CMC, vol.42, no.1, pp.75-102, 2014

High Velocity Impact Behaviour of Layered Steel Fibre Reinforced Cementitious Composite (SFRCC) Panels

Amar Prakash[1], Srinivasan, S. M.[2] and Rama Mohan Rao, A.[3]

Abstract: Behaviour of layered steel fibre reinforced cementitious composite (SFRCC) panels is studied under high velocity impact of short projectiles. The panels consist of slurry infiltrated fibre concrete (SIFCON) layers in external faces and an intermediate (core) layer of latex modified concrete (LMC) and steel wire mesh embedded in cement sand slurry. In order to minimize acoustic impedance mismatch at the interfaces, judiciously selected materials are provided in the layers with appropriate lay-up sequences. For relative evaluation of high velocity impact performances of these panels', impact experiments are conducted in controlled environment. Two most commonly used types of short projectiles having calibre diameter of 5.56 mm and 7.62 mm are used in this study. Various important response parameters like depth of penetration (DOP), crater size, spalling, and cracking in the panels are considered for the performance evaluation. This paper presents the results of experimental study conducted on SFRCC panels. Considering the results obtained from experimental study, relative assessment of impact performances of SFRCC panels is carried out with respect to the materials of core layer. Influence of steel fibre volume on impact performance of the panels is also investigated and expressions are proposed based on regression analysis. In order to determine the residual impact resistance of the SFRCC panel after first hit, the same panel was impacted consecutively two to three times, generally within the damage zone of the first hit. Promising potential to resist high velocity impact is exhibited by the SFRCC panels. The structural integrity of the SFRCC panels is found intact even under multiple hits.

Keywords: Fibres, Layered structures, Delamination, Impact behaviour, Lay-up.

---

[1] CSIR-Structural Engineering Research Centre, Chennai-600113, India.

[2] Department of Applied Mechanics, IIT Madras, Chennai-600036, India.

[3] CSIR-Structural Engineering Research Centre, Chennai-600113, India.

1 Introduction

Construction of layered steel fibre reinforced cementitious composite (SFRCC) panel to resist high velocity impact of short projectile is a challenging task. It requires judicious selection of materials to be provided in each layer and, an appropriate lay-up sequence. Most important function of an impact resistant (or protective) structure is to dissipate the kinetic energy of a particular projectile without undergoing fragmentation and perforation. It is also, equally important for such structures, to resist repeated hits within the vicinity of damaged zone of previous hits, without losing structural integrity.

Innovations in the field of development of construction materials have exhibited excellent materials for impact resistance. Presently, research in this area has attracted great interest among researchers over the past few decades [Soe, Zhang, and Zhang (2013)]. Steel bar reinforced concrete has extensively been used in the construction of protective structures over the years. Usually the RCC protective structures have bulky volume to resist high velocity impact of projectiles [Dancygier (1998); Tham (2006)]. In addition to this, steel bar reinforced concrete is brittle, weak locally in tension and its shatter resistance is also very low. Hence, catastrophic failure occurs in RCC protective structures under high velocity impact of short projectiles [Maalej, Quek, Zhang (2005)].

Studies to overcome the brittleness of concrete by incorporating discrete fibres into plain cementitious matrix are reported in literature [Naaman, Otter, Najm (1992)]. Fibre reinforced concrete (FRC) consisting of discrete short fibre volume between 1% and 3% mixed with concrete has shown substantial improvement in the engineering properties like; tensile strength, ductility, fracture toughness and resistance to shatter, in comparison with RCC and plain concrete. In the fibre reinforced composite materials, both the fibre and matrix retains their original physical and chemical identities. But, synergetically together they produce a combination of enhanced mechanical properties that cannot be achieved with either of the constituents acting alone [Kim and Mai (1998)]. During the impact, strong bond between fibre and matrix prevents crack propagation by means of crack bridging. Depending upon the steel fibre lengths varying from10 mm to 60 mm, their volumes vary between 0.5% and 30% in fibre concrete [Shah and Ribakov (2011)]. It has been reported that sizes, shapes and volumes of fibres influence impact resistant properties of cementitious composites. Therefore, a careful selection of fibres and their optimum content in concrete are essential factors for the efficient construction of impact resistant structures. Special fibre composites having high fibre volume between 3% and 20% named as slurry infiltrated fibre concrete (SIFCON) reported [Farnam, Moosavi, Shekarchi, Babanajad, Bagherzadeh (2010)] to show further improved energy absorption at high strain rates. Unlike FRC, short discrete fibres are preplaced in random orientations into the forms, then sand-cement rich flowable slurry is poured to infiltrate through voids between steel fibres. Superior mechanical properties than FRC, RCC and plain concrete, such as compressive, tensile, shear, and flexural strengths with extraordinary toughness values are obtained for SIFCON due to fibre interlocking mechanism. Experimental studies [Tham (2006); Dancygier, Yankelevsky; Hanchak, Forrestal, Young,. Ehrgott (2007)] were conducted to determine the penetration and perforation in RCC and concrete targets.

Hanchak, Forrestal, Young, and Ehrgott, (1992) have reported that light to moderate reinforcement has little effect in controlling penetration and scabbing. O'Neil . Neeley, and Cargile (1992) have adopted the use of very high strength mortar for impact resistance with inclusion of 1.5% to 3 % of steel fibres. But, no significant improvement in penetration resistance of targets was observed except minimizing the visual damage near impact point. Anderson, Watson, and Kaminskyj (1992) have also reported reduction of spalling and scabbing in specimens made of slurry infiltrated fibre concrete (SIFCON) with high fibre content (8-11%). However, penetration resistance did not improve. The reason for this behaviour of SIFCON targets has been reported to occur due to the absence of coarse aggregates. The existence of coarse aggregates in target contributes to penetration resistance not only by increasing dynamic strength of concrete at higher strain rates, but also by diverting the travel path of the projectile [Bindiganavile and Banthia (2002)]. Such diversions in the travel path of the short projectile occur due to the differences in strength and hardness between the coarse aggregate and mortar matrix. Luo Sun, and Chan (2000) have compared impact resistance of reinforced high strength concrete and high performance fibre reinforced concrete (HPFRC) targets having 7% to 10% fibres. They found that target made of HPFRC remained intact with minor cracks whereas reinforced high strength concrete targets disintegrated even with lower velocity impact. Hence, it is observed from the literature review that the high volume fibre inclusion alone is not sufficient for efficient impact resistance to short projectiles. Proper understanding of the functional requirements during impact resistance mechanism plays vital role in the selection and tuning of materials and their lay-up sequences for the development of high performance layered cementitious composite targets.

The researchers Quek, Lin, and Maalej (2010), have applied functional grading of materials to enhance the impact resistance of the layered cementitious targets. They have conducted experiments on layered cementitious composite panels with fibrous-ferrocement in front and back faces and after front layer tough aggregates layer and thicker mortar core layer for short projectile impact resistance. It was reported that in layered composite target the main role of material in core layer is to counter impact effect by inertial forces. Hence, a modified concrete with adequate fracture toughness and presence of coarse aggregates is essential. They concluded that an aggregate core layer helps in stopping short projectile impact. But severe cracking seems to occur in core layer under single hit of non-deformable steel projectile leading vulnerability to further hits.

Kustermann, Karl-Christian, Christian, Manfred, Rupprecht (2009) have studied various combinations of materials like marbles, glass and steel pebbles, ceramic and strong aggregates to provide tough layers on front and HSFRC rear face. It was concluded that the presence of hard and shatter resistant materials on the front face provided best results. However, it was observed that after single hit hard pebbles got detached from front face of the panels leading to vulnerability of panels for repeated hit.

