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Structural protective design with innovative concrete material and retrofitting technology

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Abstract

Retrofitting technology and high performance construction material are now widely investigated so as to increase structural ductility and robustness under extreme loading conditions. In the present study, some recent developments in structural protection against blast loads are compiled. Metallic foam materials with varying foam density and gradient are used in the cladding design, their energy absorbing capacities and stress-strain relationships are studied based on uniaxial compression tests. These foam material are used to cast sacrificial claddings on the concrete slabs in the field blast tests. Damage and structural deformation are measured to check the effectiveness of the claddings. Besides sacrificial foam cladding, concrete material with new reinforcement scheme including steel wire mesh and micro steel fiber is developed, and the static test results indicates the excellent ductility and crack control ability of this novel design. In the field blast tests, concrete slabs with different steel wire mesh reinforcement are exposed to varying blast loads. The effectiveness of the slab reinforcing design is discussed based on field performance.

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Keywords: Aluminum foam cladding, steel wire mesh reinforcement, blast load;

1. Introduction

Industrialization and rising of terrorism over the past decades highlight the necessity of structural protection against extreme loads including impact and blast. Blast loads not only have direct impact on personal safety through

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instantaneous overpressure and fragments, but also cause structural failure. The latter one is more critical that usually leads to massive loss. A reliable structural protective analysis and design requires thorough understanding on material and structural performance under both static and dynamic loading environments.

For most existing structures, protective retrofitting can enhance their resistance against blast loads during the service life. Through maintaining the structural strength and redundancy, the risk of structural progressive collapse can be reduced and injuries and fatalities can be minimized. Until now, a number of solutions have been taken towards the protective design of structures under blast loads.

Perimeter protection including wall, fence and bollard is often taken as the most effective way to protect the structure in an explosion, however, this method is often impractical in urban area where space is at a limitation. Due to the extremely fast nature of the blast load, the inertia force plays critical role in resisting the blast load, adding mass (concrete cover) can therefore help improve the structural performance. However, the retrofitting can be expensive and time consuming, the added weight can also influence the structure foundation. The stress wave induced concrete fragmentation cannot be solved as the added concrete cover is still weak in tensile.

Surface retrofitting with fiber reinforced polymer (FRP) is used in structural protection against seismic and blast loads. Due to the superior properties of the modern FRP composites including high strength to weight ratio, anti-corrosion, rapid construction and minimal disruption to the structure function, this retrofitting technique is now widely used worldwide. However, it is important to note that the use of FRP is often dictated by strain limitations [1]. The large differences in strength and coefficients of thermal expansion can result in bond deterioration and splitting of concrete [2]. Similarly, steel studs and plates have been used either on the tensile surface or the entire surface of the existing concrete components, and such retrofitting can substantially increase the structural energy absorbing capability thanks to the high strength and ductility of steel [3].

Besides steel and FRP cladding, metallic foam cladding is also under extensive study in recent years. The typical behavior of metallic foams under compression features a linear-elastic state, a plateau stress state, and a densification state. Before fully densification, metallic foam undergoes significant plastic deformation that consumes large amount of energy. Until now, the most widely used metallic foam material is made of aluminum. This mobile and lightweight foam material allows high energy absorption due to its long, nearly constant stress level under compression. When blast occurs near a structure retrofitted with sacrificial aluminum foam, based on the momentum conservation, the impulse applied on the foam is the same as the transmitted impulse applied on the structure. The foam layers prolong the blast loading, and they reduce the peak overpressure impacting on the contact surface between the foam and the protected structural member.

Some previous experimental studies acknowledged the beneficial effects of metallic foam material in resisting impact [4] and blast loads [5]. However, some other experiments observed opposite results. Impact tests [6, 7] found that beyond a critical impact velocity, shock front formed in the foam followed by the stress enhancement on the protected structures. Hanssen et al. [8] observed that the addition of aluminum foam panels significantly increased the energy and impulse transfer to the protected structure. Analytical studies found that the efficiency of energy absorption of metallic foam material depends only on the initial density of the foam, the density of the constitutive material of the foam, but also depends on the Mach number and the critical stress of the foam. Apparently, more experiments and analysis on the effectiveness of the metallic foam cladding in the protective design are necessary.

