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Steel fiber reinforced concrete panels subjected to impact projectiles with different caliber sizes and muzzle energies

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ABSTRACT

In special situations like terrorist attacks, concrete structures are occasionally subjected to impact loads such as firearms. Since concrete is brittle, it often shatters into several pieces under impact loadings. In order to alleviate this brittleness, fibers are generally incorporated into concrete. In this study, steel fiber reinforced concrete panels subjected to projectile impact loads with different geometries was investigated. The impactors in the form of bullets came in three different caliber sizes 9, 11, and 7.62 mm, providing muzzle energies of 468, 1972, and 3259 J, respectively. Hooked end type steel fibers were used at 3 vol fractions of 1–3%. The specimens were cast in square panels with dimensions of 400 × 400 mm and varying thickness from 10 to 100 mm. Each panel was subjected to a single impact at the center. Data in the form of velocity (prior to and after impact event), failure modes, and spalling diameters were collected. Results showed that four typical failure modes were commonly found in panels: perforation, scabbing, spalling, and cracking. For piercing type bullets, the thickness played an important role on the impact resistance of the panels. However, for large and blunt tip bullets, both thickness and fiber volume fraction must be considered together to provide sufficient impact resistance.

1. Introduction

A firearm refers to a portable handheld gun capable of driving a bullet in a projectile path to a target by highly expansive pressure gas resulting from the chemical exothermic combustion of propellant within a cartridge [1]. Wide varieties of firearms can be classified by barrel length (hand gun, rifle), barrel type, loading mechanism (automatic or manual), firing mechanism, bore diameter, or caliber size, etc. The main function of a firearm is to ignite the gun powder, thus creating pressure to push out a bullet (a projectile) down the barrel and out of the muzzle. Bullet size can be classified by diameter or caliber. After ignition, a bullet turns into a kinetic projectile with different muzzle energies and velocities ranging from subsonic to supersonic levels (120–1200 m/s) [2].

Under an attack by firearm, concrete structures may experience different types of failure modes such as, complete fracture, perforation (full penetration), penetration, scabbing, spalling, or cracking. Among them, the perforation mode can

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cause the most serious damage and must be considered carefully. For any bulletproof element, a minimum protection requirement is that it must also be able to prevent perforation or damage from perforation.

Concrete is a brittle material, and to improve its brittleness small fibers may be mixed and distributed uniformly in it. The effect of fiber bridging across the cracks can help increase ductility and prevent catastrophic failure. Fiber reinforced concrete (FRC) is also known to provide excellent impact resistance [2–6].

For a certain type of impact force, such as projectile impact, some studies have been carried out to investigate the resistance of FRC to projectile impact force. Zhang et al. [7] tested projectile impact resistance of plain and steel fiber reinforced high strength concrete using a 12.6 mm ogive nose projectile at velocities ranging from 620–700 m/s. They found that incorporation of steel fibers in the concrete could reduce crater diameter and crack propagation. Luo et al. [8] used an armor piercing impact head with diameter of 37 mm to test on high strength reinforced concrete (RHSC) and high-performance steel fiber reinforced concrete (HPSFRC). The impact velocity of about 365–378 m/s was used in their test. Their results showed smash failure in the RHSC targets while the HPSFRC targets remain intact with several radial cracks on the front faces. Almusallam et al. [9] used a bi-conic impact head with diameter of 40 mm travelling at a subsonic level velocity of 300 m/s. The targets included plain and hybrid (steel and polypropylene) fiber reinforced concrete slabs. They concluded that the existence of fiber in concrete led to smaller crater volumes and reduction in spalling and scabbing damage.

Sukontasukkul et al. [10,11] tested double layer concrete panels made of rubberized and steel fiber reinforced concrete subjected to impact projectiles of 9 mm and 11 mm bullets with muzzle velocity of 362 and 270 m/s, respectively. The test results showed that the insertion of a soft material (rubberized concrete) layer helped absorb part of the impact energy and allowed less impact force to reach the FRC layer. Maho et al. [12] tested multilayer SFRC panels with a rubber sheet insertion subjected to 9 mm FMJ bullet with muzzle velocity of 398 m/s. They concluded that, in order to prevent perforation, the impact energy absorption of the panel must be equal or higher than the impact energy of the bullet. The incorporation of rubber sheet insertion helped in trapping bullets and prevented ricocheting.