Latex-modified concrete (LMC) is reported [Barluenga and Hernandez-Olivares (2004); Allan (1997)] to have better impact resistant properties in comparison with conventional mortar and concrete. Experimental investigation [Zai, Prasad, Gupta, Munirudrappa, and Muthumani, (2010)] reported better impact behaviour of latex modified steel fibre reinforced concrete beams. Due to improved impact performance of LMC, it is considered as a suitable material as compared to aggregate and plain concrete, especially in core layer of layered composite panels. Hence in the present study LMC is used in core layer to achieve reduction in fibre content without affecting impact performance of layered SFRCC panels.

From the review of recent literature it is inferred that the construction of layered cementitious composite panels requires both, judicious selection of material and their appropriate lay-up sequence. It is obvious that suitable materials, tuned to cater various material phase (i.e. Hydrodynamic, plastic and elastic) dependent strength requirements, perform well during impact resistance. Hence, the concepts reported in literature about the requirements of materials and high velocity impact damage modes in layered cementitious composite target panels are duly considered. In this paper three types of layered composite panels are tested under normal impact of short projectiles having calibre 5.56 mm and 7.62mm.

The impact performances of the layered SFRCC panels with core layers namely, SIFCON (10% fiber by volume), LMC and wiremeshed reinforcement are relatively compared. Depending on the material used in face (front and back) and core layers, the SFRCC panels are designated as SSS, SLS and SWS as shown in Figure1. In order to determine residual impact resistance of the target panels after first hit, similar panels are tested under two to three additional hits near the previous hits.

Influence of variation in steel fibre volumes (0, 2, 4, 6, 8, and 10%) on impact performance of 100 mm thick SSS type panels is also investigated. Empirical expressions are proposed for depth of penetrations, crater diameters and crater depths due to impact of both the projectiles. The proposed empirical expressions for depth of penetration of 7.62 mm projectile in layered SFRCC panels are found to match well with the existing formulae [Bangash (1993)] for concrete targets given by Army Corps of Engineers (ACE) and National Defence Research Committee (NDRC).

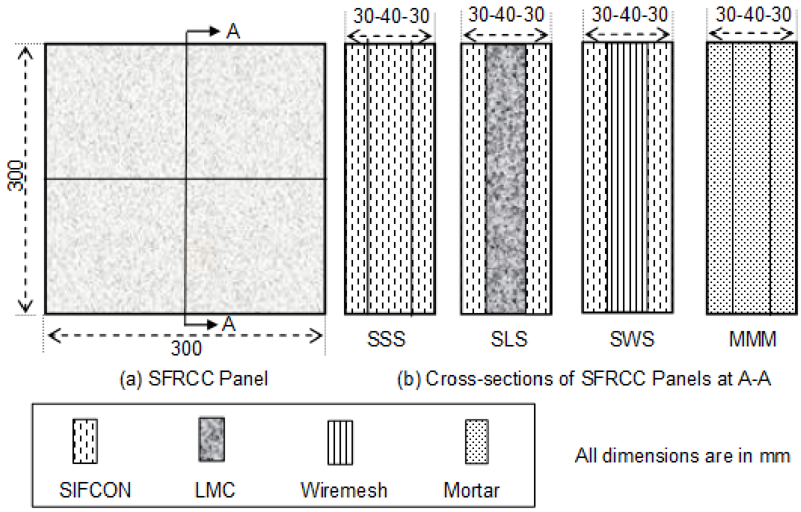


Figure 1: Details of infill layer arrangements in SFRCC panels.

The main objective of this paper is to study the impact behaviour of layered SFRCC panels through experimental investigations. Panels are prepared considering requirements like suitable energy absorbing materials, lay-up sequence, materials with matching acoustic impedance for smooth stress wave propagation through the layers. High velocity impact tests are conducted in reasonably controlled environment where the munitions as well as ammunitions are kept common for all the impact tests. Besides this the distance of shooting, angle of impact and boundary conditions are kept same during impact tests. Impact performances are assessed relatively based on both destructive and non-destructive tests. The results are compared with the existing empirical relations for depth of penetrations. The results of experimental investigations on layered SFRCC panels show excellent impact resistance even under multi-hit situations.

The present paper is organized mainly in four sections. Details of the experimental study including mechanical properties of materials used in preparation of the SFRCC panels, impact test set up and procedure of impact tests are described in section 2. The results of experimental investigations on layered SFRCC panels are discussed in section 3. Conclusions drawn based on the experimental investigations are provided in section 4. A brief explanation of the concepts behind the selection of material and layering arrangement in the SFRCC panels used in the present study is provided in appendix (A).

2 Experimental Study

An experimental study is conducted on layered SFRCC panels to understand the high velocity impact behaviour. In order to have a realistic assessment of impact performances of the panels, in-service munitions (INSAS and AK-47 rifles) and ammunitions (5.56 mm and 7.62 mm calibre projectiles) are used. The impact tests are conducted in reasonably controlled conditions. The distance of shooting point is kept 25 m primarily from safety consideration, so that no fragment after spalling can hit back the shooter and aiming becomes easier. Since far-off target distance may cause drop in the muzzle velocity of the projectile, hence it is avoided. It is worth mentioning here that the in-service weapons and ammunitions, time of tests and boundary conditions, support stand etc. are not changed during impact testing of the panels.

The plan dimensions (300 x 300 mm) of 100 mm thick layered SFRCC panels (Figure1) are chosen based on consideration of ease in handling and, also as per the empirical expressions for concrete in existing literature. Three types of layered SFRCC panels are investigated in this study. They consist of SIFCON with 10% volume of fibre (with hooked end steel fibre 30 mm long and 0.45 mm diameter i.e. aspect ratio about 66) in outer layers in order to avoid spalling and scabbing at front and rear faces of the panels. The first type of SFRCC panels is named as 'SSS' and shown in Figure 1. The SSS type of panels consists of SIFCON in all the three layers. It is basically considered to maintain zero impedance mismatches at the interfaces (refer Figure A.2).

To study the effect of fibre content on impact resistance in 100 mm thick SSS type of panels, varying fibre volumes namely; 2, 4, 6, 8, and 10% are also considered as a parametric study. The second type of SFRCC panels are named as 'SLS' due to its core layer of LMC keeping face layers same as of SIFCON. It is basically considered to reduce the fibre content in SFRCC panel by having minimum impedance mismatch (Table 4) between adjacent layers. In addition to this, the energy absorption of LMC is better than the plain concrete, and, water absorption is also much lesser than normal concrete. These engineering properties of LMC provide great help in achieving better bond at interfaces than normal concrete. The third type of SFRCC panels is named as 'SWS' due to its core layer having reinforcement in mesh forms. The reason behind selection of wiremesh and weldmesh embedded in slurry the as core material is, to compare the impact behaviour of steel reinforcement in meshed form, to that with the randomly distributed discrete fibre reinforcement as in the case of SSS type panel.

Table 1: Materials used in SFRCC panels.

