Critical Overview of Blast Resistance of Different Concrete Types

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Abstract

Past attacks against buildings and civil infrastructure highlight the need for blast-resistant structural materials. Numerous studies have been conducted on various related techniques and some design guidance has been developed to increase the resistance of structures to blast loading. Generally, a blast results in a high amplitude impulse loading typically with a very short duration. Hence, the material's response to such loading will differ from that to regular types of loading. Consequently, the analysis and design of structures subjected to blast loads require a full understanding of the behaviour of materials and structural elements under blast loading. This paper presents an overview of the behaviour of concrete elements subjected to blast loads. A critical discussion of the state-of-the-art on blast resistance of conventional and modern concrete materials is provided, along with an overview of effective retrofitting and strengthening techniques.

Keywords: *Concrete structures; Composite structures; Concrete technology and manufacture.*

1. Introduction

Structures around us can be susceptible to various kinds of vandalism, accidental damage, or even military or terrorist attacks. For instance, bombings that took place in London (2005), Madrid (2004), and Istanbul (2003) resulted in casualties and damage to surrounding structures (Buchan and Chen,2007). Such attacks have motivated extensive research to innovate new defensive philosophies that can secure lives and reduce damage to surrounding structures (Naito and Wheaton,2006). Hence, standards (e.g. DOD,2002) and design methods (e.g. TM5-1300,1990;DOD,2005) were developed to analyse structural performance under blast loads. Moreover, the US Army produced a step-by-step analysis and design procedures for structures to resist explosions (TM5-1300,1990).

Generally, the design philosophy for structures to withstand blast loading is to increase the energy absorption capacity for its elements (Razaqpur *et al.*,2009). This can be achieved by increasing its strength, ductility and/or mass. However, adding new mass to an existing building is undesirable since it increases its self-weight, possibly exceeding the foundation’s design capacity. Thus, focus was directed to increasing the structural strength and ductility (Razaqpur *et al.*,2009). This stimulates the use of new innovative construction materials such as steel fibre-reinforced and ultra-high strength concrete. However, limited research has been conducted on the blast resistance of such new types of concrete. Hence, this paper presents a review of the existing literature on the blast resistance of different types of concrete.

2.Blast Mechanism and Properties

2.1.Blast Phenomenon

During an explosion, a chemical reaction takes place resulting in a sudden rise of temperature and pressure. The generated blast shock waves travel and strike structures with pressure greater than the atmospheric pressure (**Fig.1**). In general, any exterior explosion to a building generates four types of loads including impact of primary fragments, impact of secondary fragments, overpressure, and reflective pressure (Naito & Wheaton,2006). Primary and secondary fragments are both associated with significant casualties, however, they do not contribute to major structural damage. As the radiating overpressure waves reach an object perpendicular to its path, the wave is reflected creating an elevated pressure demand (Natio & Wheaton,2006). The magnitude of this reflected pressure is dependent on the shape of the object and its orientation with respect to the blast wave. Therefore, for structural elements, the reflected pressure is considered the most destructive aspect of blast loading.

Blast loads typically produce very high strain rates in the range of 10^2 to 10^4 /second, while ordinary static strain rate is within the range of 10^{-6} to 10^{-5} /second (Ngo *et al.*,2007). Such high strain rates can affect the strength and ductility of structural materials, reinforcement bond, structural failure modes, and the energy absorption capabilities of different elements (Yi *et al.*,2009). Moreover, the corresponding structural response frequencies can be much higher than those induced by conventional loads. Materials typically exhibit increased strength under the high blast loading rate and frequency. This can be represented by the dynamic increase factor (DIF), which is the ratio of the dynamic material strength to its static strength. Therefore, under blast loading, the stress-strain relationships for structural materials are amplified by the corresponding DIF before being considered in structural design (El-Dakhakhni *et al.*,2009). This factor can be calculated using empirical relationships available in the literature. For instance, the following equations 1-2 can be used to estimate the compressive dynamic increase factor (CDIF) (Bischoff and Perry,1991).

$$CDIF = \frac{f_{cd}}{f_{cs}} = \frac{\varepsilon_d}{\varepsilon_{cs}}^{1.026\alpha} \qquad for\ \varepsilon_d \le 30\ s^{-1} \qquad 1$$

$$CDIF = \frac{f_{cd}}{f_{cs}} = \gamma \ \varepsilon_d \ ^{1/3} \qquad for\ \varepsilon_d > 30\ s^{-1} \tag{2}$$

Where, f_{cd} is the dynamic compressive strength at the strain rate ε_d , f_{cs} is the static compressive strength, $\varepsilon_{cs} = 30x10^{-6}s^{-1}$, $\log \gamma \ = 6.156\alpha - 0.49$, $\alpha = \ 5 + \frac{3\,f_{cu}}{4} \ ^{-1}$, and f_{cu} is the cube compressive strength. Then, the dynamic compressive strength can be calculated by multiplying the CDIF and the respective static strength.

To assess structural damage due to blast loading, P-I curves (i.e Pressure-impulse curves corresponding to different damage level) are widely used (Ambrosini *et al.*,2005). Each P-I curve represents different combinations of pressure and impulse (time integral of pressure) that would produce the same level of damage within a structural element (Baker *et al.*,1983). These curves can be obtained by simple single-degree-of-freedom analysis, complicated numerical simulations, or conducting field blast tests (Lan and Crawford,2003,Zhou and Hao,2008).

For impulsive explosive loading, the response of a RC structure occurs in very short time so that no viscous damping can be invoked (Millard *et al.*,2010). Consequently, the first displacement peak will be the most severe, followed by a number of displacement peaks that are significantly lower in magnitude. The structure is likely to undergo excessive permanent deformation during its first displacement, while it is unlikely to fail during the second displacement peak. Therefore, the first displacement peak is usually considered in analysing structural response to explosive loading (Low and Hao,2002).

2.2.Blast Wave

Explosion is a large-scale, rapid and sudden release of energy due to violent oxidation of explosive material. The oxidation occurs within a few milliseconds producing a highly pressurized volume of very hot gasses (Hudson and Darwin,2005). These gasses expand causing rapid release of energy and resulting in a blast wave. The wave front (so called “shock front”) travels faster than the speed of sound, creating incident overpressure (Ibrahim *et al.*,2011). Fast movement of the wave overshoots ambient pressure. This results in the creation of a vacuum behind the blast wave, known as negative phase or under-pressure (Barakat and Hetherington,1999). During such a negative phase, partial vacuum is created and air is sucked in. This is further accompanied by high suction winds that carry debris over long distances away from the explosion source (Sun *et al.*,2011).

2.3.Charge Weight and Stand-off Distance

In order to calculate the blast wave pressure-time history from a conventional explosion, two critical factors should be considered: the charge weight and the stand-off distance (SOD). The charge weight reflects the mass of explosive being detonated. It is usually represented by the equivalent weight of trinitrotoluene (TNT). For cylindrical charges, peak overpressure and impulse are dependent on the detonation locations. For low ratios of length-to-diameter, more energy is directed in the axial direction, while for high length-to-diameter ratios, more energy is directed in the radial direction. Thus, charge orientation can substantially influence the peak overpressure and impulse (Wua *et al.*,2009).

The SOD measures how close the building is to where the explosion happens (**Fig.1**). Therefore, it is a function of the physical characteristics of the surrounding site (Sun *et al.*,2011). SOD is measured from the centre of gravity of the charge located in the vehicle bomb to the building components (FEMA 427,2003). Defining the appropriate SOD for a given building component to resist the effects of explosive blast is difficult. Often in urban settings, it is neither possible nor practical to obtain appropriate stand-off distance. Furthermore, predicting the explosive weight of the weapon is generally infeasible. However, the (DOD,2005) prescribes minimum SOD based on the required level of protection. If the minimum SOD can be met, conventional construction techniques can be used to achieve adequate protection level, otherwise the building must be hardened.