Based on the above literature reviews, most ballistic tests on cementitious materials were carried out using projectiles with velocity ranging from 270 to 700 m/s. There is still a lack of information in projectile with velocity higher than 700 m/s. This study was intended to fill the gap of such information by using bullets with velocity up to about 842 m/s (muzzle energy of 3259 J).

In this study, the impact resistance of fiber reinforced concrete panels subjected to impact projectiles with different muzzle energies was investigated. Three types of bullets were used: 9, 11 (.44 magnum), and 7.62 mm. The 9 mm caliber provided muzzle energy of 468 J and velocity of 342 m/s which is in the same range to the sound velocity of 340 m/s. The 11 and 7.62 mm calibers provided muzzle energies of 1972 and 3259 J and velocities of 499 and 842 m/s, respectively, which are considered in the supersonic range (higher than sound velocity). Hooked end steel fibers were used at 1–3 % volume fraction with thickness of concrete panels varied from 10 to 100 mm. Results in terms of failure modes, velocity prior to and after impact, and impact energy absorption were collected. The relationship between muzzle energies and failure mode, panel thickness, and fiber content was discussed.

2. Experimental procedure

2.1. Materials

Materials used in this study consisted of Portland cement type I (ASTM C150), river sand with FM of 2.75, tap water, and superplasticizer Type F. Single hooked end steel fibers with tensile strength of about 1000 MPa was used at 1–3 % volume fractions (Table 1). Three types of bullets with different diameter and muzzle energies were used (Table 2).

2.2. Mix proportion and specimen preparation

Mix proportion of fiber reinforced concrete was set at water/cement ratio of 0.30, cement/fine aggregate ratio of 0.50, and fiber volume fraction of 1–3 % (Table 3). This yielded the compressive strength of about 77.1, 89.5 and 89.7 MPa for 1, 2 and 3% SFRC, respectively. To prepare the specimens, cement and sand were mixed together for 3 min, then water was added, and the mixing continued for another 3 min. Steel fibers were added into fresh mortar and the mixing continued for 3 more minutes to ensure uniform distribution of fibers.

The specimens in the form of square panels with dimensions of 400 × 400 mm and varying thicknesses from 100 to 600 mm were prepared. After the mixing had finished, the fresh concrete was poured into steel molds, compacted with a steel rod for 25 times and vibrated on a shaking table. After completion, the excess concrete was removed from the top surface and the specimens were covered with plastic sheets for 24 h. The specimens were demolded on the next day and cured in water for 28 days.

Table 1
Properties of Steel Fiber.

Materials	Specific Gravity	Shape	Length (mm)	Section (mm)	Aspect Ratio (l/d)	Tensile Strength (N/ mm^2)
Steel	7.8	Hooked End	35	dia.- 0.55	64	1000

Table 2
Properties of bullet.

No.	Caliber	Bullet Weight	Bullet Description	Muzzle Velocity	Muzzle Energy	Classification
1	9 mm	8.0 g	FMJ	342 m/s	468 N.m	Low Impact Energy
2	11 mm (.44 Magnum)	15.6 g	SJHP	499 m/s	1942 N.m	Medium Impact Energy
3	7.62 mm	9.6 g	FMJ	824 m/s	3259 N.m	High Impact Energy

Table 3
Casting Schedule.

Name	Fibre content (%)	Impact test			
		Thickness (mm.)	9 mm	.44 Magnum	7.62 Rifle
1S10	1	10	3	3	–
1S20		20	3	3	–
1S30		30	3	3	–
1S40		40	3	3	–
1S50		50	3	3	–
1S60		60	–	3	–
2S10	2	10	3	3	3
2S20		20	3	3	3
2S30		30	3	3	3
2S40		40	3	3	3
2S50		50	3	3	3
2S60		60	–	3	3
2S70		70	–	–	3
2S80		80	–	–	3
2S100		100	–	–	3
3S10	3	10	3	3	3
3S20		20	3	3	3
3S30		30	3	3	3
3S40		40	3	3	3
3S50		50	3	3	3
3S60		60	–	3	3
3S70		70	–	–	3
3S80		80	–	–	3
3S100		100	–	–	3

2.3. Projectile impact test

General test setup began with placing and locking a specimen on a 400 × 400 mm steel support. Two ballistic chronographs capable of measuring velocity from 1.5–3047 m/s were placed at the front and back of the target with a distance of 2500 and 300 mm, respectively. Three types of bullets were used as mentioned in Table 2. Two striking distances were adopted: 5 m for 9 mm and 11 mm caliber test and 15 m for 7.62 mm caliber test (Fig. 1). The test was carried out in accordance to Ballistic Resistance of Body Armor NIJ Standard-0101.06.