Besides surface retrofitting, novel construction material has experienced fast development over the past decades. As a notable representative, ultra-high performance concrete (UHPC) features high compressive and tensile strength. Its exceptional material ductility allows sustaining large flexural and tensile loads, even after initial cracking. Extensive studies had been carried out to understand its static and dynamic performance [9] and also its application in the extreme loading environments [10-12]. One drawback of the UHPC is its high material cost which is largely caused by the fiber material consumption. Protective design with UHPC normally requires doubly reinforcement with high strength steel so as to satisfy the cross-sectional capacity in resisting the high intensity blast loads, and this requirement increases the construction cost and does not take full advantage of the UHPC properties such as the material self-compacting capability and fire resistance capacity.

In the present study, some recent field blast tests results are presented. Performances of reinforced concrete slabs with and without aluminum foam cladding are compared. In addition, high strength concrete slabs with new reinforcing scheme, i.e. the steel wire mesh and micro steel fiber, are also experimentally investigated. Through static material tests and field blast tests, the effectiveness of the novel design is demonstrated and steel wire mesh reinforcement as well as fiber reinforcement are tested.

2. Effects of aluminum foam cladding

In the present study, two kinds of closed-cell aluminum foams are considered, i.e. uniform density foam and functionally graded density foam, and the later one allows better design ability and attracted great attentions recently [13]. Graded density foam with multi-layers are involved in various optimizations to achieve a controlled energy absorption and safety protection. Typical stress strain curves of uniform foam and graded foam material under compressive load are illustrated in Fig. 1 [14].