3.Behaviour of Concrete Exposed to Blast

3.1. Reinforced Concrete

Reinforced concrete (RC) is a normal concrete made of the standard mixture constituent materials (i.e. cement, aggregate, water, etc.) and reinforced with conventional steel rebar. The typical compressive strength values of normal concrete vary between 20 and 70 MPa and its density ranges between 2240 and 2400 kg/m^3. Under blast loading RC members show a unique behaviour known as “scabbing”. Scabbing occurs on the side of the member opposite to the detonation. As the initial compressive wave generated by the blast travels through the member and reflects at the free surface, the shock wave is converted into a tensile wave, which causes high levels of cracking in the concrete. As the member begins to rapidly deflect, it causes a high speed discharge of concrete (Leppanen,2005).

Moreover, the experimental work conducted at the Weapons System Division (Australia) on RC panels identified two predominant failure stages. In the first stage, damage was caused by high-speed stress wave propagation; while in the second; further damage was caused by deformation due to element free vibration. During the first stage, damaged concrete elements may be ejected as fragments since damage occurs at high strain rate. It was observed that spalling occurred at the panel centre with maximum cavity depth of 50mm.

On the other hand, a parametric study was conducted on a series of 12 RC columns to investigate the effect of the transverse and longitudinal reinforcement ratio, long-term axial load ratio, and column aspect ratio on its response to blast loading. This study focused on the effects of overpressure and reflected pressure (Bao and Li, 2010). Results showed that using seismic reinforcement detailing can significantly reduce the level of direct blast-induced damage and subsequent collapse of RC columns. Also, comparing the reduction in axial strength with respect to the axial load ratios indicated that the residual axial strength was small under large long-term axial load. Moreover, the effect of axial load ratio was more critical for columns having a low transverse reinforcement ratio. Results also indicated that the ratio of residual axial capacity generally increased with increasing longitudinal reinforcement ratio. It should be mentioned that the reinforcement ratio and type can also affect the performance of concrete under blast loading. Robert and Johnson (2009) tested concrete slabs with different reinforcing ratios of vanadium micro-alloyed steel and conventional Grade-60 reinforcing bar. The concrete with micro-alloyed vanadium steel deformed the least and withstood larger loads than any of the other specimens. Therefore, increasing blast resistance can be gained by using high-strength steel (Robert and Johnson,2009).

Several studies had investigated the performance of RC elements under blast loading including several parameters such as the charge weight, SOD, element dimensions, steel reinforcement and loading ratios. However, due to safety requirements and costs associated with experimental blasting tests, a number of models have been proposed to capture the performance of RC elements under different blast loading configurations.

A finite difference (FD) model accounting for strain-rate effects, shear and flexural deformations, variations in cross-section geometry, strength and loading over the tested element length, while analysing the dynamic response of the structural member under blast loads was proposed by (Jones *et al.*,2009). The results of the model were validated by comparing the predicted maximum deflection with that obtained experimentally from previous tests (Wu *et al.*,2009). The simplicity of the model, its ability to capture several important features of the structure exposed to blast loading, along with the good agreement between the FD predicted values and experimental results supported the use of this proposed model in design applications.

Furthermore, Ibrahim *et al.*(2011) gathered a wide range of blast data for various damage and non-damage cases of concrete. These were linked to three main independent variables: the charge weight, the SOD, and the slab thickness. Using an artificial neural network, they estimated the damage size experienced by the tested RC element. This damage model was able to perform post-blast global dynamic response assessment of structural systems.

Numerical simulation conducted by (Zhou and Hao,2008) had confirmed the applicability of combing the effect of both stand-off distance and charge weight on RC elements in one term referred to as “scaled SOD”. Results showed that that increasing the SOD results in considerable reduction in the peak pressure acting on the RC elements for the same charge weight. Also, the sensitivity of the peak pressure to the charge weight decreased significantly as the SOD approached around 20 m.

As a conclusion, literature is full with data regard the RC element behaviour under blast loading and existed models can simulate it. From safety point of view, RC elements resistance for blast loading is not adequate. The discharge and flying fragments of concrete can be extremely dangerous to people located around the concrete member exposed to blast load. This pave the way for new generation of concrete called “Fibre Reinforced Concrete”

3.2.Fibre Reinforced Concrete (FRC)

FRC is similar to RC; however, conventional steel rebar is partially or totally replaced by discrete fibres. These fibres can be classified based on their material, type, length, shape, volume fraction and surface texture. Adding fibres to a concrete mixture can significantly increase its toughness by bridging micro- and macro-cracks in the cementitious matrix (Bentur and

Mindess,2007). As a result; FRC exhibits a more ductile behaviour compared to that of normal concrete (NC) without fibres. Fibres can enhance the engineering properties of a cementitious matrix depending on their properties and quantity with respect to the total concrete volume (Brandt,2008). This has motivates research to consider FRC as an alternative to NC under blasting conditions.

The behaviour of steel-fibre reinforced concrete (SFRC) structural elements under blast loading was investigated by (Nam *et al.*,2011). Results showed that the bending and tensile strengths were significantly enhanced by steel fibres. By examining the spalled concrete depth and crater diameter, adding steel fibres reduced damage due to blast loading significantly. Moreover, under the blast loading, NC members suffer large scabbed surface areas and fragments flied off in multiple directions, while SFRC panels do not scab and show minor spalling (Chu-Jie *et al.*,2008).

Moreover, the steel fibre volume (V_f) had a significant effect on the the performance of high strength concrete panels under blast loading. (Chu-Jie *et al.*,2008) showed that increasing the V_f can drastically reduce the blast stress waves in the FRC, decrease the peak acceleration at the bottom of the concrete panels and the destruction of panel faces.

Similar performance was exhibited by polyethylene fibre-reinforced concrete (PFRC) under blast loading (Yamaguchi *et al.*,2011). PRFC was effective in reducing spall damage and launching of concrete fragments than NC. However the crater size in both PRFC and NC specimens was equivalent, the total damage depth in the PRFC slab was comparatively lower. This can be attributed to the higher toughness provided by fibres (Yamaguchi *et al.*, 2011). PFRC exhibited higher flexural toughness than SFRC (Yamaguchi *et al.*,2011). This flexural toughness is a very important mechanical characteristic for elements subjected to blast loadings since the spall damage depends mainly on the tensile stress wave being reflected from the back side of the tested slab.

(Maalej *et al.*,2005) investigated hybrid FRC (using combinations of steel and Polyethylene fibres in the same concrete mixture). They concluded that using hybrid FRC increased blast resistance, led to lower scabbing, spalling and fragmentation, and exhibited better energy absorption.

In addition to the fibre type, the concrete matrix strength has a significant effect on the overall behaviour of FRC under blast. Recently, (Song *et al.*,2012) evaluated the performance of ultra-high strength steel fibre reinforced concrete (UHSFRC) under blast loading. Specimens showed higher strength and superior performance in terms of anti-explosion capability compared to conventional RC. The compression coefficient of UHSFRC under contact explosion was 0.041, which was around 3 times that of normal FRC. Indeed, the advent of ultra-high strength concrete has attracted growing interest to utilize its superior properties in preventing crack and dissipating of energy of blast loading.

3.3.Ultra High Strength Fibre-Reinforced Concrete (UHSFRC)

UHSFRC is a relatively new generation of cementitious material. Its mixture design characterizes with high cement content and a very low water/cement ratio. Eliminating coarse aggregates and optimizing the particle size gradation of its ingredients results in a high particle packing density and minimize non-homogeneity. UHSFRC has very high energy absorption; its fracture energy ranges from 20,000 up to 40,000 J/m^2 (Millard *et al.*,2010). Some concerns have arisen related to the potential brittle mode of failure of UHSFRC and its high cost relative to the obtained performance. The blast resistance of UHSFRC compared to that of NC was investigated by (Yi *et al.*,2012). Deflection, strain, and accelerometer measurements from blast tests revealed that UHSFRC specimens exhibited higher blast-resistance than that of NC specimens. This was attributed to the presence of short steel fibres which provided improved crack-bridging characteristics and energy absorption capacity. In contrast to NC specimens, UHSFRC specimens showed lower deflection and less cracks. Surface crack patterns of blasted specimens showed that using UHSFRC enhanced the performance of tested specimens significantly under blast loading.

