\sigma_r^c = \frac{p}{a_{1f} + a_{2f}p} \tag{7}$$

The eight free parameters, namely, a0y, a1y, a2y, a0, a1, a2, a1f, and a2f are to be determined from experimental data. With the specification of the three strength surfaces, the loading surfaces representing strain hardening after yield are defined as

$$\Delta\sigma_L = \eta\Delta\sigma_m + (1-\eta)\Delta\sigma_y \tag{8}$$

The post-failure surfaces, denoted b$\Delta\sigma_{pf}$y, are defined in a similar way by interpolating between the maximum failure surface$\Delta\sigma_m$ and the residual surface$\Delta\sigma_1$

$$\Delta\sigma_{pf} = \eta\Delta\sigma_m + (1-\eta)\Delta\sigma_r \tag{9}$$

The variableη in eqns. (8) and (9) is called the yield scale factor, which is determined by a damage functioλn:

$$\lambda = \begin{cases} \int_0^{\bar{\varepsilon}_p} \frac{d\bar{\varepsilon}_p}{[1+p/f_t]^{b1}} & p \geq 0 \\ \int_0^{\bar{\varepsilon}_p} \frac{d\bar{\varepsilon}_p}{[1+p/f_t]^{b2}} & p < 0 \end{cases} \tag{10}$$

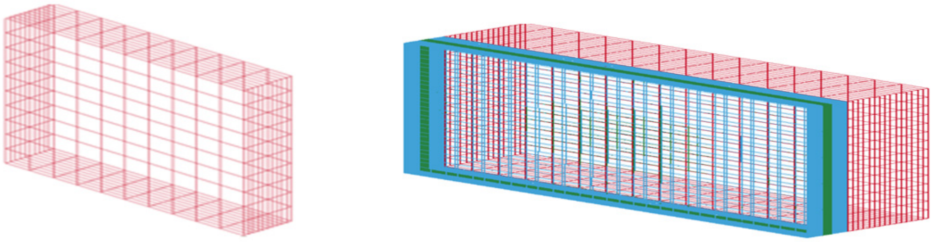
where ft is the quasi-static concrete tensile strength, $d\bar{\varepsilon}_p$is effective plastic strain increment, and $d\bar{\varepsilon}_p = \sqrt{\frac{2}{3}d\varepsilon_{ij}^p d\varepsilon_{ij}^p}$ with $d\varepsilon_{ij}^p$ being the plastic strain increment tensor.

It is to be noted that the damage function has different definitions for compression ($p \geq 0$) and tension($p < 0$) to account for different damage evolution of concrete in tension and compression. The evolution of the yield scale factor η follows a general trend: it varies from “0” to “1”, when the stress state advances from the initial yield surface to the maximum failure surface, and changes from “1” back to “0”, when the stress softens from the failure surface to the residual surface

5.2 Finite element model

The target is made of concrete with compressive strength of 35 MPa. The size of the target is a square slab with dimensions of 500 mm x 500 mm x 100 mm. To represent nonlinearity in the concrete target, concrete damage model is employed. The FE model of the Targets is shown in Figure 20. Reinforcement has been modelled by using discrete approach. In discrete reinforcement, the reinforcement is given as an individual bar. The length of reinforcement required for beam/bar element is calculated and it varies depending on the percentage of reinforcement. The beam elements are spaced depending on the interval of solid element nodes. The discrete model has been placed with 20mm cover thickness. Analysis has been carried out for various percentage of reinforcement. Perfect bond is assumed between the reinforcement and the concrete. RC slab (500 mm x 500 mm x 100 mm) is strengthened with FABcrete panel of size 500mm x 500mm x 15 mm for the above mentioned percentage of reinforcement. The FABcrete is modeled as three layers, namely; top and bottom layer of bilinear kinematic hardening material (cementitious matrix) and the middle layer of linear isotropic material (AR-Glass fabric). The concrete slab, FABmix and Fabric are meshed using solid elements of 50x50x10mm, 25x25x0.25mm and 25x25x0.1mm size respectively. The fabric reinforcement is modelled as smeared layer. The impactor is meshed uniformly with an element size of 0.2.