To analyze the results, the specimen was shot from the distance mentioned above. The failure modes and bullet velocity prior to impact were obtained. In the case where the perforation failure mode occurred, the bullet's residual velocity (after impact) was also measured. Both velocities prior to and after impact were then used in calculating kinetic energies using Eq. 1. Assuming no energy loss to other forms and constant bullet mass during the impact event, the energy loss by the bullet can be calculated using Eq.2. Also by further assuming that the kinetic energy loss by the bullet is equal to the energy absorbed by the panel, the energy absorption by the panel can be calculated by Eq.3.

Initial Kinetic Energy, $E_i = \frac{mv_i^2}{2}$

Residual Kinetic Energy, $E_r = \frac{mv_r^2}{2}$ (1)

Energy Loss by a bullet, $\Delta E = E_i - E_r = \frac{m(v_i - v_r)^2}{2}$ (2)

Energy Absorption by Panel, $E_{Ab} = \Delta E$ (3)

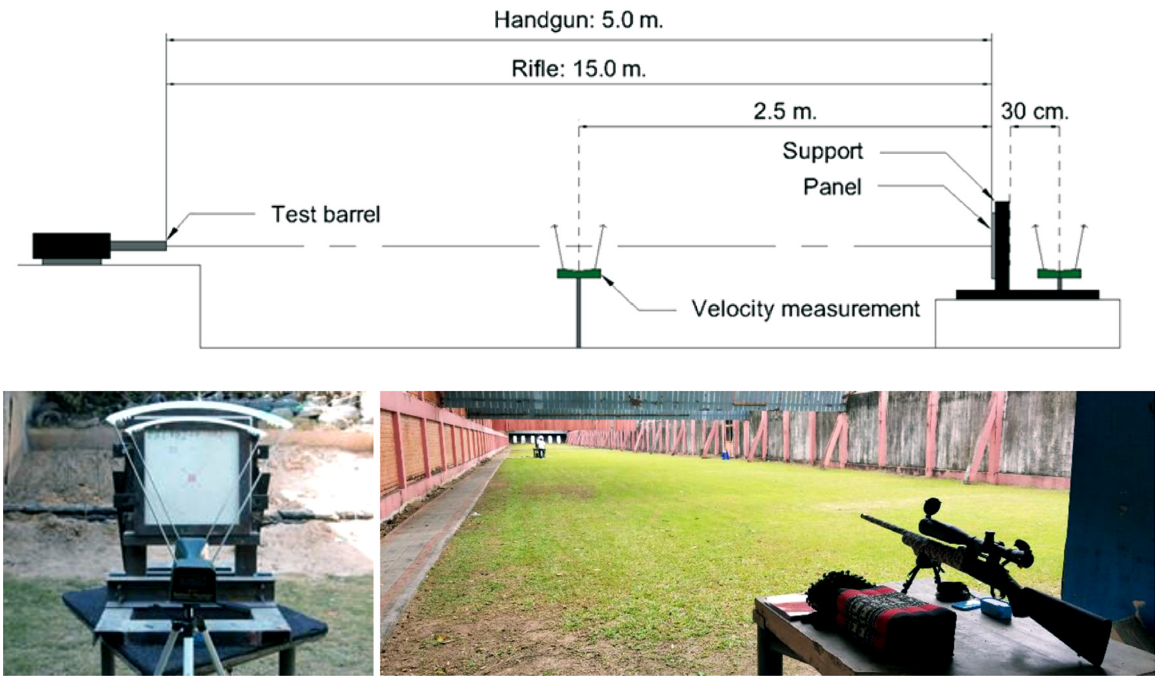

Fig. 1. Impact Test Setup.

where ΔE = energy loss by the bullet during impact (Joule)
E_{Ab} = energy absorbed by the panel (Joule)
m = bullet mass (kg)
V_i = initial bullet velocity (prior to striking) (m/s)
V_r = residual bullet velocity (after striking) (m/s)

2.4. Casting schedule

For each test, at least three specimens were tested. The total number of specimens are summarized in Table 3.