3.4. Frangible Concrete

Frangible concrete is a new type of high-performance concrete that is optimized for frangibility rather than strength (**Fig.2**) (O'Neil *et al.*,2012). The term "frangible" refers to a material that breaks into small pieces when it fractures. Previously, stand-off barrier walls made of massive concrete was used to limit vehicles from close access to the structure. However, the wall would become part of the problem. If a vehicle bomb was exploded outside the wall, the concrete could break into large fragments, becoming deadly projectiles thrown at the facility and its residents. Therefore, concrete is designed to break into small pieces rather than large fragments (**Fig.3**). Frangible concrete will absorb energy, both through the process of fracturing and by loss into the atmosphere. The concept behind frangible concrete is that stresses due to shrinkage encourage the formation of micro-cracks in the matrix both before and after failure. To have good frangibility and adequate strength, the volume of paste coupled with the proper aggregate gradation should be just enough to coat each aggregate particle. Frangible concrete has inter-particle void space and high frangibility, but it lacks strength because it has insufficient paste to hold aggregates together.

Frangible concrete produce approximately 10 times as many fragments generated from conventional block wall. Typically, conventional block fragments ejected twice the distance of the frangible concrete fragments. The number and size of the fragments were consistent with the assumption that smaller fragments lose more energy due to air resistance than larger ones. In addition, the distance that the small fragments travelled away from the standpoint toward the targeted structure was significantly shorter than that of the large ones.

3.5. Concrete Strengthened with Fibre-Reinforced Polymers (FRP)

For existing structures or buildings that have been exposed to blast loading, new methods for retrofitting and strengthening are needed. Fibre-reinforced polymers (FRP) are composite materials made of a polymeric matrix reinforced with fibres with various mechanical and geometric characteristics. The improved mechanical properties and enhanced energy absorption capacity of retrofitted members led to utilizing FRP laminates in blast resisting systems. Different blast tests have been carried out on FRP-retrofitted RC members. For instance, (Muzsynski and Purcell, 2003) conducted a series of full-scale explosive tests on RC walls retrofitted with either carbon fibre reinforced polymer (CFRP) or glass fibre reinforced polymer (GFRP). Results showed that retrofitting the wall on its tensile surface enhanced its blast resistance compared to that of unretrofitted walls. Results for walls retrofitted on their compression and tension surfaces showed that the FRP-retrofitted walls were able to resist higher stresses and displacements without failing compared to that of the control walls, which failed in shear.

Razaqpur *et al.*(2007) investigated possible improvements in blast resistance of RC panels retrofitted on each face with two laminates of GFRP arranged in a crucifix form, with each laminate being parallel to one of the edges of the panel (**Fig.4**). At low blast loads (i.e. ammonium nitrate/fuel oil (ANFO) blast tests with detonation =22.4kg and SOD=3.1m), the GFRP retrofitted panel exhibited significantly higher blast resistance with respect to the non-retrofitted panel. The post-blast static strength of the retrofitted panel was 75% greater than that of the non-retrofitted panel. At high blast loading (i.e. ANFO blast tests with detonation =33.4kg and SOD=3.1m), the performance of replicate retrofitted panels compared to that non-retrofitted panels was inconsistent. In some cases, the retrofitted panel performed better than the companion non-retrofitted panel, while other cases showed an opposite trend. Generally, the retrofitted panels had higher residual strength than that of the non-retrofitted panels, yet gain there was no consistent trend. From the results of the panels subjected to the higher charge, it is difficult to draw definite conclusions on the blast mitigation effectiveness of GFRP bonded laminates.

A new blast retrofit material was proposed by (Ha *et al.*,2011), which consists of using combined CFRP and sprayed polyuria (PU). This material can improve stiffness, ductility, and the fragment catching effect of RC members as it is a combination of highly stiff and strong material (i.e. CFRP) and a highly ductile material (i.e. PU). Tested specimens were NC, and CFRP, PU, and CPU (hybrid CFRP with PU) retrofitted concrete.

Discrete turtle back type of crack patterns were observed in NC samples. The crack lines took the shape of a cone prism type of plastic yield line from the centre to the four corners, indicating a 2D membrane plastic failure mode. Also, diagonal shear cracks formed on the side surfaces, indicating the panel’s susceptibility to shear failure. The shear crack distributions indicate that the design of NC protective structures must consider the shear resistance capacity. CFRP retrofitted specimens had spalling and serious damage at their centre and edge. Polyurea specimens showed more spalling and cracks compared to that in CFRP specimens. Hybrid CFRP/Polyurea specimens exhibited small damage on their top surface, indicating better retrofitting effect. Based on test results, the CFRP, Polyurea, and hybrid CFRP/Polyurea specimens had retrofitting effects of 21.4%,15.7%,and 37.4%, with respect to NC specimens, respectively. This indicates that hybrid CFRP/Polyurea samples had the highest energy absorption and a likely blast resistance retrofitting system.

Likewise, (Ohkubo *et al.*,2008) investigated the effectiveness of using fibre sheets as strengthening for concrete plates exposed to blast loads. The failure modes of regular and strengthened concrete plates were examined. Two different types of fibre sheets were evaluated including carbon (CFRP) and aramid (AFRP). The concrete sample thickness was 100mm and the concrete compressive strength was 25.9MPa. The deterioration of the control concrete specimen was a crater in the side facing the blast with significant spalling in the back side. For concrete slabs retrofitted with one carbon fibre sheet, failure modes were crater, spalling, diagonal cracks and interface damage with less degree of spalling than that of non-strengthened concrete panels. For specimens retrofitted with one aramid fibre sheet, failure modes included crater and interface damage (**Fig.5**).

Increasing the number of strengthening sheets to two, CFRP panels did not show significant change in their failure modes with respect to panels strengthened by one sheet. Conversely, using two sheets of AFRP, the failure mode ranged between slight craters to nothing. Therefore, AFRP was much more efficient in improving concrete blast resistance than CFRP in reducing blast damage. The reduction in crater diameter for the slabs strengthened with one CFRP sheet was 10% compared to the 43% reduction for the slabs strengthened with one layer of AFRP. The improvement is even more pronounced when two layers were used as depicted by the 40% reduction in crater diameter for CFRP and just over 62% for AFRP sheets (**Fig.6 a**). The effect of doubling the number of both CFRP and AFRP sheets on the crater depth was insignificant. However, the specimens strengthened with AFRP sheets exhibited about four times reduction in crater depth compared to the ones strengthened with CFRP sheets (**Fig. 6b**).

This can be attributed to AFRP's higher energy absorption capacity. In addition, spall and fragmentation were prevented completely by AFRP. Generally, the fibre sheet can enhance blast resistance in terms of reducing the crater diameter. This improvement will be a function in the FRP number of layers and type of material.

Moreover, steel reinforced polymer (SRP) sheets have been proposed as a potential alternative to CFRP as strengthening for RC beams. Due to their steel composition, SRP sheets have lower capital cost and can be installed on square columns with minimal corner preparation. The blast resistance was compared (Carriere *et al.*,2009) between un-strengthened and SRP strengthened specimens. Strengthening RC members with SRP wraps showed less concrete damage (**Fig.7**). This can be attributed to the confinement effect induced by the SRP sheets. Moreover, axially loaded concrete fails once it is crashed. However, as SRP wraps confined the crashed zone, it allowed the concrete to resist higher strains and thus increasing its blast resistance (Carriere *et al.*,2009).