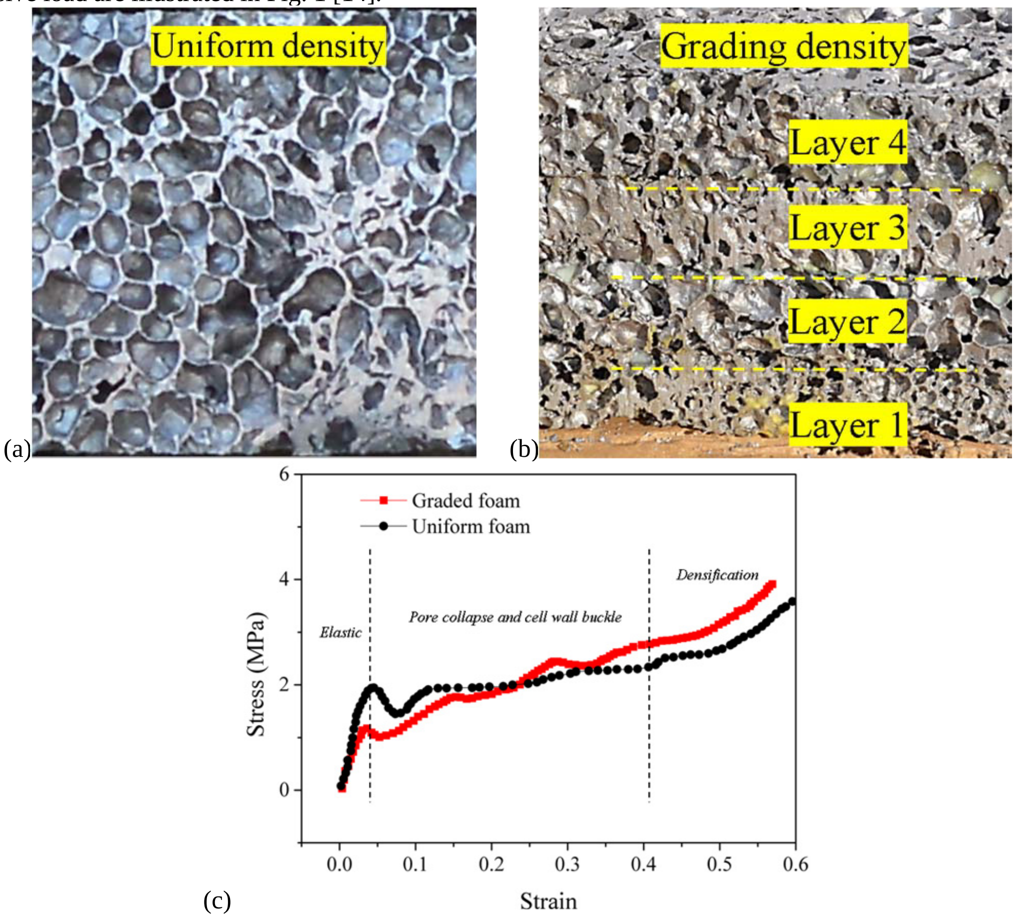

Fig.1. (a) Uniform density foam structure; (b) Grading density foam structure; (c) uniaxial compressive stress-strain relationship of foam material.

Abundant researches were carried out to characterize the dependence of the plateau stress upon foam relative density. Based on the deformation mechanism, formulae had been developed that relates the plateau stress to the relative density of the foam [15]. Based on the equation given in [15], Ruan et al. [16] proposed an expression for the plateau stress as a function of strain rate and relative density. In some other researches, the plastic stress dependency was extended to not only on the relative density but also on the pore sizes [17]. Despite these efforts, there are no established dependencies of foam stress on the foam relative density, and this is mainly due to the large variety of the foam topology.

In the present study, uniaxial compression tests were carried out and the results on foam material are summarized in Fig. 2. For the uniform density foam material UD250 and UD300, and the stress plateau after initial compaction can be clearly identified as 2 MPa and 4.5 MPa, of which the densification strain were about 0.55. UD400 material had a higher plateau stress of 7 MPa but lower densification strain about 0.5. For the graded foam material, strain hardening effect was observed, rather than a stress plateau, the compressive stress increased almost exponentially, and this trend was more prominent with the increase in the gradient from 1.25 to 2. These characters of graded foam material are understandable, and the initial compaction stress on the graded foam was controlled by the weakest layer along the depth where the density was also the lowest. The second lowest density layer started to crush after the densification stress of the first layer reached the plateau stress of the second layer.

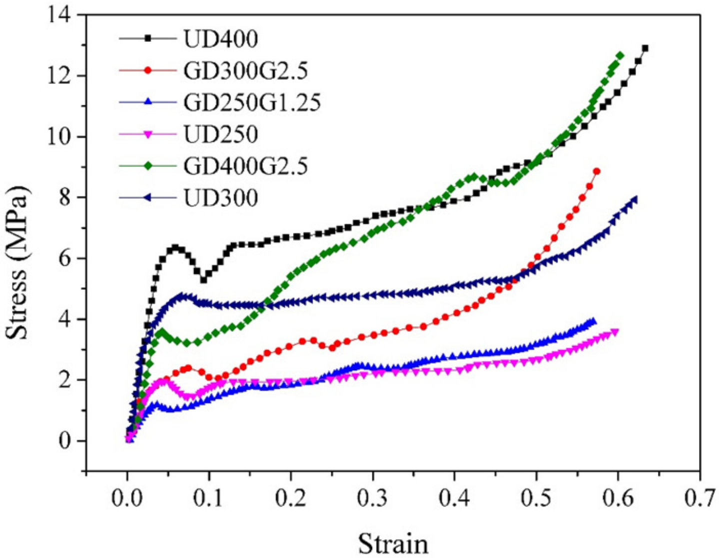

Fig. 2. Stress-strain curves of aluminium foam under compressive load

Field blast test setup and slab configuration is shown in Fig. 3. In all the tests, the charge weight was kept constant as 8 kg TNT in cylindrical shape, and the explosive was set to detonate at 1.5 m above the slab surface. The foam cladding information of the three slabs are shown in Table 1. In addition, one normal strength concrete slab without foam cladding was tested under the same blast loads. The unconfined compressive strength of the concrete was 35 MPa while the yield strength of all reinforcing steel bars (12 mm longitudinal rebar and 10 mm stirrup rebar) was 350 MPa. A thin layer (1.13 mm) of steel plate was used to cover the foam cladding, and such setup was aimed at engaging more foam material to resist the blast loads.