3. Results and discussion

3.1. Failure patterns

Typical failure patterns of a panel subjected to a single straight shot can be classified into 4 modes which were also defined previously by Sukontasukkul et al. [13] (Fig. 2):

1) Perforation + Back spalling (P/Sp) – Bullet fully penetrated through the panel thickness creating a circular puncture hole (or crater at the front surface and back surfaces) and spalling area at the back surface with flying debris (Fig. 2a). This was the only mode that the bullet penetrated through the thickness and allowed the measurement of bullet velocity after an impact event. A similar mode of failure was also reported by Atapek and Karagoz [14] when impact tests was carried out on tempered bainitic steel using 7.62 mm armor piercing projectile. Although the tests were carried out with a steel material, the perforation failure with small front crater was also observed in specimens.
2) Front scabbing + Back spalling (Sc/Sp) – Bullet partially penetrated the front surface creating scabbing zone and large spalling area at the back surface with flying debris (Fig. 2b). This mode was often found in panels hit by a bullet with medium to high muzzle energy (11 mm or 7.62 mm) because the energy must be high enough to not only create spalling pieces but also debonding them from fibers (becoming flying debris). Typically, the back spalling diameter was always larger than the front scabbing diameter. This is because the compression stress wave was larger on the back than on the front surface [15].
3) Front scabbing + Back cracking (Sc/Cr) – Bullet partially penetrated the front surface creating scabbing zone and cracks at the back surface without flying debris (Fig. 2c). This mode often occurred in panels with just sufficient thickness to resist bullet energy. The bullet's energy level was sufficient in causing cracks but not enough to overcome the bond strength between fibers and spalling pieces.