3.6.Aluminium Foam-Protected Concrete

Aluminium foams are newly developed lightweight materials that can be deployed as sacrificial protective layers for structures. They are characterized by high energy absorption capacity with relatively low cost (Mukai *et al.*,1999; Ma and Ye,2007). Metallic foam encompasses a matrix of metal (often aluminium) impregnated with pockets of air. Because of its long, plastic plateau in compression, metallic foam allows high energy absorption at a nearly constant stress level. This makes it a perfect material for reducing the effects of explosive loads on a structural system (Ashby *et al.*,2000). As explosion occurs over a foam cladding-protected RC member, the foam layer undergoes great deformation and absorbs a high amount of energy released by the explosion, which in turn enhances the member resistance to blast loads.

Field blast tests have been carried out to study the performance of aluminium foam as sacrificial protection layers (Hansen *et al.*,2002). Results revealed that the energy and impulse during impact pendulum tests increased when foam layers were added. The behaviour of RC members protected with aluminium foam was investigated (Wu *et al.*,2011) under blast loading. Their experimental program was conducted on RC slabs with and without protection (**Fig.8**). Results confirmed the high energy dissipation ability of aluminium foam. It acts as a cellular solid, which is characterized by early onset of plastic yielding and large plastic deformations.

4. Concluding Remarks

In this review paper, the performance of different types of concrete under explosive loading has been examined. For high-risk facilities such as public and commercial tall buildings, design considerations against extreme events (e.g. bomb blast, high velocity impact) are paramount. Moreover, the selection of adequate materials during the design stage and in retrofitting and strengthening play a critical role in defining the structure's ability to resist blast loading. High strength, high energy absorption and ductile materials are recommended since such materials help in improving the structure's performance under severe load conditions.

By examining the behaviour of concrete specimens subjected to various blast loading scenarios, it can be deduced that the type of concrete and its mechanical properties play a major role in determining the blast resistance capacity of concrete members. High-strength fibre-reinforced concrete dissipates more energy compared to that of normal concrete due to its higher tensile strength and the substantial influence of fibres in bridging potential cracks. Spalling and ejected concrete fragments can be mitigated using steel or polyethylene fibre-reinforced concrete owing to enhancing the toughness and ductility of such concrete. Changing the dosage and/or type of fibre can result in variation of the crack pattern and maximum deflection at failure.

Likewise, increasing the steel reinforcement ratio in RC members enhances their axial load capacity and energy absorption when exposed to accelerated stress waves. Thus, designing concrete members according to seismic detailing can be improved to enhance the blast resistance for different charge weights and standoff distances. Furthermore, retrofitting concrete elements with externally attached FRP can enhance its shear capacity, impact resistance and energy absorption.

For existing structures, deploying a sacrificial material, such as aluminium foam, on concrete elements can increase their resistance to blast loading since such materials can absorb significant amounts of energy. Frangible concrete fences can also be an effective protection methodology when placed at a safe standoff distance to minimize the effects of charge detonation. Indeed, the fracture of frangible concrete into small pieces is typically accompanied by vast energy dissipation.

There is need for developing accurate and predictive numerical models considering the existing experimental works on blast loading of concrete. An enhanced understanding of the effect of blast waves on concrete structures needs to be gained in order to better quantify the influence of an extensive number of parameters. This should provide engineers with a rational and practical tool for designing blast resistant concrete members.