Name of material	Details	Remarks
Steel fibre	MSH4530 (30 mm long and 0.45 mm dia. and aspect ratio as 66.66)	Hooked end 
Steel wiremesh	290 x 290 mm with mesh size 3 mm	Wire diameter = 0.45 mm
Steel weldmesh	290 x 290 mm with mesh size 25 mm	Wire diameter = 2.34 mm
Cement	OPC 53 grade	
Coarse aggregate (passed 12 mm sieve size and retained on 4.75 mm size)	Specific gravity 2.70 Bulk density =1890 kg/m^3	Fineness modulus = 3.60
Fine sand (below 4.75 mm sieve size)	Sp. Gravity 2.68	Fineness modulus = 2.76
	Bulk density 1685 kg/m^3	
Super plasticizer	(CONPLAST SP430)	Sulphonated Napthalene Formaldehyde
Mix for slurry (Cement: sand: W/C: Super plasticizer)		
	1: 1: 0.4: 0.5 (SP% by weight of cement)	

Finally, a type of control panel with plain cement mortar (Slurry) without any reinforcement is fabricated and named as MMM. It is prepared simply to have an idea about the unreinforced panel behaviour under impact of short projectile. A brief description of materials used in the preparation of SFRCC panels and mix proportions of cement sand slurry are given in Table 1.

The material quantities used for cement sand slurry and LMC as per design mix are given in Table 2.

The quantities of materials shown in Table 2 are given with respect to each batch of mix, considering the capacity (that is 50 kg load) of pan type concrete mixer used in the study.

Table 2: Quantities of materials.

Materials	Plain Slurry	LMC
Cement OPC 53 grade (kg)	20	10
Fine sand (2.36 mm and below) (kg)	20	17.66
Coarse aggregates (12mm and below) (kg)	nil	22.88
Water (L)	8.0	3.4
Nitobond SBR (Styrene-Butadiene Rubber) (mL)	nil	600
Super Plasticizer CONPLAST SP430, (0.5%) (mL)	100 ml	nil
Mix proportion for LMC is 1 : 1.35 : 2.19 plus 6% by weight of water replaced with SBR liquid		

The engineering properties namely, average density, UPV, modulus of elasticity uniaxial tensile strength and uniaxial unconfined compressive strength, for the materials (i.e. SIFCON, LMC and Plain slurry) used in the present study are determined as per standards [ASTM Standard C39 and JSCE-SF4]. These strengths of materials obtained after 28 days of the casting of the specimens as given in Table 3.

Table 3: Material properties

Percent of fibre	Average density	Ultrasonic pulse velocity	Modulus of elasticity	Uniaxial tensile strength (f_t)	Unconfined compressive strength (f_c)
%	Kg/m^3	m/s	GPa	MPa	MPa
Plain slurry- 0 %	2265.5	4000.0	31.57	3.14	59.6
SIFCON-2 %	2358.8	4110.1	36.43	5.10	60.2
SIFCON-4 %	2458.5	4130.7	36.56	12.19	74.6
SIFCON-6 %	2568.8	4285.7	37.97	16.11	85.6
SIFCON-8 %	2623.4	4327.1	39.94	17.42	98.4
SIFCON-10 %	2638.4	4137.6	41.55	18.42	106.2
LMC	2488.2	4761.9	42.72	4.95	71.0

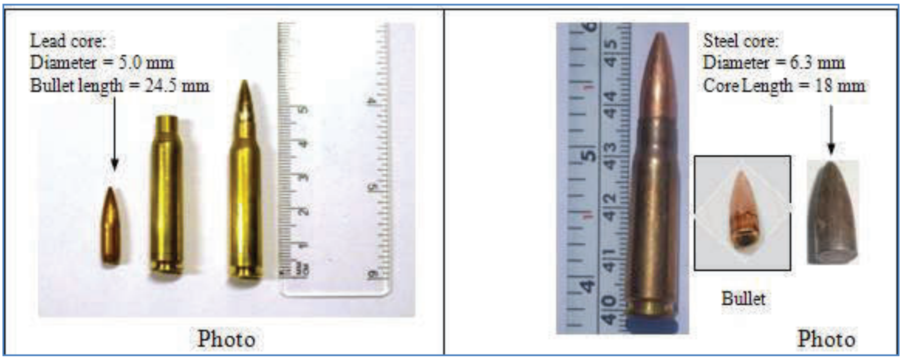
Table 4: Data related to acoustic impedances for LMC and SIFCON.

Material	Density (ρ) kg/m^3	Sound velocity(c) m/s	Acoustic impedance (ρ.c) MRayls	Impedance mismatch, I	R
SIFCON	2638.4	4137.6	10.92	0.0017	0.9213
LMC	2488.2	4761.9	11.85		

2.1 Projectiles used

An important issue in the study of impact behaviour of SFRCC panels is the consideration of actual munitions for impact tests. In practical situation impact resistant structures are subjected to attack using in-service weapons and actual ammunition rounds (projectiles). These in-service projectiles composed of thin metal jacket (0.3 mm to 1.5 mm thick) and a core made of either soft material like lead or hard metal like steel or Tungsten etc. However, the projectiles used in most of the laboratory experiments are usually homogenous projectile made of high strength steel [Irenmoger (2010)]. Due to this reason the empirical formulae reported [Bangash (1993)] for the non-deformable projectiles result into an overestimate of depth of penetrations as compared with in-service projectiles. The behaviour of metal jacketed projectiles with Lead core is explained by Borvik and Dey (2009). It has been demonstrated by them that on impact the soft core undergo mushrooming and breaks down. Due to very high temperature and pressure the core gets fractured and comminuted with target material. On the other side the metal jacket gets deformed under very high strain rate loading. As the projectiles tries to penetrate into the target its deformed metal jacket pieces starts spraying backwards. They have also reported that due to high kinetic energy, the projectile penetrates into target and eventually gets destroyed. Projectiles used in the present study are shown in Figure2.

The mass of 5.56 mm calibre projectile is determined as 4.16 ± 0.10 g. For full metal jacket (FMJ) projectile of 5.56 mm calibre, the jacket is made of cartridge brass (70% C_u and 30% Z_n) and solid core of Lead. For 7.62 mm projectile the mass is obtained as 8.0 ± 0.20 g. For full metal jacket (FMJ) projectile of 7.62 mm calibre jacket is made of gilding copper (95% C_u and 5% Z_n) and solid ogive nosed core of steel.



5.56 mm calibre 7.62 mm calibre

Figure 2: Geometric details of projectiles.

2.2 Preparation of SFRCC panels

A steel mould having four partitions [Figure 3(a)] which is able to cast four panels at a time is placed over vibrator table. All the air gaps are plugged with plaster of Paris to avoid any leakage of slurry during casting. A thin coating of lubrication oil is applied on the inner surfaces of the mould for easier demoulding.

Cement-sand slurry having designed mix proportions is prepared using pan type mixer [Figure 3(b)]. It is then poured in the moulds, first up to a thickness of about 5 mm, after that steel fibres are distributed randomly over the slurry layer in the steel mould as shown in Figure 3 (c). Manual tamping of fibre is carried out with steel tamping rods such that entire fibres get embedded in slurry layer. To achieve a uniform fibre distribution across the SSS type panel thickness of 100 mm, the fibres are spread in 18 layers changing the orientation each time in order to achieve approximately uniform spread of fibres. This will contribute to minimize honeycomb formation.

Besides this, the orientation of fibres is also changed within each layer by varying the hand stroke direction while placing the fibres. This process of slurry pouring and the steel fibres placement continued alternatively till entire thickness of panel is attained as shown in Figure3 (d).