The projectile is made of steel with density of 7.82 kg/m^3. The details of projectile are given below in Figure 21. It is Ogive-nosed with diameter – 1.059in (27 mm), Shank length, $l_{1:}$ 8.142in (207 mm), Nose edge length, l_2: 1.401in (36 mm).



a) RC Slab **b) FABcrete Strengthened RC Slab**

Figure 20: Finite element models

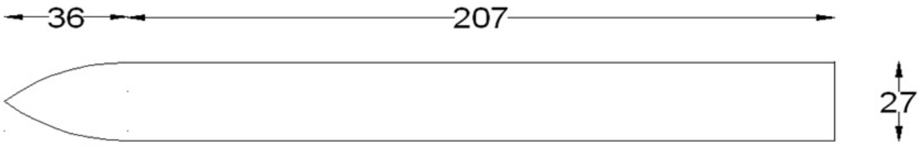


Figure 21: Projectile geometry (Dimensions in mm)

Contact algorithm employed between target and projectile is “surface-to-surface-automatic”. Equation of state has been defined in the form of volumetric strain and corresponding pressure. Nonlinear transient dynamic analysis has been carried out by using LS-DYNA software and the results are viewed in LS-PREPOST. Table 1 shows the computed penetration depth for both the cases, namely, reinforced concrete slab and FABcrete strengthened RC slab for different percentage reinforcements and velocities. From Table 1, it can be observed that the computed penetration depth obtained in the case of FABcrete strengthened RC slab is approximately reduced by 50% compared to the value obtained in the case of RC slab for the same velocity. In general, it can be observed that penetration depth decreases with the increase of percentage of reinforcement and increases with the increase of velocity. It can also be noted that in the case of RC slab, perforation has occurred for 0.4% reinforcement corresponding to velocity of 773 m/s.

Table 1: Comparison of penetration depth of projectile

Velocity (m/s)	Penetration Depth (mm)					
	Reinforced Concrete Slab (100 mm thick)			FABcrete Strengthened Reinforced Concrete Slab (115 mm thick)		
	0.4 %	0.6 %	0.8 %	0.4 %	0.6 %	0.8 %
432	30	25	17.5	15	13.25	9.5
590	50	42	40	22.5	19.5	18
773	Perforation	75	75.5	52.5	42	30.5

The various outputs obtained from LS-PREPOST such as variation of kinetic energy, internal energy, total energy and velocity of projectile with time for the projectile velocity of 590m/s on the target with 0.8% reinforcement are presented below.

The X-stress contour of RC slab with 0.8% of reinforcement is shown in Figure 22 (a) and it can be inferred that the damage is only in the area vicinity to the point of projectile impact and there is no development of stress in other areas of the target. The X-stress contour of FABcrete strengthened RC slab with 0.8% of reinforcement is shown in Figure 22 (b) and it can be observed that the stress development is not only in the area of vicinity to the point of projectile impact, it occurs over the entire surface of the FABcrete. Since the FABcrete behaves ductile, the impact intensity to the RC slab is reduced leading to lesser penetration depth and reduced damage of the main RC slab.

From Figures 23 & 24, it can be seen for the case of RC slab that, the variation of kinetic energy and total energy with respect to time is similar to each other which shows that all the kinetic energy of projectile is available to penetrate the target and there is no loss, as in the form of strain energy of projectile which indicates that it is rigid (hard missile) compared to target. The peak value of kinetic and total energy observed is about 18 J.

Figure 25 shows the variation of internal energy (J) of target with time (ms) for the case of RC slab, and it can be inferred that there is a gain of internal energy in the target after the impact of projectile in the form absorption and dissipation of energy. The peak internal energy observed is +7J and -12J, so the net value is -5. The negative symbol denotes that there is a dissipation / loss of energy in the target due to impact event.

Figures 26 and 27 show the variation of kinetic energy and total energy history for the case of FABcrete strengthened RC slab. It can be observed that they are similar