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List of figures

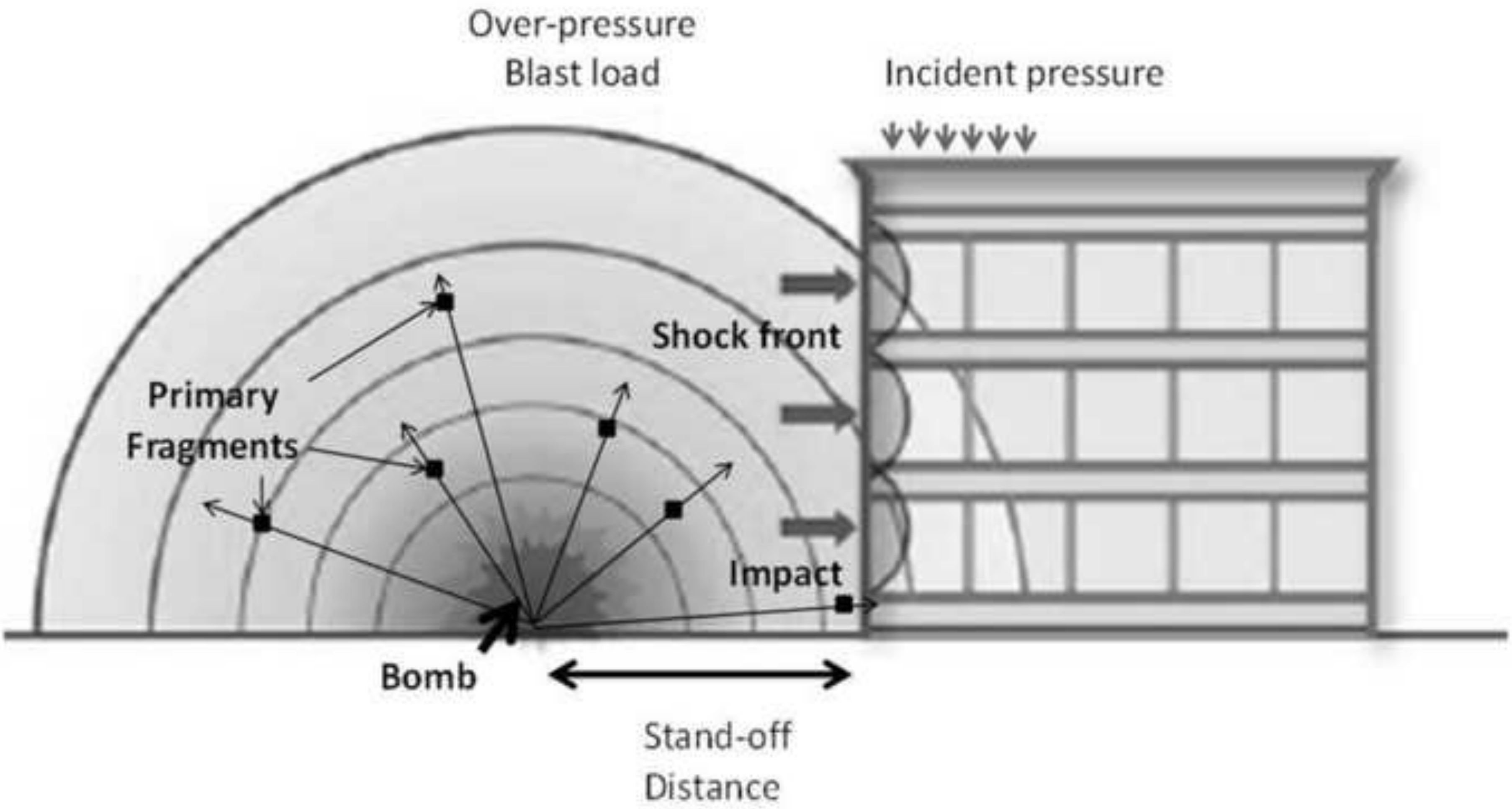
Ms. Ref. No. MACR-D-13-00096

Title: Critical Overview of Blast Resistance of Different Concrete Types

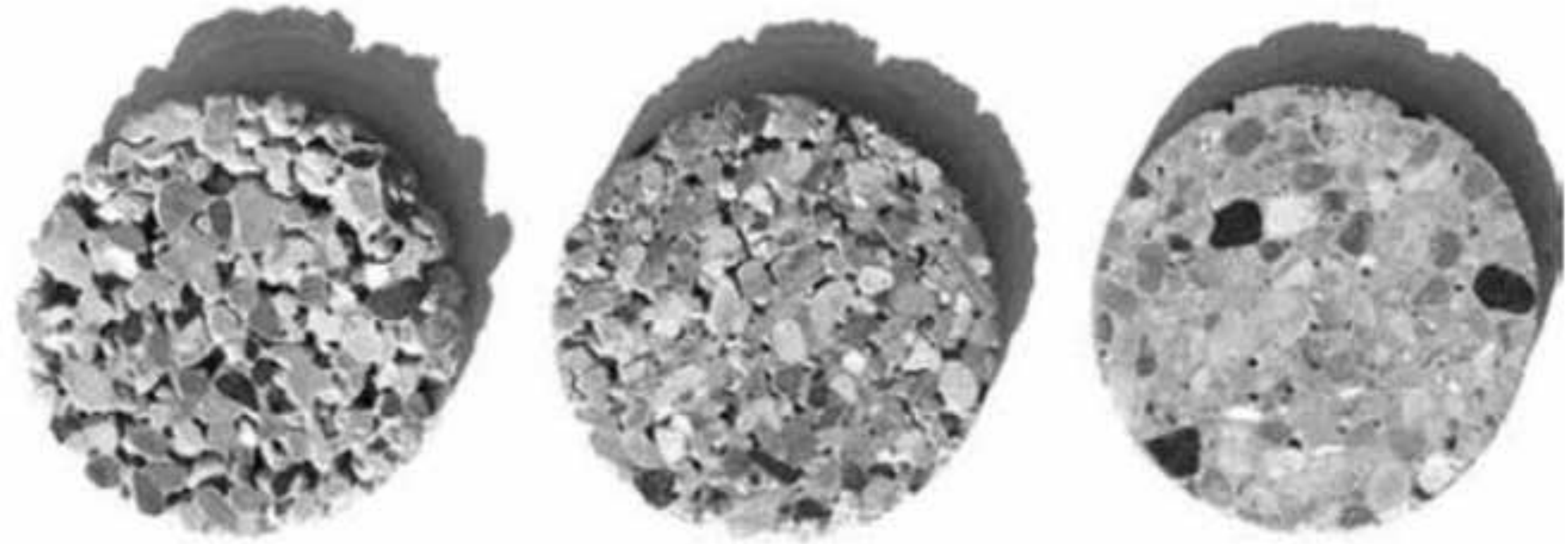
Authors: Alhadid, M., Soliman, A.M. and Nehdi, M.

Table 1: Specific Comments of Reviewer # 1:

Abbreviated Comment of Reviewer #1	**Actions/ Corrections of the Authors**	**Location in the Revised Manuscript**
"... real comparison of the work carried out by different authors, both in terms of materials (e.g. what does 'normal concrete' NC means for different works?) ....”	As recommended, an attempt was made to include a comparison between different existing works and to define clearly the various types of concrete in the revised manuscript.	**Page 7, Lines 5-8** **Page 9, Lines 20-22,** **Page 13, Lines 6-11,** **Page 16, Lines 15-16**
"The concluding remarks are vague and ....analysis of the different strategies that have been proposed to improve the blast resistance of concrete"	As recommended, the conclusion section was extended to include a synthesis of the different strategies discussed in the manuscript.	**Page 17, Lines 16-22** and **Page 18, Lines 1-20**


Over-pressure
Blast load
Incident pressure
Shock front
Primary
Fragments
Impact
Bomb
Stand-off
Distance