In case of the infill layer of LMC, the procedure is altered slightly. First the moulds are marked for the 30 mm and 70 mm levels using permanent marker and then SIFCON layer upto 30 mm thickness is cast using the procedure explained earlier. Immediately LMC mix is poured over the SIFCON layer up to the mark of 70 mm with proper compaction using vibrator table. The surface of the LMC layer is

a) Steel mould b) Pan Mixer c) Distribution of fibres d) Casting of panels

e) Wiremesh f) Weldmesh g) Control specimens

Figure 3: Preparation of SFRCC panels.

roughened with hatching to obtain good bond with the outer SIFCON layer. Then a time gap of about 2 hours is provided to allow for final setting of the LMC core layer. Remaining 30 mm thick layer of SLS type panel is then cast with SIFCON.

In case of SWS type of panels first the SIFCON layer of 30 mm was cast in similar manner as explained for SSS and SLS type panels. Then the core layer is casted with wire meshes [Figure 3 (e)] and weld meshes [Figure 3 (f)]. While the SIFCON layer was still fresh, three wire mesh pieces of sizes (290 mm x 290 mm) and then one weld mesh pieces of same size are laid up over the SIFCON layer and then slurry was poured to embed these meshed reinforcement layers. This process is repeated until the thickness of 70 mm mark is reached.

Later beyond 70 mm mark fibres and slurry are again distributed without any time delay to complete the outer SIFCON layer. After 24 hours of the casting of these panels, the demoulding of both the SFRCC panels and control specimens for material strength testing is carried out. These demoulded specimens [Figure 3(g)] are then transported to curing tank. Curing was carried out by submerging the SFRCC panels as well as control cylinder and cube specimens in the water tank. After 28 days of curing, the SFRCC panels are removed from water tank and kept for drying. Then surfaces of the panels are painted white and designated with different panel IDs namely, SSS, SLS, SWS and MMM based on infill material. The description related to each panel square in plan as designated with respect to the layer arrangement shown in Figure 1 is given in Table 5.

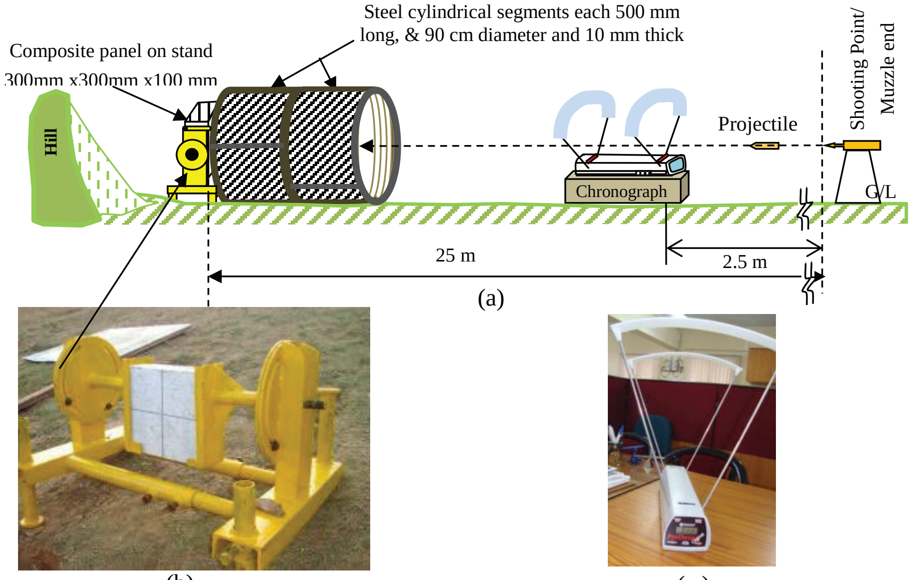
Table 5: Details of the SFRCC panel designations.

Designation of Panels	Projectile calibre	Layering thickness (mm)	Material in layers		Total Panel thickness (mm)
Total no. of panel # ID-% Fiber volume	mm	(Front-Core-Back)	Face layers	Core layer	
1# SSS-10%	5.56	0-50-0	SIFCON	SIFCON	50
1# SSS-10%	7.62	0-50-0	SIFCON	SIFCON	50
3# SSS-2%	5.56	30-40-30	SIFCON	SIFCON	100
3# SSS-4%	5.56	30-40-30	SIFCON	SIFCON	100
3# SSS-6%	5.56	30-40-30	SIFCON	SIFCON	100
3# SSS-8%	5.56	30-40-30	SIFCON	SIFCON	100
3# SSS-10%	5.56	30-40-30	SIFCON	SIFCON	100
3# SSS-2%	7.62	30-40-30	SIFCON	SIFCON	100
3# SSS-4%	7.62	30-40-30	SIFCON	SIFCON	100
3# SSS-6%	7.62	30-40-30	SIFCON	SIFCON	100
3# SSS-8%	7.62	30-40-30	SIFCON	SIFCON	100
3# SSS-10%	7.62	30-40-30	SIFCON	SIFCON	100
3# SLS-10%	5.56	30-40-30	SIFCON	LMC	100
3# SLS-10%	7.62	30-40-30	SIFCON	LMC	100
3# SWS-10%	5.56	30-40-30	SIFCON	Wiremesh	100
3# SWS-10%	7.62	30-40-30	SIFCON	Wiremesh	100
1# MMM-0%	5.56	30-40-30	Plain slurry	Plain slurry	100
1# MMM-0%	7.62	30-40-30	Plain slurry	Plain slurry	100
#SIFCON consists of MSH4530 type mono-fibre only					
# LMC of grade M 60 with 6% SBR dosage					

2.3 Impact Tests

Typical set-up used for conducting high velocity impact tests on SFRCC panels is shown in Figure 4(a). A customized panel holder cum stand is fabricated with steel [Figure 4(b)] to hold SFRCC panel during impact tests. A battery (9V Alkaline) operated digital chronograph [Figure 4 (c)] is used for the measurement of projectile's velocity during impact tests. It is specified to measure velocity in the range of 7 m/s to 2130 m/s with an accuracy of ±1%. The velocities for 25 shots of each type of projectile are measured. The mean and standard deviations of projectile velocities in unit of meter per second are determined statistically for 5.56 mm calibre projectile as 891(mean) ±11.52(Standard deviation) and similarly for 7.62 calibre projectile as 721(mean) ± 14.21(Standard deviation). Accordingly the corresponding kinetic energy of 5.56 mm and 7.62 mm calibre projectile are calculated as 1.7 kJ and 2.1 kJ respectively.

Before, conducting the impact tests, the levels and orientations of panel and the stand were checked. Positions for firing points were marked on ground at a distance of 25 m. High velocity impact tests have been conducted using in-service ammunitions and the weapons. All the experiments were conducted in controlled conditions by keeping weapons, projectiles, muzzle distance, test setup to hold the panels unchanged. Initially panels of each type were tested under single hits and then measurements were taken for determining first hit responses (Figure 5). The depth of penetration, crater dimensions and cracking status was recorded. Later to determine the impact resistance of similar panels under multi-hit scenario two to three additional impacts were made on the same panel, closer to the previous hits. The visual observations are recorded and measurements of DOP and crater diameter are documented.



(a)

(b)

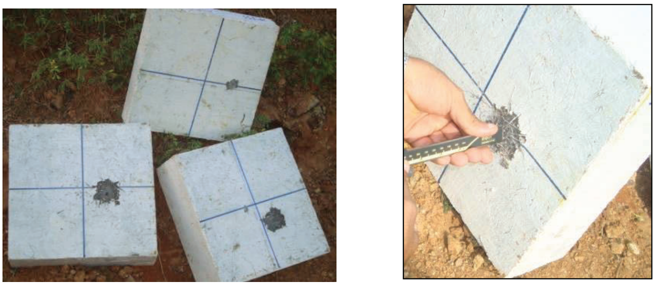
(c)

Figure 4: Impact test (a) Test set-up (b) Fabricated panel holder (c) Digital chronograph.