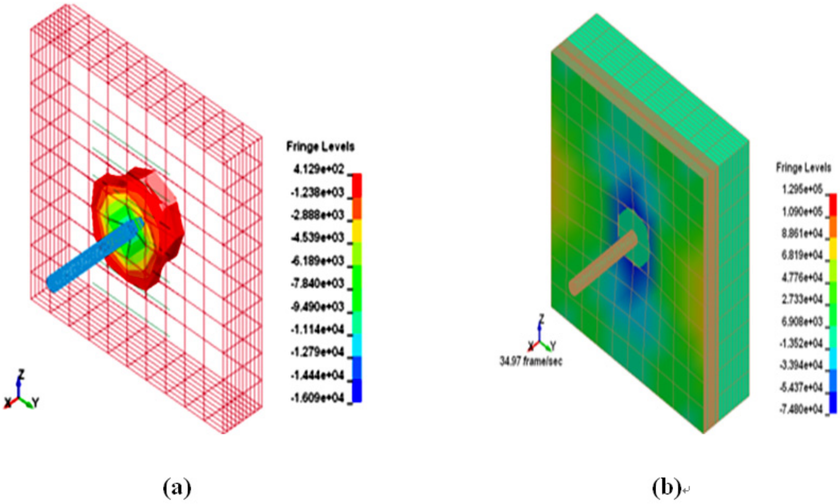


Figure 22: (a): RC slab X-Stress contour (b): FABcrete strengthened RC slab

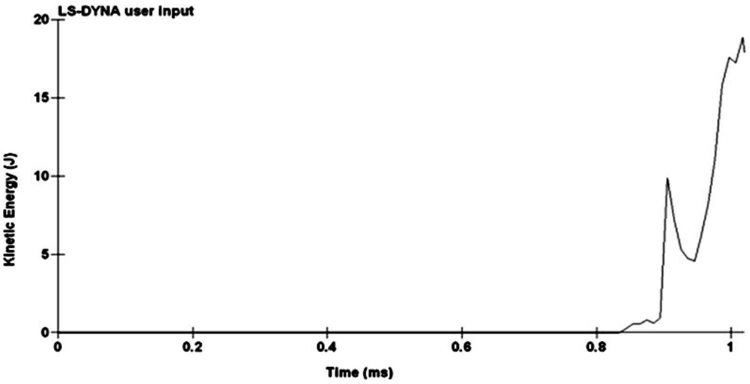


Figure 23: Variation of kinetic energy of projectile w.r.t time – RC slab

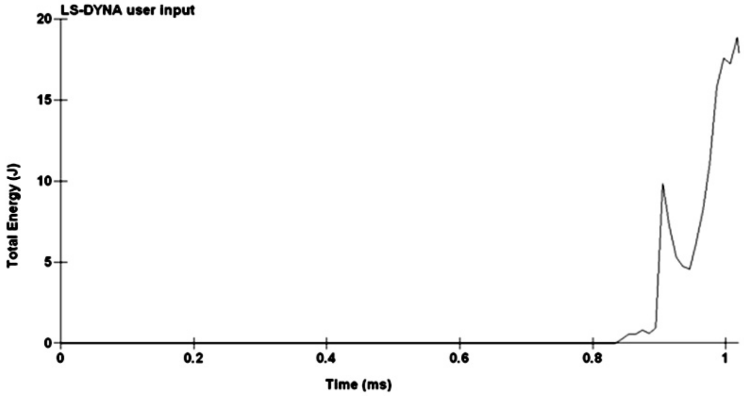


Figure 24: Vartiation of total energy w.r.t time - RC slab

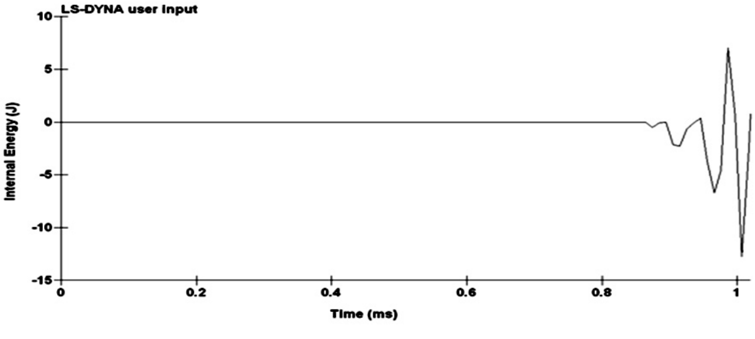


Figure 25: Variation of internal energy w.r.t time – RC slab

in all aspects which shows that all the kinetic energy of projectile is available to penetrate the target and there is no loss, as in the form of strain energy of projectile which indicates that it is rigid (hard missile) compared to target. The peak kinetic energy is observed as 90 J.