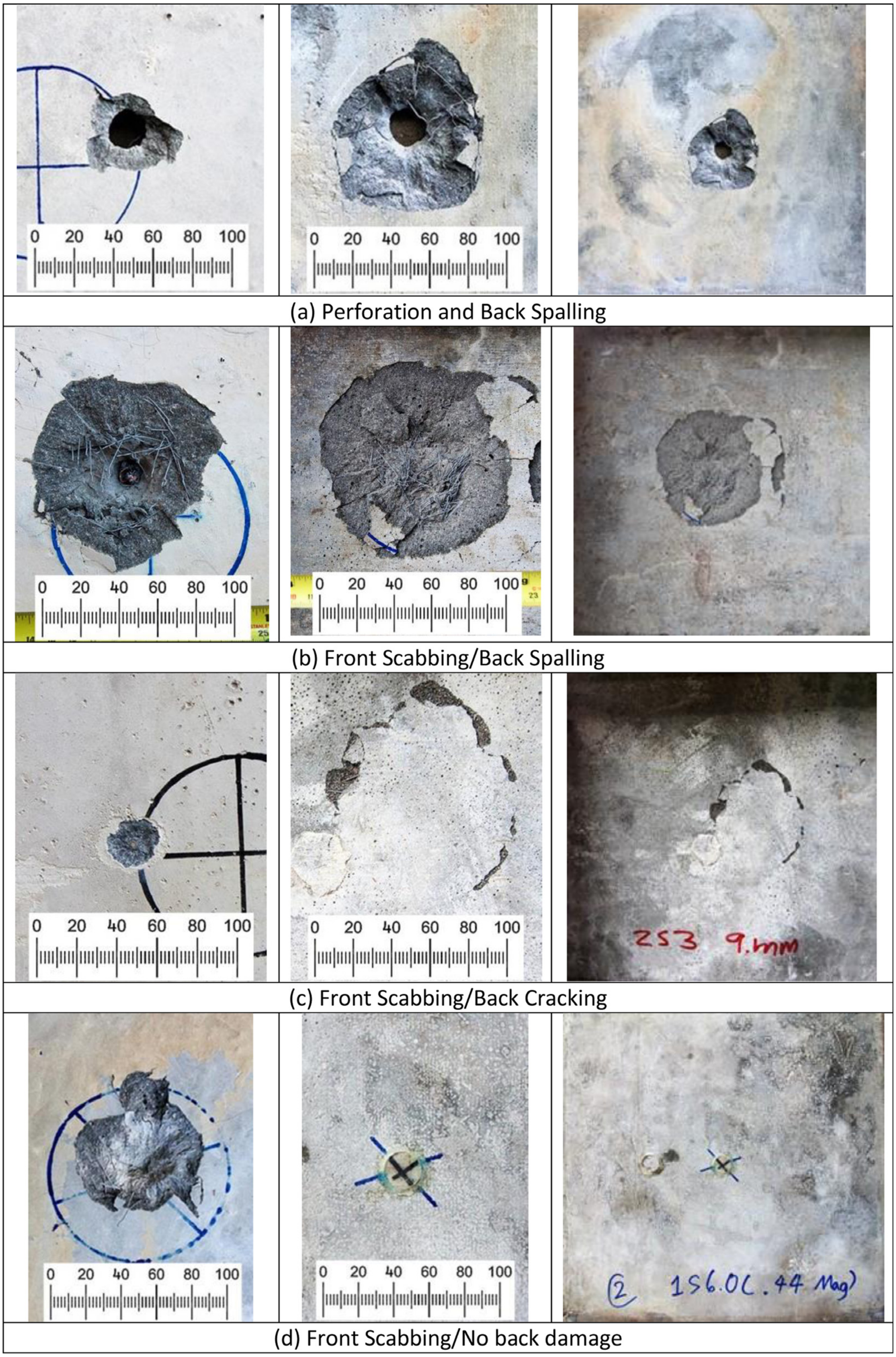

Fig. 2. Typical Failure Patterns of a Single Straight Shot (a) Perforation, (b) Front scabbing + Back spalling, (c) Front scabbing + Back cracking and (d) Front scabbing only.

Table 4
Detail Summary on Panel Type, Bullet Type and Failure mode.

Name	9 mm.	11 mm.	7.62 mm
1S10	Perforation	Perforation	–
2S10	Perforation	Perforation	Perforation
3S10	Perforation	Perforation	Perforation
1S20	Perforation	Perforation	–
2S20	Perforation	Perforation	Perforation
3S20	Perforation	Perforation	Perforation
1S30	Scabbing + Cracking	Perforation	–
2S30	Scabbing + Cracking	Perforation	Perforation
3S30	Scabbing + Cracking	Perforation	Perforation
1S40	Scabbing + No damage	Perforation	–
2S40	Scabbing + No damage	Scabbing + Spalling	Perforation
2S40	Scabbing + No damage	Scabbing + Spalling	Perforation
1S50	Scabbing + No damage	Scabbing + Cracking	–
2S50	Scabbing + No damage	Scabbing + Cracking	Perforation
3S50	Scabbing + No damage	Scabbing + No damage	Perforation
1S60	–	Scabbing + No damage	–
2S60	–	Scabbing + No damage	Scabbing + Spalling
3S60	–	Scabbing + No damage	Scabbing + Spalling
2S70	–	–	Scabbing + Spalling
3S70	–	–	Scabbing + Spalling
2S80	–	–	Scabbing + Cracking
3S80	–	–	Scabbing + No damage
2S100	–	–	Scabbing + No damage
3S100	–	–	Scabbing + No damage

4) Front scabbing + No back damage (Sc/ND) – Bullet partially penetrated the front surface creating scabbing zone but no damage at the back surface (Fig. 2d). This mode usually occurred in panels with a much larger thickness that was capable of overcoming bullet energy entirely.

3.1.1. 9 mm caliber

The 9 mm bullet is the lightest among the three bullet types in terms of weight and muzzle energy (8 g and 468 J). The perforation with back spalling failure mode (P/Sp) was observed in the panels with thicknesses of 10 and 20 mm regardless of their fiber volume fractions (1S, 2S and 3S). The failure patterns changed to Sc/Cr mode when the panel thickness increased to 30 mm. At the thickness equaled to or larger than 40 mm, the damage at the back surface disappeared and the Sc/ND mode was observed. Details failure mode and back spalling diameter are summarized in Table 4 and Fig. 3.

3.1.2. 11 mm caliber (.44 magnum)

The .44 magnum caliber is the heaviest bullet (about 15.6 g) among the three calibers. Although it has a relatively low velocity of about 499 m/s (as compared to 842 m/s of 7.62 mm bullet), because of the weight, it is able to provide quite large muzzle energy of about 1942 J. Under the impact by this bullet type, all FRC panels with thickness from 10 to 30 mm experienced P/Sp failure mode. At the thickness of 40 mm, the failure mode shifted to Sc/Sp mode for 2S40 and 3S40 while the perforation mode still occurred in 1S40. With the increasing thickness to 50 mm, the failure mode of all panels changed

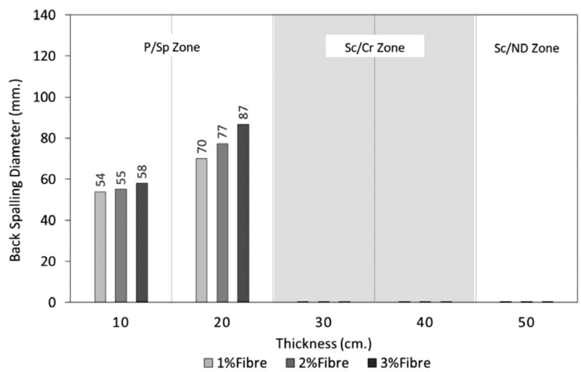

Fig. 3. Failure Mode, Back Spalling Diameter vs. FRC Panel Thickness (9 mm. Caliber).