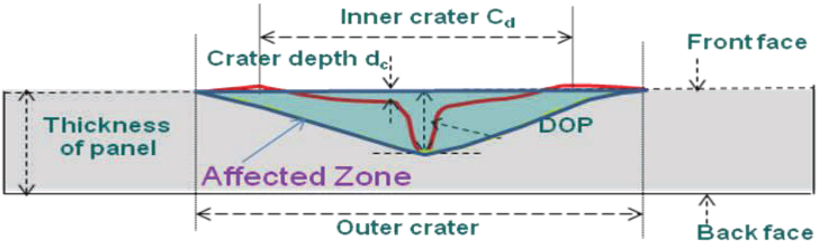
Impact more than once, near to the previous hit is considered as multi-hit in the present paper. Multi-hit is defined in this paper based on the scenarios as, (i) when the craters formed on the surface for any two hits overlap fully or partially on each other, or (ii) when the sub-surface damage zone caused by a hit intersects with the damage zone due to any of the previous hits.

It is noted that the visible crater sizes on surface of panel are smaller than the damage zone below the surface of SFRCC panel as depicted in Figure 5(e). It is noted that even well separated craters on the surface of panel may be intersecting with neighboring sub-surface damage zones.

(a) Front face (b) Back face



(c) Tested Panels after single hit (d) Measurements



(e) Definition of impact response measurements

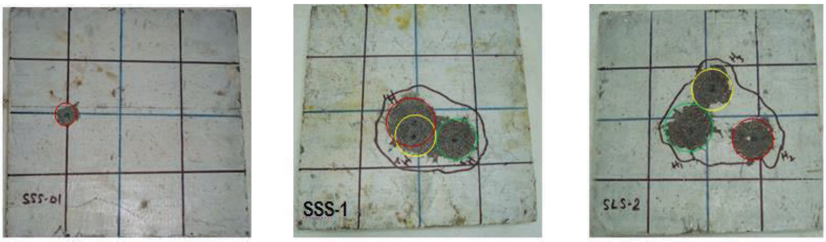
Figure 5: SFRCC panels after first hit.

3 Results and Discussions

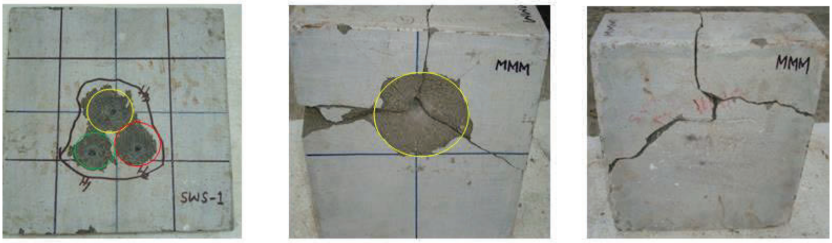
The results of impact tests on SFRCC panels are discussed based on the measurement of depth of penetration, crater depth and crater dimensions. Visual inspection is also carried out for determining the final status of the panels in terms of cracking and delamination. The following observations are made after investigations on impact tested of the SFRCC panels:

3.1 Visual inspection on impact tested SFRCC panels

Crater sizes on front face of the SFRCC panels after the multi-hits within the damaged regions of previous hits are shown in Figure 6. The SFRCC panel with 50 mm thickness is hit only once with 5.56 mm calibre and it was perforated without any fragmentation. Whereas the MMM type panel got fragmented under single hit of 5.56 mm projectile. The diameter of crater formed in MMM type panel due to single hit is almost twice the crater diameter formed in SSS, SLS, SWS type panels. Impedance matching is only one of the conditions for smooth propagation of shock waves through the materials. Necessarily there is a need for tensile strength and energy absorption both of which are absent in case of MMM. Hence it shows large crater on the front face, and fragmented into large size pieces.



SSS-01 = 22.7 mm SSS-1 = 50 mm SLS-2 mm = 45 mm



SWS-1 = 47.5 mm MMM (front face) = 80 mm MMM (Back face)

Figure 6: Crater diameters on front face in few of the tested SFRCC panels (Photos).

1. It is observed from Figure 7 that the SFRCC panels designated as SSS have shown no cracking except the spalling on the front face at locations where projectile hit. Hence the concept of no impedance mismatch holds true as demonstrated by SSS type panels, where no well defined interface exists within the panel.

   Thus the entire material (SIFCON) in SSS type panels exhibited impact performance like a homogenized material at macro scale. It is also noted that the panels have maintained better structural integrity even though the hits are made closer to the previous hits rather within overlapping damage zones of previous hits. The SSS type panels with 10% fibre volume show better impact performance.

Front faces

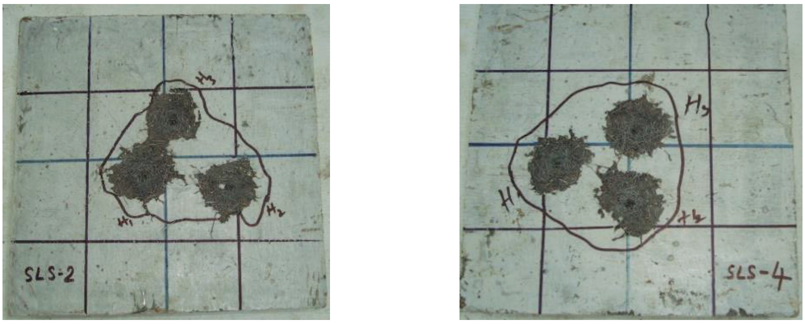
Back faces

Figure 7: Final damage in SSS type panel under three hits.

2. Interface crack locations in the edge faces of SLS type panels appear at the nearer interface with respect to front face. Even though sufficient care was taken to establish good bonding between top SIFCON layer and middle LMC layer, minor cracking could not be avoided. It is obvious that the interface nearer to front face (I/F1-2) subject to severe impulse and the crack appears there as visible on edge faces (Refer Figure A.1and Figure 8). Whereas rear

(far) interface (I/F2-3) subjected to the impulsive forces on a wider area as compared to front (near) interface. It means that the entire kinetic energy of the projectile get dissipated in spalling and cracking at front face. In the SLS type panels interface cracks on the edge faces in addition to the front spalling are observed.

However the maximum interface crack widths measured are less than 1mm. Since the stresses developed by impulsive force due to impact is much higher than the tensile strength of the material the spalling takes place. With proper layer arrangement, the crater size is reduced to almost half as compared to that in panel made of plain concrete.



Front faces

Back faces

Edge faces

Figure 8: Damage in SLS type panel.

3. The SWS type panels consist of infill layers having wire meshes embedded in

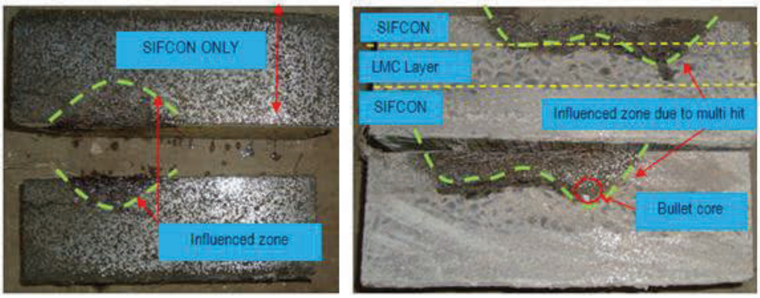
high strength slurry. It can be observed that SWS panels exhibited interface cracks on the edge faces as shown in Figure 9.

