Composite Structures 127 (2015) 426–435

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

# Perforation resistance of corrugated metallic sandwich plates filled with reactive powder concrete: Experiment and simulation

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ARTICLE INFO

*Article history:*
Available online 28 February 2015

*Keywords:*
Hybrid
Impact behavior
Concrete
Finite element analysis (FEA)

ABSTRACT

Motivated by the current development trends in the protection fields towards high performance, low cost and lightweight, this study investigates experimentally and numerically the ballistic performance of a novel hybrid-cored sandwich construction: metallic corrugated sandwich plate filled with high performance reactive powder concrete (RPC). Three different types of target plate are fabricated, including monolithic RPC plate, corrugated sandwich directly filled with RPC, and corrugated sandwich with RPC prism insertions and void-filling epoxy resin. The ballistic resistance of each plate vertically penetrated by a projectile at its center is experimentally measured. Numerical simulations with the method of finite elements are subsequently carried out. Corrugated sandwich plate with RPC prism insertions and void-filling epoxy resin achieves the best ballistic performance, as filling the interstices with epoxy resin improves the structural integrity of the sandwich while confinement of the RPC is supplied by the corrugated plates.



## 1. Introduction

Concrete is widely applied in building as well as protection fields because of its low density (less than 3.0 g/cm$^3$), low cost, and easy fabrication process. The ballistic performances of normal concrete [1], steel reinforced concrete [2], and fabric jacked concrete [3–5] have been studied extensively. However, the low compressive/tensile strength of traditional concrete structures restrict their application to relatively low velocity impact. In search for high strength concrete (HSC), Bludau et al. [6] demonstrated experimentally that aggregates having higher toughness and hardness led to enhanced ballistic resistance while reactive powder concrete (RPC) invented by the Bouygues Group, which is typically fabricated by mixing silica sand, Portland cement, silica fume, superplasticizer, etc, could achieve a compressive strength exceeding 200 MPa [7], much higher than that of traditional concrete. Subsequently, its was demonstrated that adding steel fibers could increase further the compressive/tensile strength, toughness, and impact resistance of the RPC. Experimentally, Hanchak et al. [8] found that the ballistic resistance of a RPC plate was enhanced as its compressive strength increased, exhibiting shallower penetration depth and smaller crater area relative to traditional concrete plate. Theoretically, Markovich et al. [9] revised the concrete damage model to describe the response of normal concrete under complex loading, while Holmquist et al. [10] put forward a general constitutive model for concrete subjected to large strain, high strain rate, and high pressure. On this basis, Tai [11] carried out numerical studies on the ballistic performance of RPC plates penetrated by flat ended projectiles, and provided a set of parameters for the constitutive model of RPC.

Along a separate research frontier, highly porous all-metallic sandwich constructions with fluid-through cellular cores have emerged as novel lightweight multi-functional structures [12,13]. For instance, in addition to carry structural loads, these sandwich structures can also dissipate heat. The cellular cores exploited thus far are typically periodic, including two-dimensional prismatic cores (e.g., honeycombs and corrugated plates) and three-dimensional lattice truss cores (e.g., pyramidal, Kagome and brazed wire screens). Compared with monolithic plates, metallic sandwich plates have the advantage of lightweight and high stiffness/strength. With good energy absorption capabilities, they can also effectively withstand impact and blast loads [14,15].

More recently, it has been demonstrated, both experimentally and theoretically, that metallic corrugated sandwich plates filled with ceramic insertions outperform the corresponding empty ones

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http://dx.doi.org/10.1016/j.compstruct.2015.02.059
0263-8223/

in terms of ballistic penetration resistance [16–18]. The outstanding ballistic performance of such a hybrid-cored sandwich plate lies in its ability to yaw the projectile and absorb the impact energy through the deformation and failure of the substructures. However, high temperature sintering procedure is typically required to process complex ceramic components, adding considerably the fabrication cost. In comparison, with competitive mechanical performance and low density, RPC can be prepared at room temperature and cast into different shapes. Hence, as a replacement of ceramic, the relatively low-cost RPC and its composite metallic sandwich plates show promising potential for protection applications.

Whereas existing studies on the penetration resistance performance of RPC plates considered mainly monolithic constructions, Remennikov et al. [19] demonstrated that axially-restrained steel–concrete–steel sandwich panels were capable of withstanding blast load or high speed impact. However, the concrete examined in [19] was normal concrete other than RPC. Motivated by the current development trend of high performance, low cost and lightweight in protection fields, the present study aims to investigate, both experimentally and numerically, the ballistic performance of RPC and its composite metallic sandwich structures. In addition to monolithic RPC plates, two different types of sandwich construction are considered: corrugated metallic sandwich plates directly filled with RPC, and corrugated metallic sandwich plates with RPC prism insertions and void-filling epoxy resin. Upon validating the finite element (FE) simulation results with experimental measurements, the ballistic limit velocity, failure mechanisms as well as energy absorption capacity of each target plate are systematically investigated. Under the constraint of same total mass, a preliminary optimization is performed.