*Figure



*Figure

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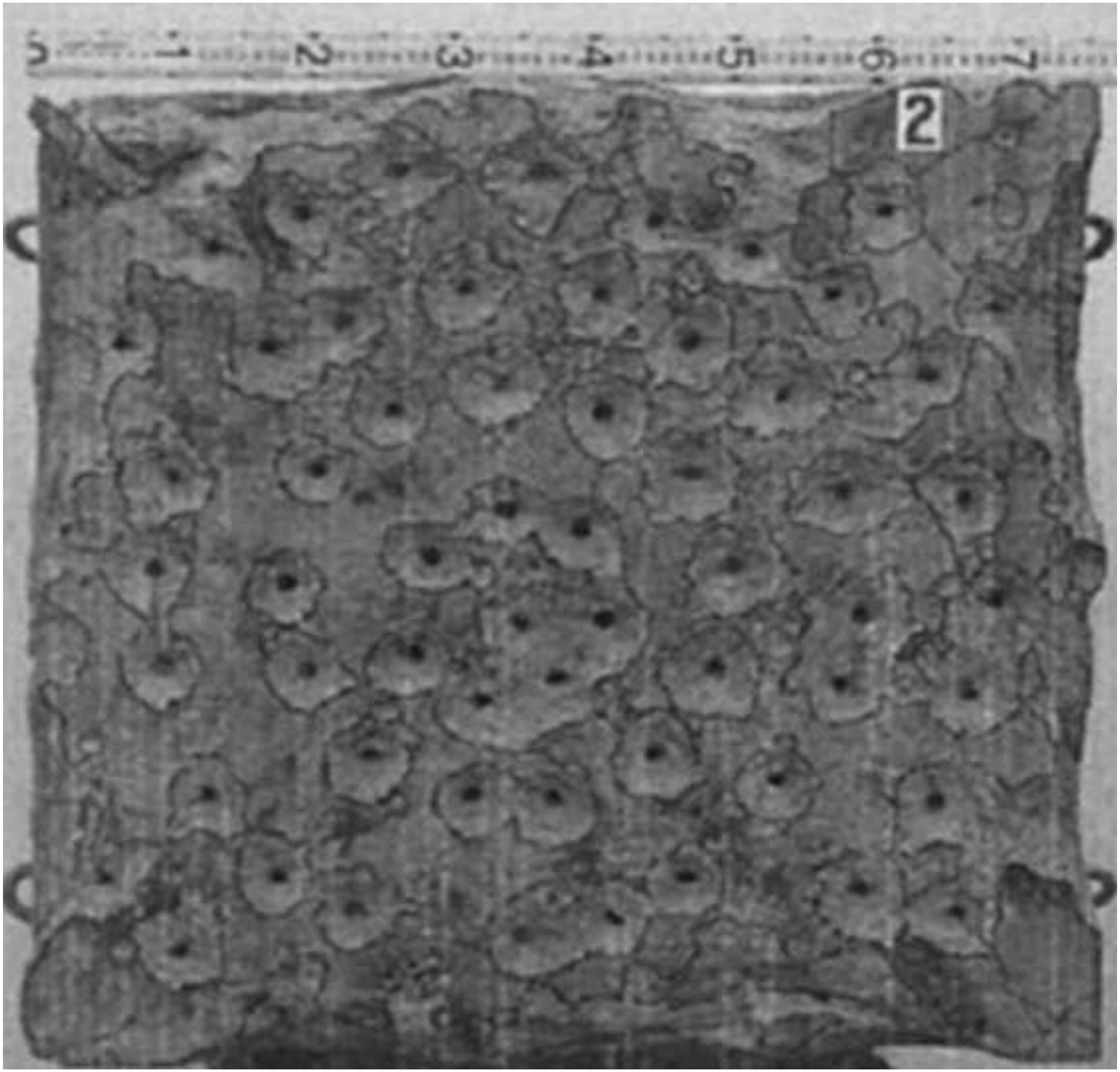
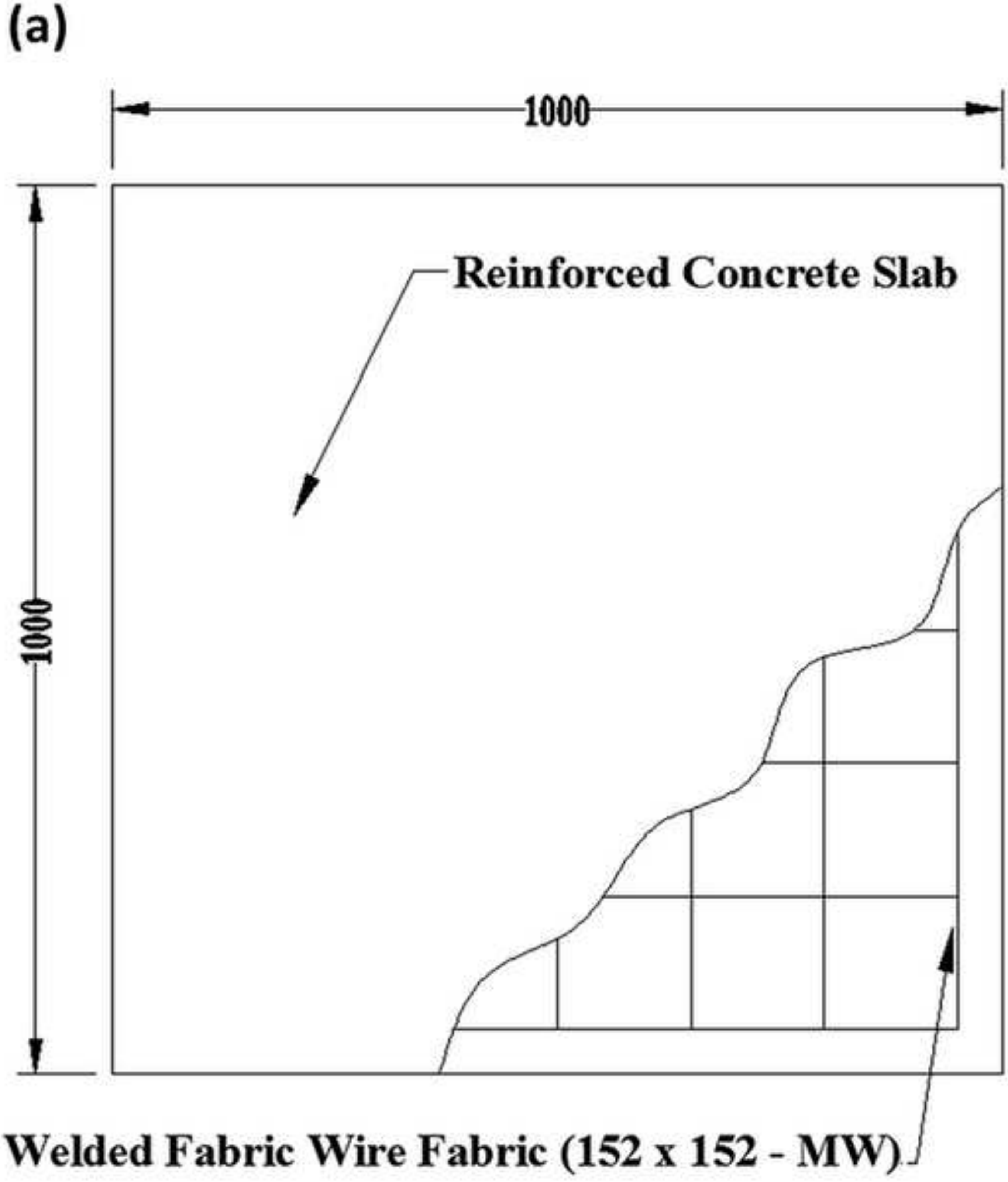