Table 1. Foam cladding properties

Type	Layer Density (kg/m3)				Average Density (kg/m3)	Density Gradient (kg/m3/mm)
	1	2	3	4		
GD250G1.25	215	230	261	293	250	1.25
UD300	--	--	--	--	300	--
GD300G2.5	204	269	333	360	300	1.25
GD400G2.5	327	355	431	463	400	2.5

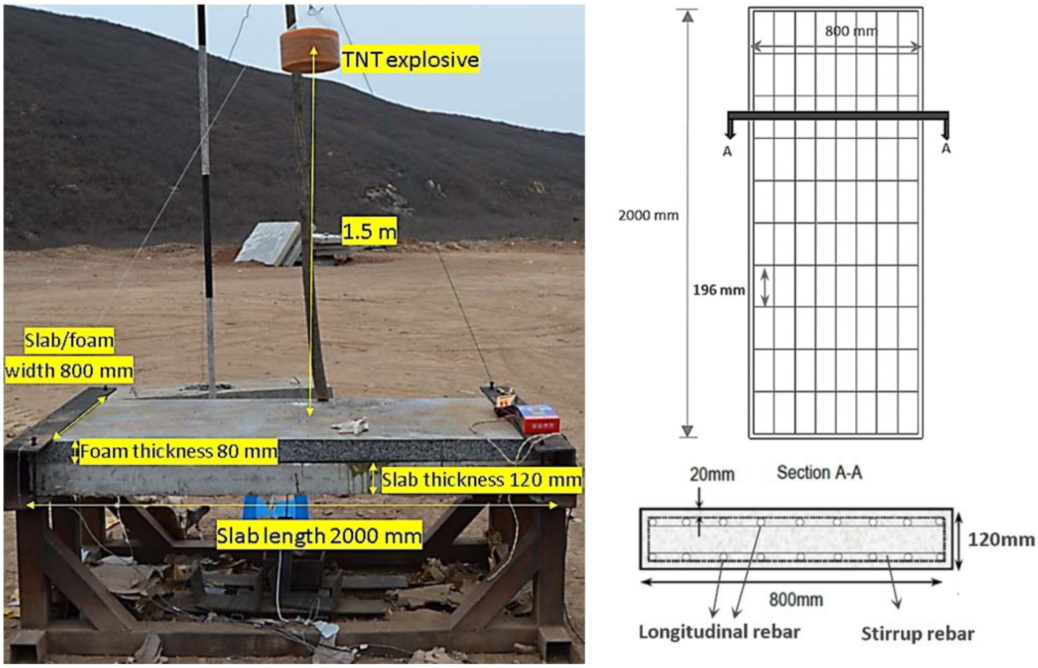

Fig. 3. Test setup and slab configuration

Post failure observation on these slabs are shown in Fig. 4. All slabs, with and without foam cladding, failed in flexural mode with mid-span reinforcement yielding and concrete cracking. Due to the nature of the close-in detonation, the blast load was not evenly distributed along the slab surface. The foam material that located directly beneath the explosion experienced the most severe compaction. Because of the size limit of the slab, blast clearing effect occurred at the slab short edge leading to unsymmetrical foam compression zone.

Post-blast mid-span permanent deflection was measured manually. The slab without foam cladding experienced a permanent deflection of 190 mm. Slabs with sacrificial foam cladding yielded lower deflection as presented in Fig.4. Despite these observations indicated the beneficial effect of adopting foam material in the blast resistance design, concerns remained if possible shock wave was induced, associated with the formation of strain discontinuity. In [7], the impact velocity under which the shock wave can occur in foam materials with strain hardening was defined. The shock wave may initiate where the impact velocity V exceeds the acoustic wave speed C in the foam.

$$V(t) > C(\varepsilon) \tag{1}$$

$$C(\varepsilon) = \sqrt{\frac{d\sigma}{d\varepsilon}\frac{1}{\rho_f}} \tag{2}$$

It is apparent that is C is a function of material strain hardening, and this implies that shock waves in materials that exhibit noticeable hardening will occur at higher impact velocities compared to the stress wave speeds in materials with negligible strain hardening [18]. For the current foam material like UD300, the wave speeds defined by Equation (2) increase from approximately 100 m/s at the initial foam yielding to approximately 650 m/s at ε = 0.7 and increase further for the higher strains. Due to the limitation in the field blast tests, the impact velocity from the blast load was not measured in the field blast tests, in the future numerical analysis, the phenomenon of shock wave can be studied and its influence on the foam protection can be detailed discussed.