## 2. Fabrication of test specimen and ballistic experiment

### 2.1. Test specimen

With reference to Fig. 1, three different types of test specimen are fabricated, including monolithic RPC plate (RPC plate), corrugated metallic sandwich plate directly filled with RPC (RPC-Corrugated plate), and corrugated metallic sandwich plate with RPC prism insertions and void-filling epoxy resin (RPC-Corrugated-Epoxy plate). The overall dimensions of the RPC plate are 180 mm × 150 mm × 19 mm, while both the RPC-Corrugated and RPC-Corrugated-Epoxy plates have 180 mm × 150 mm × 17 mm.

The monolithic RPC plate is made from a mixture of six raw materials: 42.5# ordinary Portland cement, silica fume, quartz sand, water reducing admixture (polycarboxylate), brass coated steel fibers (0.18–0.23 mm in diameter, 12 mm in length) and distilled water, with mass proportion of 0.9:0.1:1:0.018:0.083:0.15.

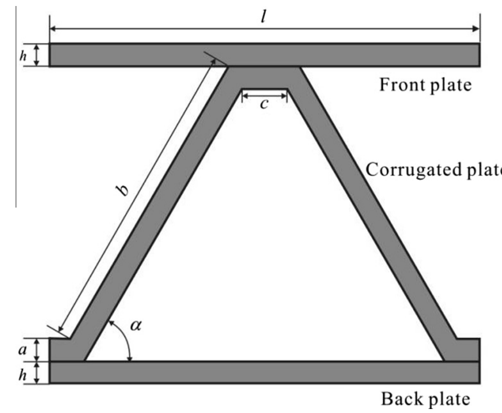


**Fig. 2.** Schematic of a unit cell of empty corrugated sandwich plate.

After about 3 min of stirring, the mixture is cast into a mould, followed by water oven curing (80 °C for 8 h). The as-fabricated monolithic RPC plate has an areal density of 43.6 kg/m$^2$, a mass density of 2.29 × 10$^3$ kg/m$^3$ and an axial quasi-static compressive strength of 175 MPa.

To fabricate the RPC-Corrugated and RPC-Corrugated-Epoxy plates, empty corrugated sandwich plates are firstly prepared with AISI 304 stainless steel (with a density of 8.0 × 10$^3$ kg/m$^3$) using the brazing process. Fig. 2 displays the side view of a unit cell of the empty sandwich. The thickness of the front and back face sheets as well as that of the core plate is fixed at $a = h = 1.0$ mm. The corrugated plate has a side length of $b = 18.3$ mm, width of 150 mm, and an inclination angle of $\alpha = 50°$; to facilitate brazing, a small platform of $c = 1.6$ mm is allowed at the apex of the corrugation (Fig. 2).

To fabricate the RPC-Corrugated plate, raw RPC is directly poured into the prismatic voids of the empty sandwich. Upon casting, the RPC-Corrugated plate is placed at room temperature for 24 h and then cured under the same condition as the monolithic RPC plate. The as-fabricated RPC-Corrugated plate has an areal density of 55.4 kg/m$^2$ and a mass density of 3.26 × 10$^3$ kg/m$^3$.

For the RPC-Corrugated-Epoxy plate, RPC prisms are firstly fabricated following the same procedures as those for the monolithic RPC plate. In order to leave space for epoxy resin, these RPC prisms have slightly smaller transverse dimensions (base 20 mm and height 12 mm) than the prismatic voids of the corrugated plate. Subsequently, epoxy resin is poured into the prismatic voids before the RPC prisms are inserted, with extra epoxy resin extruded out after the insertion is complete. Finally, the hybrid-cored sandwich plate is placed at room temperature for 7 days to solidify the epoxy resin. The as-fabricated RPC-Corrugated-Epoxy plate has an areal density of 50.6 kg/m$^2$ and a mass density 2.97 × 10$^3$ kg/m$^3$.

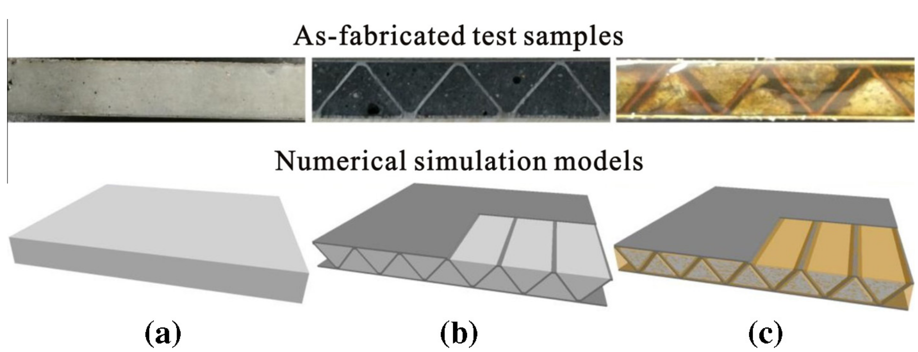


**Fig. 1.** Comparison between numerical (finite element) model and as-fabricated test sample for protective application: (a) monolithic RPC plate, (b) corrugated metallic sandwich plates directly filled with RPC, and (c) corrugated metallic sandwich plates with RPC prism insertions and void-filling epoxy resin.