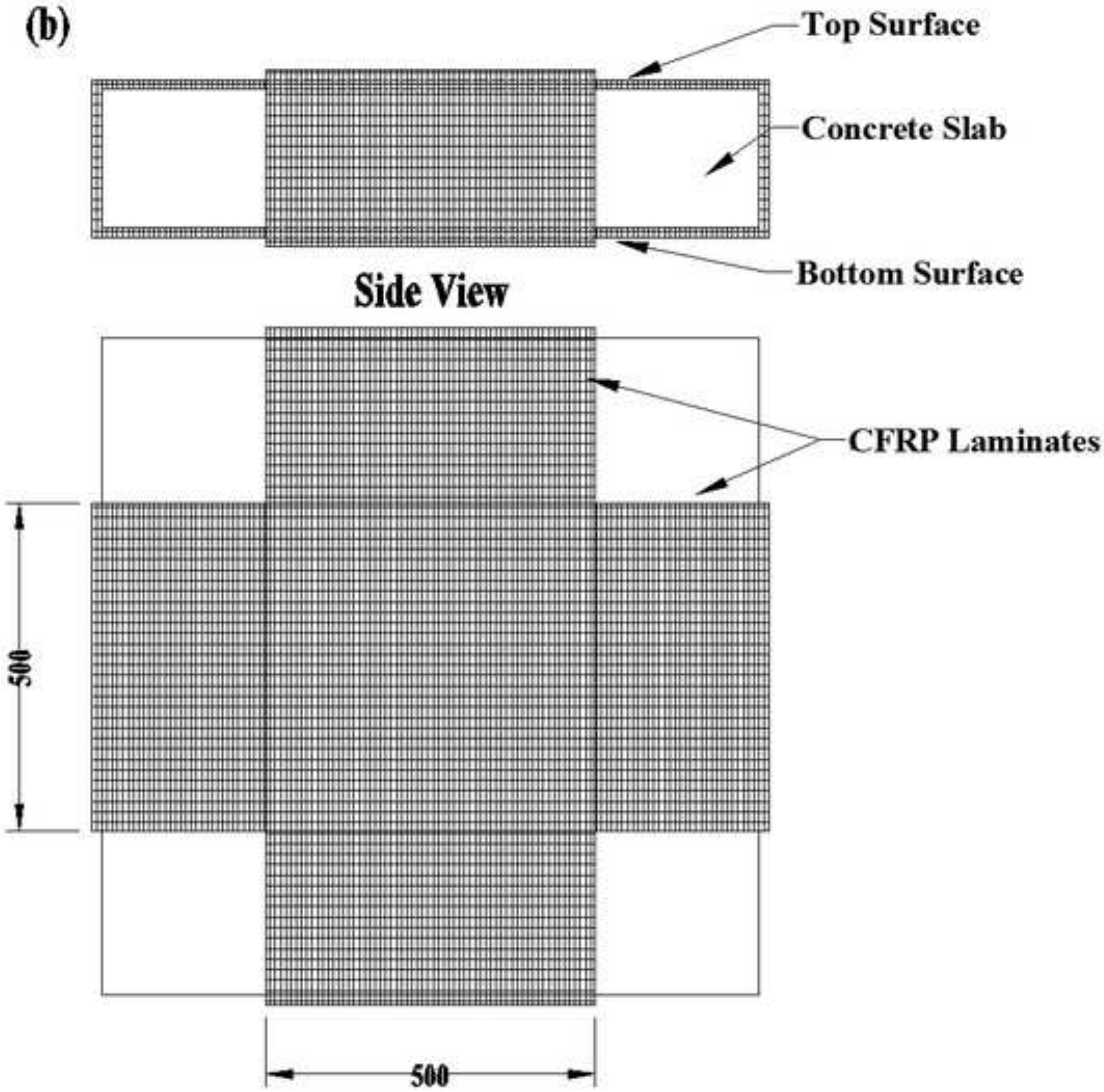
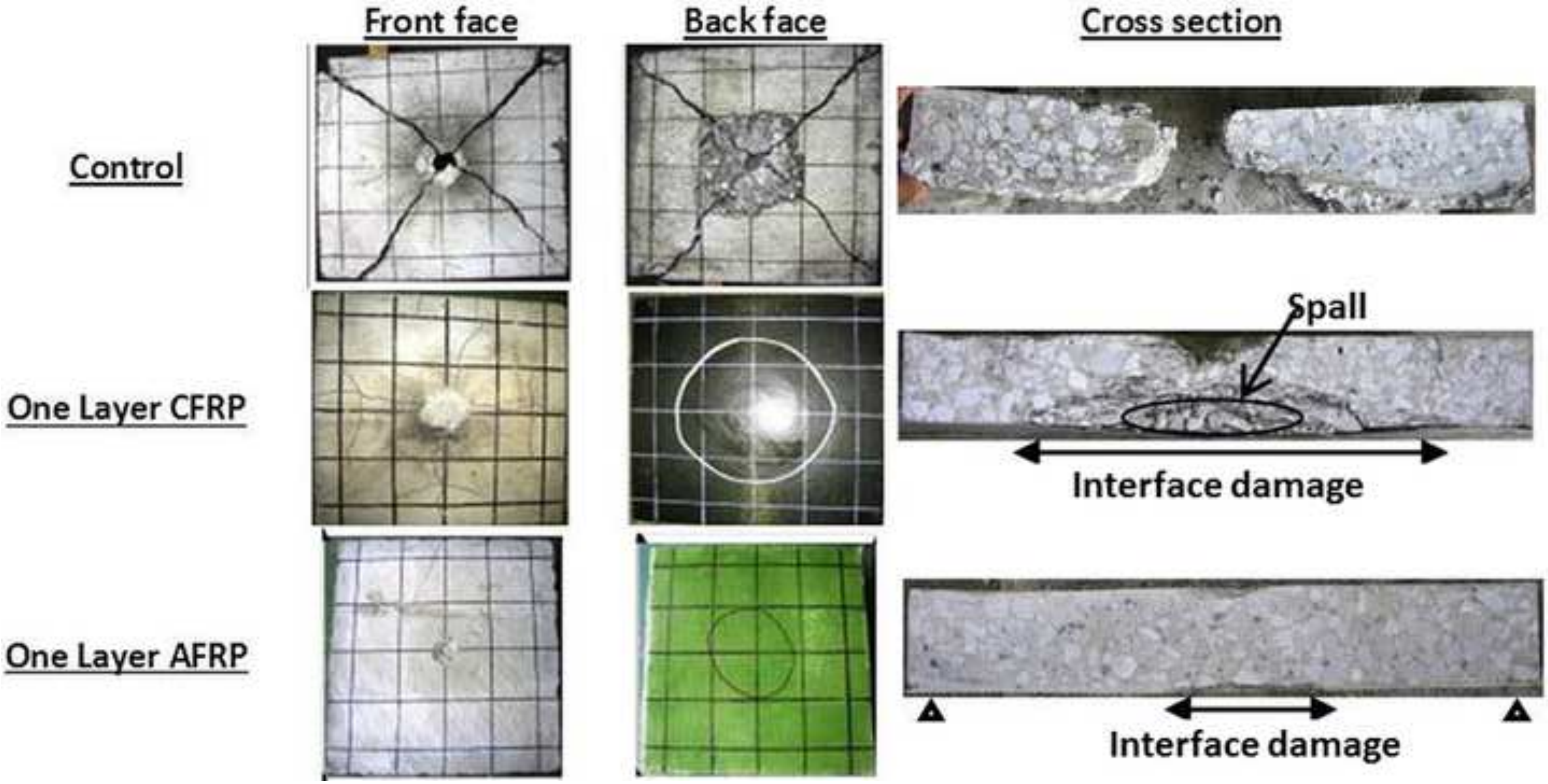
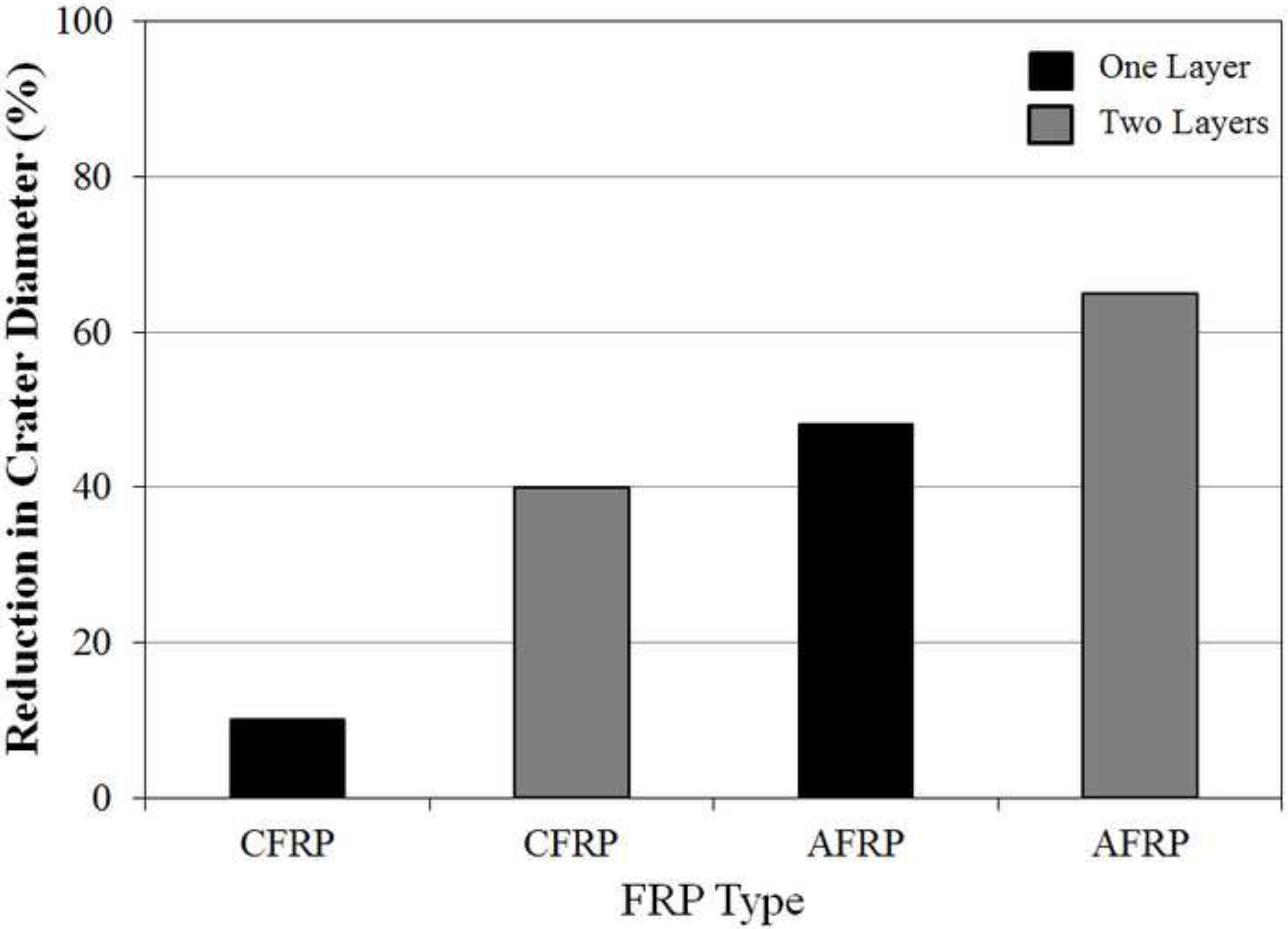
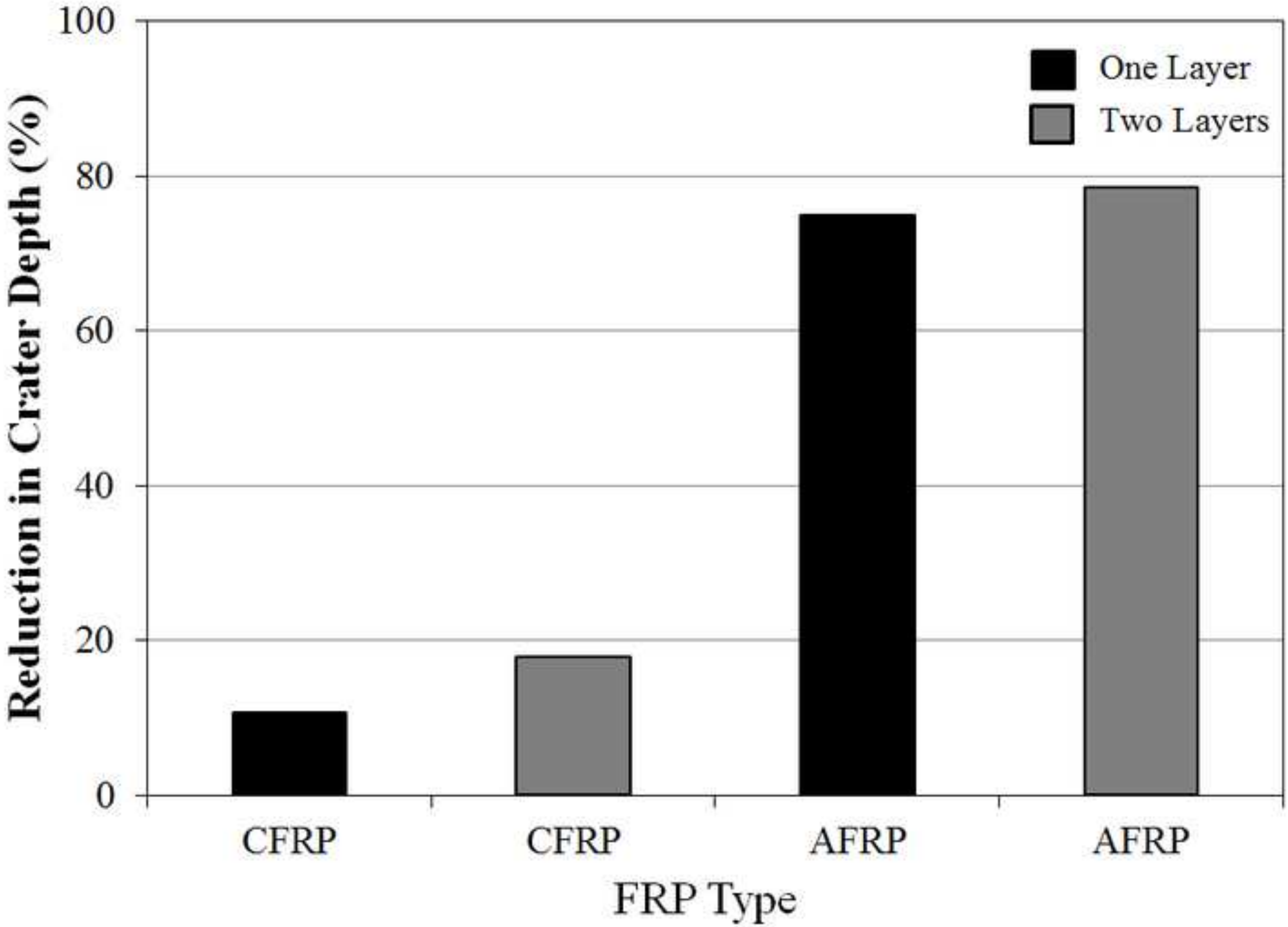