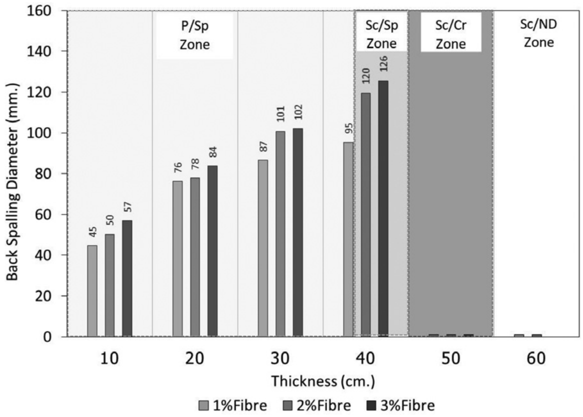

Fig. 4. Failure Mode, Back Spalling Diameter vs. FRC Panel Thickness (.44 magnum Caliber).

to Sc/Cr with crack lines at the back surface. The damage at the back surface disappeared (Sc/ND mode) when the thickness was equal to or larger than 60 mm. Details are summarized in Table 4 and Fig.4.

3.1.3. 7.62 caliber

Although the 7.62 caliber is the smallest in terms of size, due to its high velocity (824 m/s), it provides the highest impact energy of 3259 J. With large muzzle energy together with the sharp tips, the 7.62 mm bullets are considered armor piercing bullets. The results showed that they were capable of penetrating through all types of SFRC panels with thickness ranging from 10 to 50 mm easily (perforation failure mode). With increasing thickness to 60 mm, the failure mode changed to Sc/Sp mode with flying debris. At the thickness of 80 mm, the back spalling reduced to cracking and the failure mode shifted to Sc/Cr mode. Beyond 80–100 mm, the damage at the back surface disappeared completely (Sc/ND mode). More details are summarized on Table 4 and Fig. 5.

3.2. Impact energy absorption

In order to determine the relationship between the energy absorption and thickness of FRC panels, the data on velocities prior and after impact of those failed under perforation failure mode were used. Although the bullet was deformed during an impact event, its mass was assumed constant. Using Eq. 1–3 in section 2.3, energy absorption by a panel can be calculated and the results are shown in Fig. 2–4. Regardless of bullet type and geometry, the impact energy absorption was found to increase with the increasing thickness [16].

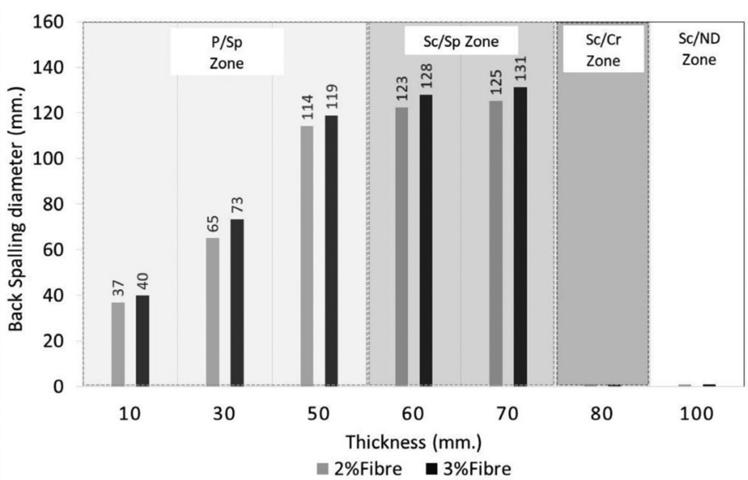

Fig. 5. Failure Mode, Back Spalling Diameter vs. FRC Panel Thickness (7.62 mm Caliber).

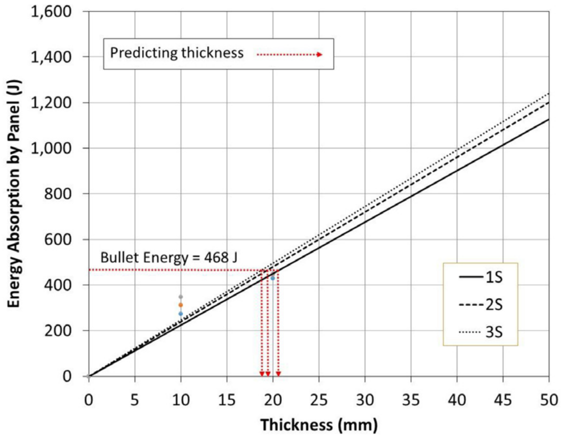

Fig. 6. Energy Absorption vs. Thickness (9 mm).