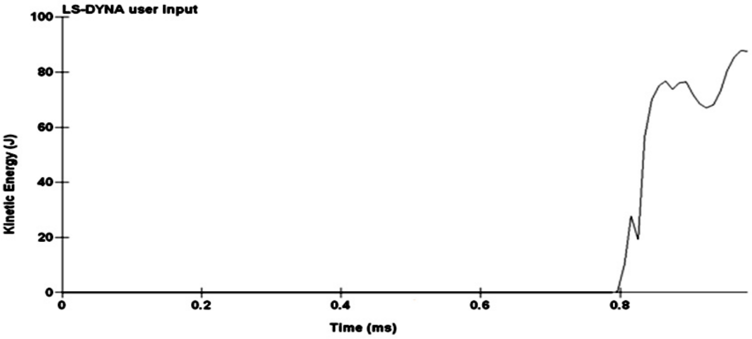


Figure 26: Variation of kinetic energy w.r.t time – FABcrete strengthened RC slab

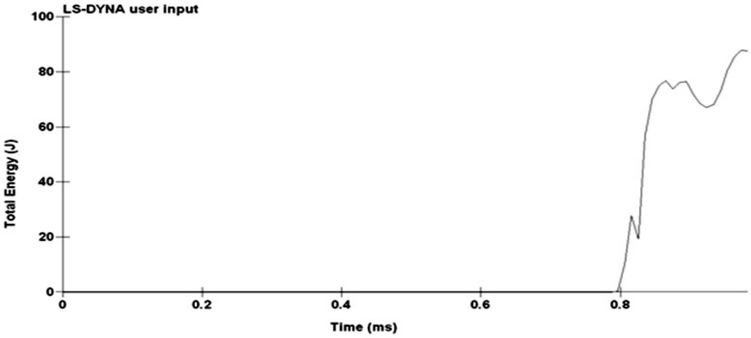


Figure 27: Variation of total energy w.r.t time – FABcrete strengthened RC slab

From Figure 28, it can be observed that in the case of FABcrete strengthened RC slab, the curve moves upward (positive direction) leading to increase in internal energy in the target after the impact of projectile in the form absorption of energy which could be due to the elastic behaviour of fabric, acts as reinforcement for the FABcrete material. The peak value is observed as 78 J.

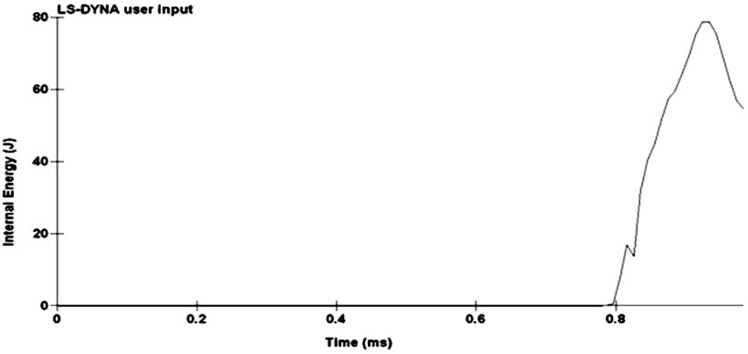


Figure 28: Variation of internal energy w.r.t time – FABcrete strengthened RC slab

6 Summary & Concluding Remarks

Fabric reinforced concrete (FABcrete) panels have been investigated under low and high velocity impact. Drop weight impact test has been performed on a square FABcrete panel of size 350x350x15mm with alkali resistant glass fabric of volume fraction 1%. The drop weight of 20 kg is used for the study and the drop heights have been varied as 100mm, 200mm and 300mm. It is observed that the FABcrete specimen is resisted up to an impact force of 50 kN. Numerical simulation of drop impact test has been carried out by using LS-DYNA and various responses have been compared. The results are found to agree with each other. Nonlinear transient dynamic high velocity impact analysis has been carried out for RC slab and FABcrete strengthened RC slabs to assess the suitability of FABcrete as a strengthening material for RC components towards high impact resistance. Based on the studies, it is observed that the computed penetration depth is significantly reduced for the case of FABcrete strengthened RC slab compared to unstrengthened slab. It is also observed that the peak value of kinetic energy is about five times higher in the case of FABcrete strengthened RC slab compared to unstrengthened slab indicating that FABcrete could be a suitable material for impact applications.

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