Location of cracking at edge face is shifted towards mid plane of panel. However in case of welded mesh interface bond becomes an important issue leading to slip of wire mesh. Therefore, cracking at the mid plane along the periphery is due to bond-slip between meshed reinforcement layers.

Front faces Back faces

Figure 9: Damage in SWS type panels.

To measure internal damages zones, few of the tested composite panels are cut across the thickness using concrete cutting machine. The cross-sections of SFRCC panels after cutting are shown in Figure 10. It is noted that there is no visible cracking in the core layers. It is also found that well separated surface craters due to multi hits get overlapped internally.



(a) SSS type (b) SLS type

Figure 10: Cross-sectional views of SFRCC panels after cutting.

The maximum, minimum and average values of depth of penetrations and average craters diameter in SFRCC panels under first hits are measured using digital Vernier caliper and furnished in Table 6.

Table 6: Results of high velocity impact test on SFRCC panels.

Designation of Panel	Projectile calibre	Depth of penetration (DOP)	Crater diameters	Total Thickness
ID	mm	mm	mm	mm
SSS-10% (2 Nos.)	5.56 7.62	50.0 (Perforated) 50.0 (Perforated)	22.7 (Average) 40.0 (Average)	50 50
SSS-10% (3Nos.)	5.56	31.60 (Max) 24.00 (Min) 27.10 (Average)	65.6 (Max) 48.3 (Min) 57.6 (Average)	100 100 100
SSS-10% (3Nos.)	7.62	41.91 (Max) 33.17 (Min) 38.36 (Average)	79.0 (Max) 53.6 (Min) 64.9 (Average)	100 100 100
SLS-10% (3Nos.)	5.56	33.10 (Max) 30.60 (Min) 31.72 (Average)	73.9 (Max) 48.3 (Min) 58.6 (Average)	100 100 100
SLS-10% (3Nos.)	7.62	48.08 (Max) 32.22(Min) 40.50(Average)	75.3 (Max) 52.5 (Min) 59.1 (Average)	100 100 100
SWS-10% (3Nos.)	5.56	33.04 (Max) 25.45 (Min) 28.66 (Average)	66.5 (Max) 49.8 (Min) 56.0 (Average)	100 100 100
SWS-10% (3Nos.)	7.62	49.70 (Max) 34.10 (Min) 40.10 (Average)	70.2 (Max) 51.2 (Min) 57.9 (Average)	100 100 100
1# MMM-1 1# MMM-2	5.56 7.62	Fragmented Fragmented	80.0 (Average) 115.0 (Average)	100 100

3.2 *Effect of fibre volume*

Results of SSS panels with varying fibre volumes indicate that the fibre volume less than or equal to 4% show cracking at the back face of panels. The crater dimensions do not vary much with fibre volume beyond 6%, but the depth of penetration does show reduction. Empirical expressions are being proposed based on the regression analysis of experimental data. The proposed expressions for depth of penetrations are compared well with ACE and NDRC formulae for concrete targets. Based on the results of impact tests on 24 numbers of specimens following empirical equations are proposed (Table 7).

Table 7: Proposed expressions based on tests for different volume of fibres.

Impact performance indicator	**For calibre 5.56 mm**	**For calibre 7.62 mm**
Depth of penetration (DOP)	$DOP = 75.538[V_f]^{-0.436}$ $R^2 = 0.9821$	$DOP = 58.505[V_f]^{-0.146}$ $R^2 = 0.9143$
Crater diameter (C_d)	$C_d = 84.758[V_f]^{-0.179}$ $R^2 = 0.9548$	$C_d = 79.386[V_f]^{-0.092}$ $R^2 = 0.9119$
Crater depth (d_c)	$d_c = 15.632[V_f]^{-0.231}$ $R^2 = 0.7155$	$d_c = 20.778[V_f]^{-0.238}$ $R^2 = 0.6628$

- The results furnished in this table are for first hit on the panels only.
- This table does not incorporate the cracking in the panels which is qualitative parameter. However it was observed that panel with fibre content 6% and above by volume did not showed any cracking on side face or back face except spalling on impact face.

3.2.1 Comparison of experimental and empirical formulae [Bangash, (1993)]

(a) Army Corps of Engineers (ACE) Formulae (SI Units)**:** For hemispherical nose N=1 but for ogive nose N=1.14. It can be applied for non-deformable projectile.

Depth of penetration:

$$X = \frac{NM}{12.61} \cdot \frac{1}{\sqrt{F'_c}} \left[\frac{V_0^{1.5}}{d^{1.785}} \right] + 0.5d \tag{1}$$

Where, M is mass of non-deformable projectile, F_c' is unconfined uniaxial compressive strength of concrete, d is projectile diameter, V_0 is impact velocity.

(b) NDRC Formula (SI Units)**:** The National Defense Research Committee formula also provides DOP for non deformable projectile impact on concrete. The depth of penetration is determined by following expression (2):

Depth of penetration:

$$X = \frac{1}{\sqrt{F'_c}} \cdot \frac{NM}{104} \left[\frac{V_0}{d} \right]^{1.8} + d \tag{2}$$

Parameters are same as in ACE formulae; N is nose shape factor which is 1.14 for ogive nose projectiles. Using experimental value and the expressions (1) and (2) for depth of penetration the values are compared well as shown in Table 8 and plotted in Figure 11.

Table 8: Comparison of empirical and experimental results.

Volume of fibre	Compressive strength of Fibre concrete F'_c	DOP (mm)			Cracking at back face or edge faces
		For 7.62 mm calibre			
%	MPa	ACE	NDRC	Experiment	
0	59.57	52.06	48.46	Fragmented	Yes
2	60.25	51.79	48.23	52.87	Yes
4	74.56	46.93	44.13	47.79	Yes
6	85.63	44.05	41.69	45.04	No
8	98.38	41.35	39.40	43.19	No
10	106.22	39.94	38.21	41.80	No
For mass M=8.0 g, V_0 =720 m/s, d =7.62 mm and, N =1.14, DOPs are calculated.					

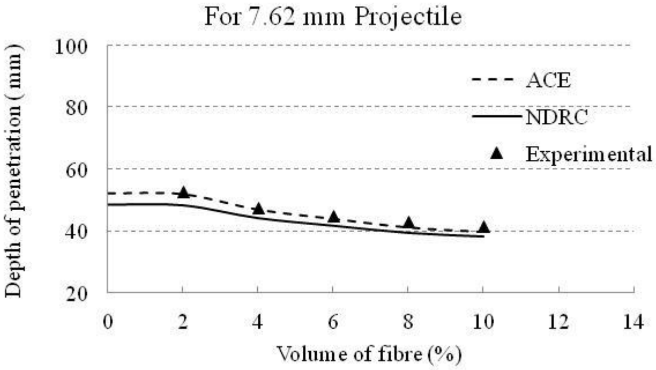


Figure 11: Comparison of experimental and empirical results for 7.62 mm Projectile.

4 Conclusions

In this paper result of an experimental study highlighting the impact tests on steel fibre reinforced cementitious composite (SFRCC) panels have been presented. It has been found from the study that the design of impact resistant structures requires understanding of both the suitable materials and physics of the phenomenon. For the design of layered composite panels the lay-up sequence of the materials to be used in the layers, needs judicious selection for obtaining better impact performance of layered SFRCC panels. It has also been observed that SFRCC panels exhibit desirable structural integrity even after multi-hits of short projectiles of 5.56 mm and 7.62 mm calibre. The following conclusions can be drawn based on the experiments conducted and presented in this paper:

- The concept for the selection of materials used in layers and lay-up sequence in SFRCC panels is explained. It is observed from the impact tests that the SSS type panel behave like homogenized material at macro level. Further no well defined interface occurs for SSS type panels.