3.2.1. 9 mm caliber

The relationship between the energy absorption and thickness of FRC panels subjected to 9 mm bullets are shown in Fig. 6 and expressed by Eq. 4–6.

$$\text{Energy absorption of 1S panel,} \quad E_9^{1S} = 22.56.t \tag{4}$$

$$\text{Energy absorption of 2S panel,} \quad E_9^{2S} = 24.02.t \tag{5}$$

$$\text{Energy absorption of 3S panel,} \quad E_9^{3S} = 24.85.t \tag{6}$$

Using an average initial kinetic (muzzle) energy of a 9 mm. bullet of 468 J and Eq. 4 to 6, the minimum thicknesses for 1S, 2S, and 3S panels required to meet the bullet energy was predicted equal to 20.7, 19.5, and 18.8 mm, respectively. The predicted thicknesses were somewhat in line with the experimental results in which the end of perforation failure mode occurred at the thickness around 20 mm for all FRC panels.

Although, the thickness was found to decrease with the increasing fiber content, the difference in thickness was relatively small (about 0.95 mm or 5% per volume fraction of fiber). The small difference implied that the resistance of the panel increased very little with the increasing fiber content and it was the thickness that played an important role on impact resistance of panels under 9 mm caliber. The reason was perhaps due to the nature of its tip (pointy) and the relatively small caliber size as compared to the specimen size; the damage became very localized.

3.2.1.1. 11 mm. Caliber (.44 magnum). The relationship between the energy absorption and thickness of FRC panels subjected to .44 magnum calibers are shown in Fig. 7 and expressed by Eq. 7–9.

$$\text{Energy absorption of 1S panel,} \quad E_{44}^{1S} = 49.75.t \tag{7}$$

$$\text{Energy absorption of 2S panel,} \quad E_{44}^{2S} = 58.90.t \tag{8}$$

$$\text{Energy absorption of 3S panel,} \quad E_{44}^{3S} = 66.60.t \tag{9}$$

Using Eq. 7 to 9, the thicknesses of 1S, 2S, and 3S panels corresponding to the bullet muzzle energy of 1942 J were predicted at 39.0, 32.9 and 29.2 mm, respectively. Similarly, the thickness was found decrease with increasing fiber volume fraction. The predicted thicknesses of all panels were well agreed with the test results. The perforation (P/Sp) was observed in 1S panel up to the thickness of about 40 mm, the predicted thickness of 39 was about 1 mm under estimated by about 1 mm or 2.5 %. For 2S and 3S panels, the perforation mode stopped at the thickness larger than 30 mm while Eq. 8 and 9 yielded the thickness of 32.9 and 29.2 mm for 2S and 3S, respectively.

The difference in thickness between panels with different fiber volume fractions was found in average of 4.9 mm/volume fraction of fiber (or 16.7 % per volume fraction of fiber). Unlike 9 mm calibers, the 11 mm caliber yielded much larger differences in thickness. It is suspected that the tip geometry and impact behavior of the .44 magnum plays an important role on this. The .44 magnum is known as a heavy bullet with flattened point head that can produce a lot of recoil and has a large

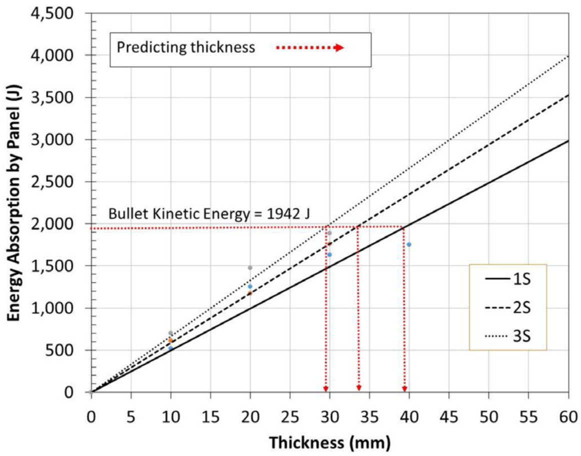

Fig. 7. Energy Absorption vs. Thickness (11 mm).

muzzle energy This allows the bullet to insert more pressure at the target and surrounding area. Unlike the piercing type bullets with small diameters, where impact zone is localized, the flattened point bullet creates a larger impact zone which, in turn, weakens the surrounding area. This showed that when subjected to impact load from bullets with larger calibers, the failure become more globalized. The consideration on thickness alone may not be sufficient to provide resistance and prevent perforation from occurring, both thickness and fiber volume fraction must be considered together for optimum design.

