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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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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