- Neither fragmentation nor scabbing at the back face is observed in the SFRCC panels under multiple hits. Significant enhancement in impact resistance of the fibre reinforced composite panels is observed as compared to panels made of plain slurry.

- Reduction in steel fibre content is achievable upto 40% in SLS type as compared to SSS type panels by providing latex modified concrete (LMC) infill, without any considerable loss in impact resistance of proposed SFRCC panels.

- The SFRCC panels, in which LMC or wire meshes are used in core layer, showed fine interface cracks nearer to the front face upon impact. While the panel with LMC core layer exhibited only hairline interface cracks, the SWS type panels showed relatively wider interface cracks at the middle of core layer instead of at the interface with SIFCON layers.

- It is inferred from the comparison between meshed reinforcement and random fibre reinforcement that the matrix between the reinforcement meshes exhibit weaker zone to resist tensile stresses. Hence randomly distributed short steel fibres provide better impact resistance. However relatively more efforts are needed in the casting of short fibre reinforced layer of SFRCC panels than layers with meshed reinforcement.

- Under the impact of 7.62 mm calibre projectiles both DOP and the crater sizes are found to slightly increase as compared to 5.56 mm calibre projectiles.
- The values of depth of penetration determined experimentally and empirically are found to match closely for 7.62 mm projectile impact cases. The SSS type panels with the fibre volume lesser than or equal to 4%, exhibited predominant cracking at both the faces.
- It is found that ACE and NDRC expressions to calculate depth of penetration given for concrete can also be used for SFRCC as shown for SSS type panels. The empirical relations are proposed for both the calibres based on the regression analysis. However, proposed expressions for 7.62 mm projectile to determine depth of penetration (DOP) could only be compared with ACE and NDRC formulae. Because, 7.62 mm projectile have solid steel core whereas 5.56 mm projectile have soft Lead core and, both the expressions by ACE and NDRC consider rigid projectile only.

Acknowledgement: The help rendered by staff of Advanced Material Laboratory and Shock and Vibration Group, during casting the SFRCC panels is gratefully acknowledged. The help and co-operation given by Dr. J. Rajasankar, Head, and Dr. (Mrs.) N. Anandavalli, project leader, Shock and Vibration group, CSIR-SERC, in fabricating the moulds and technical discussions during the field firing experiments is gratefully acknowledged. The permission and facilities provided by authorities of Officers Training Academy (OTA), Chennai for impact tests is highly acknowledged. This paper is being published with kind permission of the Director, CSIR-SERC, Chennai.

Appendix A

A.1 Shock Wave Propagation in Layered SFRCC Panels

The physics of the shock wave propagation and influence of layers on its propagation during impact resistance is described in this section. It is important to consider materials such that smooth transmission of shock waves through the layers is facilitated, which avoids interfacial delamination. An important reason of choosing cementitious materials in the preparation of the layered SFRCC panels is to take advantage of cohesiveness of similar nature materials in achieving good interface bonds. The concept and considerations in the selection of materials for the preparation of SFRCC panels investigated in this study are briefly described in the next sub-section.

A.2 Effect of layers on shock wave propagation

Three main factors that influence the wave propagation [Zukas (2004)] are impedance mismatch, interface density, thickness ratio of layers. However, impact resistance of layered composite panel depends on the loading conditions, layering sequence, materials used, and the method of its fabrication or preparation. Explicit transient solutions for one-dimensional wave propagation behavior in multi-layered structures are presented by Lin and Ma (2011). They have developed an analytical method for constructing solutions in multi-layered media. The loading conditions depend on the geometry of projectile (bullet, pellet or ball etc.), impact angle and impact velocity. The shock wave propagation in layered medium like SFRCC panels is depicted in Figure A.1. When a projectile hits the target panel, shock wave is generated at the point of impact and propagates forward direction spherically as shown in Figure A.1. Once it meets the interface between two layers of different materials, there occurs both reflection and transmission of the stress wave depending upon the impedance mismatch. It is depicted through thinner lines that when shock wave propagates its attenuation takes place and as a result, it gets weaker.

For instance, shock wave [say ‘1’] undergoes through both transmission and reflection at the interfaces. The forward moving shock wave (solid lines) or transmitted wave exerts compressive force in material whereas after reflection either from stress free surface or interfaces, it becomes tensile wave (dotted lines). The interactions between transmitted and reflected shock wave continue till equilibrium state is attained by projectile and target panels. Such multiple interactions between the tensile and compressive shock waves cause interface cracks, spalling and scabbing in target. The impedance match between layers ensures effective utilization of the total depth leading to reduced tensile strength on reflection from rear. Reflections from layers of lesser thickness lead to sharper tensile pulse. Due to this reason optimum thickness of layers are used.

Impedance ratio R= $(\rho \mathrm{C})_{hard}/(\rho \mathrm{C})_{soft}$, where ρ and C represent mass density and velocity of sound in the medium respectively. The ‘R’ is a measure of impedance of hard layer over that of the soft layer; here ‘R’ is used to represent level of impedance mismatch and R ranges from 1 to ∞. The value of ‘R’ equal to 1, indicates that there is no impedance mismatch between layers. The relation between parameters, impedance mismatches I, and impedance ratio R, can be expressed as follows [Chen and Chandra (2004)]:

$$I = \left(\frac{R-1}{R+1}\right)^2 \tag{A.1}$$

Chen and Chandra [22] have reported that ‘I’ is better parameter than ‘R’ to represent impedance mismatch of two mediums. It is also clear from the curve plotted

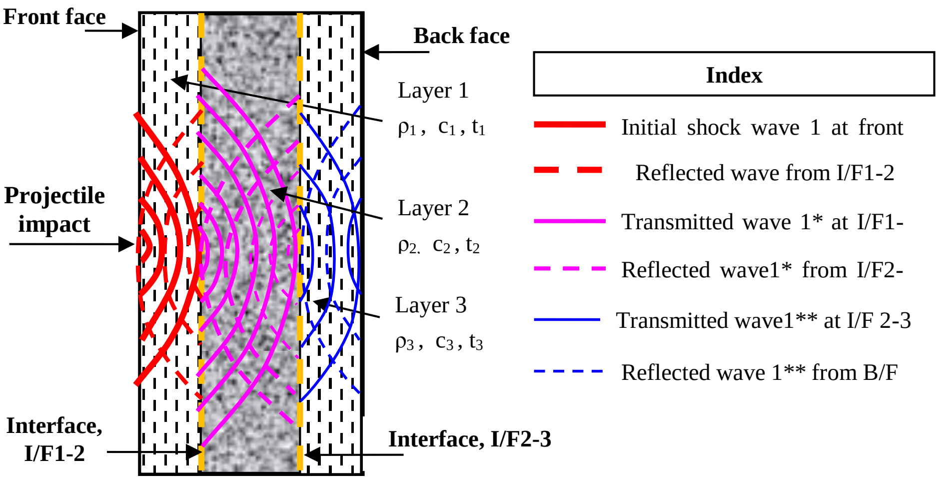


Figure A.1: Shock wave transmissions and reflections in layered SFRCC panel.