3.2.1.2. 7.62 mm caliber. The relationship between the energy absorption and thickness of FRC panels subjected to 7.62 magnum calibers are shown in Fig. 8 and expressed by Eq. 10–11.

Energy absorption of 2S panel, $E_{762}^{2S} = 58.01.t$ (10)

Energy absorption of 3S panel, $E_{762}^{3S} = 62.47.t$ (11)

For 7.62 mm caliber, the minimum thicknesses required to meet its muzzle energy of 2S and 3S panels were predicted at 56.2 and 52.2 mm, respectively. Based on the experimental results, the minimum thickness which allowed the perforation to occur was at 50 mm. At the thickness of 60 mm, the failure mode changed to Sc/Sp. The predicted thicknesses fell in between 50–60 mm which were considered well agreed with the test results. The difference in thickness between 2S and 3S panels was found around 4 mm or 7.6 % per volume fraction of fiber, which was considered relatively low as compared to the 11 mm (or .44 Magnum). Similar to the 9 mm bullet, the 7.62 mm is a piercing type bullet with pointy tip, it tends to penetrate through the target rather than damaging the surrounding area. This similarly implies that the panel thickness most likely played a more important role than the fiber content in the case of 7.62 mm bullet. However, when designing a panel for this kind of armor piercing bullet type, both thickness and fiber volume fraction must be considered together to obtain the

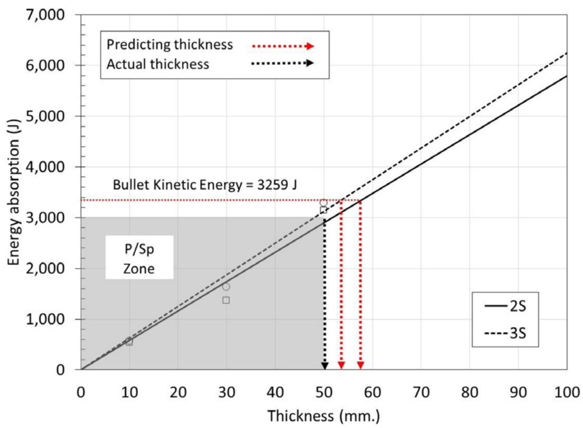

Fig. 8. Energy Absorption vs. Thickness (7.62 mm).

desired failure type. If the purpose is to prevent perforation, then perhaps the thickness can be considered alone. However, if the purpose is to prevent perforation and damage on the back surface, then both thickness and fiber volume fraction should be considered together.

4. Conclusion

Steel fiber reinforced concrete panels behaved differently under impact from projectiles with different geometries, muzzle velocities, and energies. The failure modes were found to depend mainly on the panel thickness and fiber content. Under the same type of projectile, the shifting of failure modes from perforation to scabbing or spalling or no damage was the result of increasing panel thickness and fiber content.

For panels with a thinner thickness, the perforation failure mode was mainly observed. As the thickness increased, the failure mode shifted to penetration with back spalling, and then to penetration without damage in the back surface.

Considering SFRC panels with the same fiber content, the thickness in which the failure mode began to shift from one mode to another was found to depend strongly on the bullet type and muzzle energy. The thickness in which the perforation failure mode did not occur was found to be thicker when subjected to bullets with larger muzzle energy.

Regardless of the bullet type, the impact energy absorption increased with the increasing thickness and fiber content. Under the same thickness and fiber content, the constant a was observed to depend on the bullet type. Under impact by piercing type projectiles (9 and 7.62 mm), the panel thickness seemed to play an important role on the impact resistant of FRC panels. This was because the failure modes were very localized. Under impact by blunt and larger diameter projectiles (11 mm or .44 magnum), on the other hand, the main consideration should be given on the fiber content rather than thickness because the failure modes became more globalized.

Declaration of Competing Interest

Regarding the submission of a manuscript on the title “Steel Fiber Reinforced Concrete Panels subjected to Impact Projectiles with Different Caliber Sizes and Muzzle Energies” for your consideration to be published on the Case Studies in Construction Materials, the authors declare that they have no conflict of interest.

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