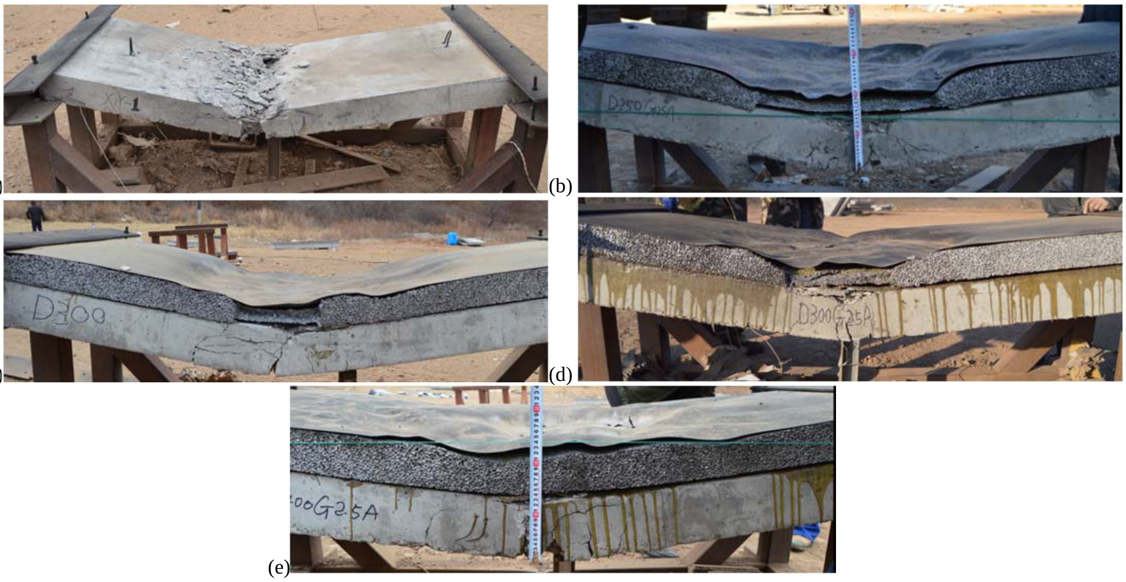

Fig. 4. Post-blast observation; (a) No cladding, 19 cm deflection; (b) GD250G1.25, 14 cm deflection; (c) UD300, 13 cm deflection; (d) GD300G2.5, 11 cm deflection; (e) G400G2.5, 10 cm deflection.

3. Effects of new reinforcement scheme

Comparing with conventional steel bar reinforcement, steel wire mesh has several beneficial characters. It can be easily adapted into different structural designs and maximize the workability of concrete. The performance of steel wire mesh reinforced concrete can be programmable with the change of steel wire mesh fraction and properties. Previous experimental studies found that steel mesh reinforcement in concrete mortar can satisfy the ultimate strength limit state under bending load [19]. In the recent study, effects of steel wire mesh reinforcement in the slab design under blast loads were experimentally investigated, and the results are briefly summarized in this paper.

Different to the concrete material that used in the foam cladding retrofitted slabs, in this series of tests, high strength concrete with adoption of high pozzolanic silica fume and superplasticizer were used. The concrete strength was about 60 MPa. In addition to the steel wire mesh reinforcement, in the concrete protective layer, micro steel fibers with a length of 3 mm and diameter of 0.12 mm were mixed at 2% volume fraction. Addition of micro steel fibers can effectively increase material compressive, tensile and shear performance, and material abrasion capacity can also be enhanced.

Four-point bending test was carried out to investigate the flexural tensile performance of a steel wire mesh reinforced beam sample with fibers in the protective layer. Fig. 5 shows the four-point bending test on beam sample with 20 layers of steel wire meshes. A desired flexural failure of the beam was observed, and the sample sustained high mid-span deflection with excellent crack control.