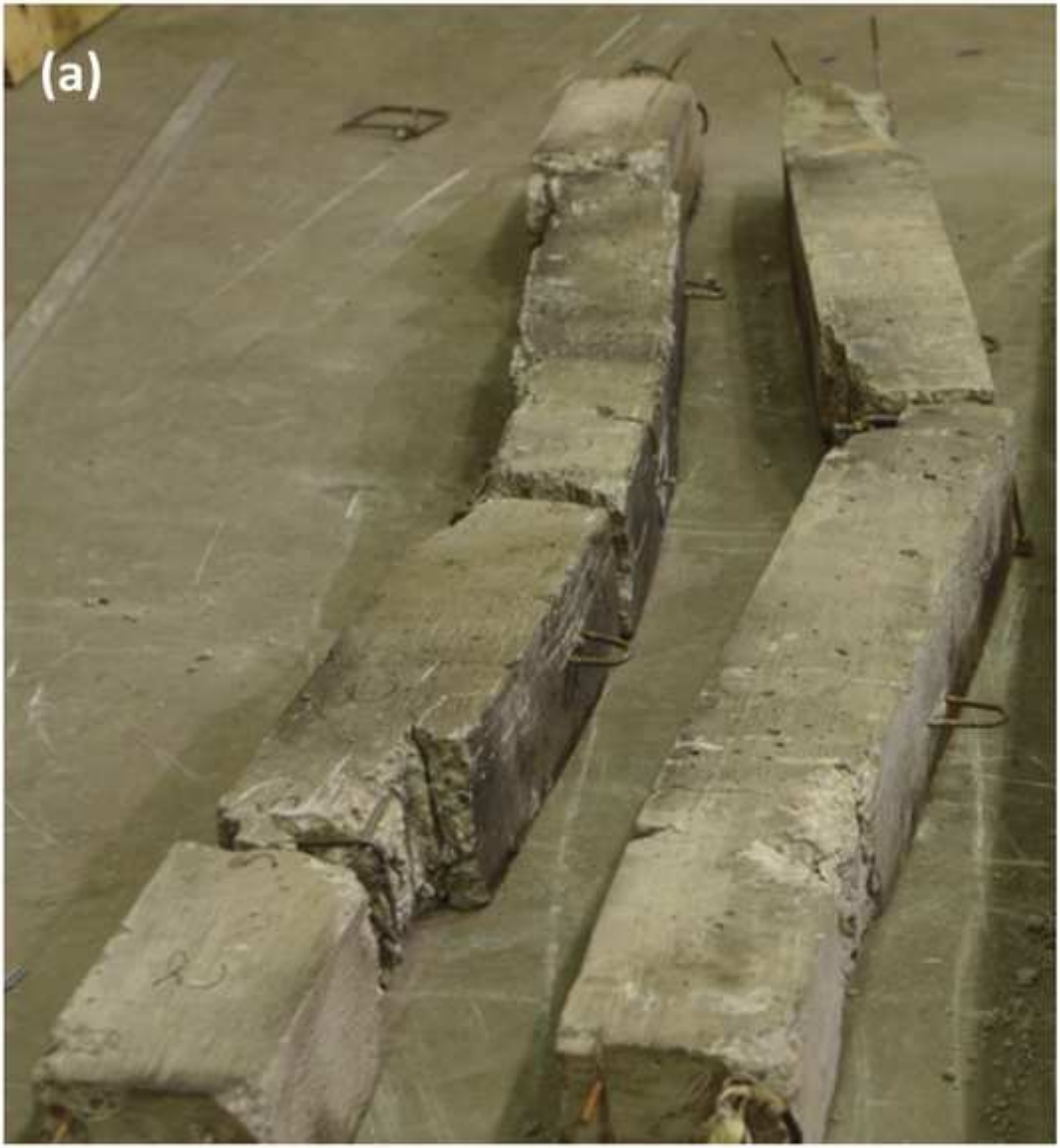

(a)
1000
1000
Reinforced Concrete Slab
Welded Fabric Wire Fabric (152 x 152 - MW)


(b)
Top Surface
Concrete Slab
Bottom Surface
Side View
CFRP Laminates
500
500


Front face
Back face
Cross section
Control
One Layer CFRP
Spall
Interface damage
One Layer AFRP
Interface damage


100
80
60
40
20
0
Reduction in Crater Diameter (%)
One Layer
Two Layers
CFRP
CFRP
AFRP
AFRP
FRP Type


Reduction in Crater Depth (%)
100
80
60
40
20
0
One Layer
Two Layers
CFRP
CFRP
AFRP
AFRP
FRP Type


(a)


(b)


(a)
EVENT 09
SLAB 4B

*Figure