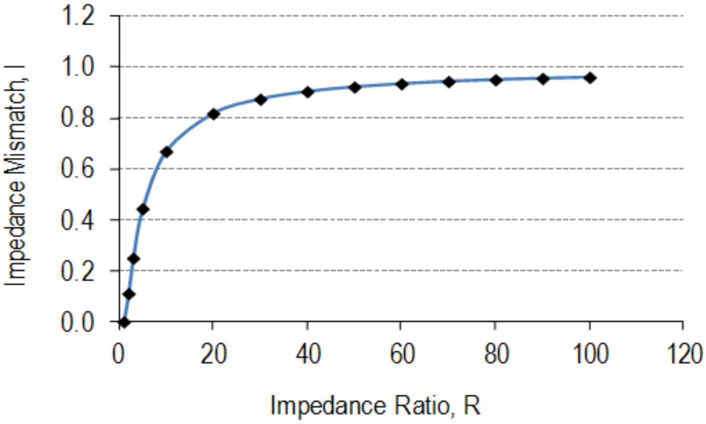


Figure A.2: Variation of I with respect to R.

using Eq. (1) as shown in Figure A.2.

It can be observed that when the impedance ratio R varies from 1 to 20, the corresponding change in ‘I’ is 0 to 0.82. Similarly, when R is varied from 20 to 100, I changes only from 0.82 to 0.961.

Delamination between layers takes place due to acoustic impedances mismatch between layers in composite panels. Hence, adequate efforts are made in the present paper to reduce the interfacial delamination by choosing the cementitious material having nearly equal acoustic impedances. In the layered SFRCC panels, interfacial bond between cementitious surfaces helps in exhibiting better performance under impact when compared to metal/cementitious interfaces. Using eqn. (A.1) for materials in adjacent layers such as SIFCON (with 10 % fibre) and LMC, it can be observed from Table 4, that the 'R' is near to 1 and, I is negligible. Therefore, the selected materials evince the condition for smooth propagation of shock wave at interface with minimum reflection.

References

ASTM Standard C39: Standard Test Method for compressive strength of cylindrical concrete specimens.

Allan, M. L. (1997): Rheology of Latex-Modified Grouts. *Cement and Concrete Research,* vol. 7.7, no. 12, pp. 1875-1884.

Anderson, W. F.; Watson, A. J.; Kaminskyj, A. E. (1992): The resistance of SIFCON to high velocity impact. *Second Intl. Conference on Structures Under Shock and Impact,* pp. 89-98.

Bangash, M. Y. H. (1993): *Impact and explosion-Analysis and Design.* Blackwell scientific publisher.

Barluenga, G.; Hernandez-Olivares, F. (2004): SBR Latex Modified Mortar Rheology and Mechanical Behaviours. *Cement and Concrete Research,* vol. 34, pp. 527–535.

Bindiganavile, V.; Banthia, N. (2002): Impact Response of Ultra-High-Strength Fibre Reinforced Cement Composite. *ACI Materials Journal*, vol. 99, no. 6, pp. 543-548.

Borvik, T.; Dey, S.; Clausen, A. (2009): Perforation resistance of five different high strength steel plates subjected to small-arms projectiles. *International journal of Impact engineering,* vol. 36, pp. 948-964.

Chen, X.; Chandra, N. (2004): The effect of heterogeneity on plane wave propagation through layered composites. *Mechanical & Materials Engineering Faculty Publications,* paper 57, (http://digitalcommons.unl.edu/mechengfacpub/57).

Dancygier, A. N. (1998): Rear face damage of normal and high-strength concrete elements caused by hard projectile Impact. *ACI Structural Jl.,* vol. 25, pp. 291-303.

Dancygier, A. N.; Yankelevsky, D. Z. (2007): Response of high performance concrete plates to impact of non-deforming projectiles. *Int J Impact Eng,* vol. 34, pp. 1768-1779.

Farnam, Y.; Moosavi, M.; Shekarchi, M.; Babanajad, S. K.; Bagherzadeh, A. (2010): Behaviour of slurry infiltrated fibre concrete (SIFCON) under triaxial compression. *cement and concrete research,* vol. 40, pp. 1571-81.

Hanchak, S. J.; Forrestal, M. J.; Young, E. R.; Ehrgott, J. Q. (1992): Perforation of concrete slabs with 48MPa (7 ksi) and 140MPa (20 ksi) unconfined compressive strength. *Int J Impact Eng;* vol. 12, No.1, pp. 1–7.

Iremonger, M. J. (2003): *Disruption of small Arms bullet using thin metal plates*, Proceedings of 11^{th} international symposium on interaction of the effects of munitions with structures, Mannheim, Germany.

JSCE SF-4: Method of test for flexural strength and toughness of fibre reinforced concrete.

Kim, J. K.; Mai, Y. W. (1998): *Engineered interfaces in fibre reinforced composites*, Elsevier Science Ltd.

Kustermann, A.; Karl-Christian, T.; Christian, B.; Manfred, K.; Rupprecht, Z. (2009): *Protection elements made of High Strength Fibre Reinforced Concrete (HSFRC) as single and multi layer constructions*, 12^{th} Intl. Symposium on Interaction of the Effects of Munitions with Structures, University of the Armed Forces, Munich Institute for Building Materials Andrea.

Lin, Y. H.; Ma, C. C. (2011): Transient Analysis of Elastic Wave Propagation in Multilayered Structures. *Computers, Materials & Continua*, vol.24, no.1, pp.15-42.

Luo, X.; Sun, W.; Chan, S. Y. N. (2000): Characteristics of high-performance steel fibre-reinforced concrete subjected to high velocity impact. *Cement and Concrete Research,* vol. 30, pp. 907-914.

Maalej, M.; Quek, S. T.; Zhang, J. (2005): Behaviour of hybrid-fibre engineered cementitious composites subjected to dynamic tensile loading and projectile impact. *Jl. of Materials in Civil Engineering,* vol. 17, pp. 143-152.

Naaman, A. E.; Otter, D.; Najm, H. (1992): Elastic modulus of SIFCON in tension and compression. *ACI Material Jl.,* vol. 88, pp. 540–548.

O'Neil, E. F.; Neeley, B. D.; Cargile, J. D. (1992): Tensile Properties of very high strength concrete for penetration-resistant structures. *Shock and Vibration,* vol. 6, pp. 237-245.

Quek, S. T.; Lin, V. W. J.; Maalej, M. (2010): Development of functionally-graded cementitious panel against high-velocity small projectile impact. *Int J Impact Engineering,* vol. 37, pp. 928-941.

Shah, A. A.; Ribakov, Y. (2011): Recent trends in steel fibred high-strength concrete. *Materials and Design,* vol. 32, pp. 4122–4151.

Soe, K. T.; Zhang, Y. X.; Zhang, L. C. (2013): Impact resistance of hybrid-fiber engineered cementitious composite panels. *Composite structures*, vol. 104, pp.

320-330.

Tham, C. Y. (2006): Numerical and empirical approach in predicting the penetration of target by an ogive-nosed projectile. *Finite element in analysis and design*, vol. 42, pp. 1258-68

Zai, S. A. K.; Prasad, G. L. E.; Gupta, N. K.; Munirudrappa, N.; Muthumani, K. (2010): Impact Behavior of SBR-latex Modified Fibre Reinforced Concrete Beams, Proceedings of the IMPLAST 2010 Conference October 12-14 2010 Providence, Rhode Island USA.

Zukas, J. (2004): *Introduction to Hydrocodes*, Elsevier B.V., Amsterdam, The Netherlands.