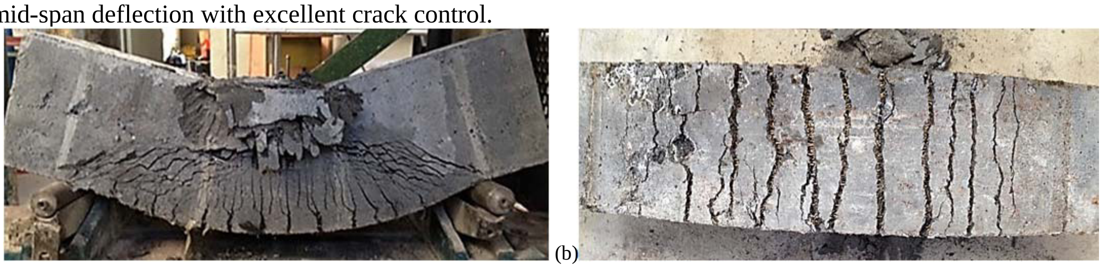

Fig. 5. Steel wire mesh reinfroced beam sample under flexural bending

In the field blast tests, slab dimension was kept unaltered from that shown in Fig. 2, and steel wire meshes were placed in the core layer of the slab. The test matrix is shown in Table 2.

Table 2. Steel wire mesh reinforced slab test matrix

Slab No.	Type	Explosive weight	Standoff distance
SWM-1	10 layer Steel wire mesh reinforced concrete	6 kg	1.5 m
SWM-2	20 layer Steel wire mesh reinforced concrete	6 kg	1.5 m
SWM-3	20 layer Steel wire mesh reinforced concrete	12	1.5 m

As shown in Fig. 6, 6 kg TNT explosion at 1.5 m standoff distance did not cause any flexural damage on the SWM-1 slab, and the slab showed elastic response, only some hairline cracks were noticed on the slab bottom and side surfaces. The same blast loads caused no damage or cracks on the SWM-2 slab, and it performed elastically under the blast loads.

(a) 

(b) 

Fig. 6. (a) SWM-1 slab under 6 kg TNT at 1.5 m distance; (b) SWM-2 slab under 6 kg TNT at 1.5 m distance

Performance of SWM-3 slab under severe blast load 12 kg TNT from 1.5 standoff distance is shown in Fig. 7. The slab responded in a flexural mode with a permanent deflection of 48 mm. Besides major cracks in the slab mid-span, hairline cracks were observed from the side of the slab indicating the slab experiences flexure greater than the cracking capacity; however as only hairline cracks are present, it implies that the internal moment is approaching, but does not reach the yield moment capacity. The cracking was minor and confined due to the bridging effect from steel fibre in the cover layer and steel wire meshi in the intermediate layer. In addition, possible membrane effect was developed in the steel wire mesh material because of the small spacing between the steel grids, and tensile membrane effect can effectively increase the moment capacity of the slab under blast loads.

Fig. 7: SWM-3 slab after 12 kg TNT detonation from 1.5 m standoff distance

4. Conclusion

In the present study, two protective designs on the concrete slab against close-in detonation are presented. In the first design, sacrificial metallic foam cladding was used to cover the concrete slab, and the energy absorbing capacity of the foam under compression effectively mitigated the blast energy transmitted to the protected slab. In the field blast tests, it was noted that blast induced damage was reduced in all retrofitted slabs, and the foam material with higher relative density had better performance, while the foam with graded density performed better than uniform density foam given they had the same average density. Further studies on the foam performance are deemed necessary to understand the blast wave propagation in this material.

High strength concrete was used in the second design aiming at high blast resistance. Steel wire mesh reinforcement in the core layer and steel fibre micro-reinforcement in the protective layer contributed to the high tensile strength and ductility. Field blast tests under severe blast load demonstrated that combination of the high strength concrete material with new reinforcing scheme, i.e. steel wire mesh effectively resisted the blast loads, and only minor damage was noted. A possible explanation to the improvement is that the close-spacing welded steel wire mesh developed localized tensile membrane effect even when small structural deflection occurred.

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