International Journal of Impact Engineering 86 (2015) 13–26

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Cellular cement composites against projectile impact

Choon Wei Roy Ong, Min-Hong Zhang, Hongjian Du, Sze Dai Pang*

Department of Civil and Environmental Engineering, National University of Singapore, 117576, Singapore

ARTICLE INFO

Article history:
Received 17 January 2015
Received in revised form
19 May 2015
Accepted 28 June 2015
Available online 6 July 2015

Keywords:
Bio-inspired
Confinement
Size effect
Numerical simulations

ABSTRACT

Increasingly, it is recognised that the abundant resources of evolutionized biological materials and structures provide an exciting opportunity for growth in the area of materials engineering for impact and projectile resistance. A bio-inspired cellular structural system is developed to contain the radial fracture damage of mortar due to projectile impact through boundary impedance mismatch, while utilizing its adjacent cells as a mutual confining mechanism to improve penetration resistance. The penetration resistance was evaluated on a hexagon cell which is confined mutually by six other identical neighbouring cells in a rigid mould and subjected to a 7.77 g, 8 mm diameter, AISI4140 High Strength Steel projectile impact at ~450 m/s. Three cell sizes (50 mm, 70 mm and 90 mm) with two types of cellular interface material (air and silicone) were investigated. These were then compared against monolithically cast mortar control specimens of their respective sizes. It was found that the cellular design was effective in significantly reducing the radial damage for an incoming projectile by up to 26%, with a modest increase in penetration depth of up to 12%. Furthermore, specimens with silicon as the cellular interface material demonstrated a 33% reduction in proximal crater damage across all specimen sizes tested, with up to 10% increase in penetration depth. Numerical Simulations using LS-Dyna in 3D quarter-symmetry has also led to better understanding of the physical shockwave interactions modified by a cellular design, allowed verification of the experimental results and supported the authors' explanations of the physical phenomena. Overall, penetration depths and crater diameters were within 10% and 20% of the experimental results respectively. This research has useful field applications when extensive radial damage is costly to repair, and penetration resistance is not the most critical consideration.

1. Introduction

1.1. The humble armadillo

Building and facility protection has been an ongoing challenge, especially with the improvements in weapon technology. Toughening of surface, subsurface, and super-structures consumes more construction resources in order to build greater global structural redundancy and better local material resistance to weapon effects. The evolution of weapon effects is not likely to be abated in the near future, and this fuels the continued need for better protection systems with more innovative ways in defeating new weapon systems. One way is to look towards nature, where the abundant resource of evolutionized biological materials and structures provides an exciting opportunity for growth in the area of materials engineering. The need for a species' survival and success has driven some mammals to develop natural protective armour systems which are flexible, self-healing, and multi-functional. These natural structural protective systems incorporate features of low density, high hardness, with high energy absorption. In particular, in the area of biological armour protection using osteoderms ("bony skins"), investigations have ventured towards the armadillo [1], amongst other animals. This research is a bio-inspired development of a cementitious structural system stemming from the natural armour protection of the "armadillo". Fig. 1 shows the make-up of the armadillo's armour. Close study of the structure of the armadillo's natural armour inspires three mechanisms that can be used for armour protection: (1) cellular design of high strength tiles to limit radial damage from an incoming projectile [*the armadillo uses osteoderms or "bony skins" made up of dead cells known as α-Keratin*], (2) energy absorbing inter-tile material [*the armadillo makes use of flexible collagen*] and (3) minimise lateral displacement of tiles through mutual confinement between tiles to improve penetration resistance [*through a hexagonal tile arrangement system*].

* Corresponding author. Tel.: +65 65162799.
E-mail address: ceepsd@nus.edu.sg (S.D. Pang).

http://dx.doi.org/10.1016/j.ijimpeng.2015.06.020
0734-743X/

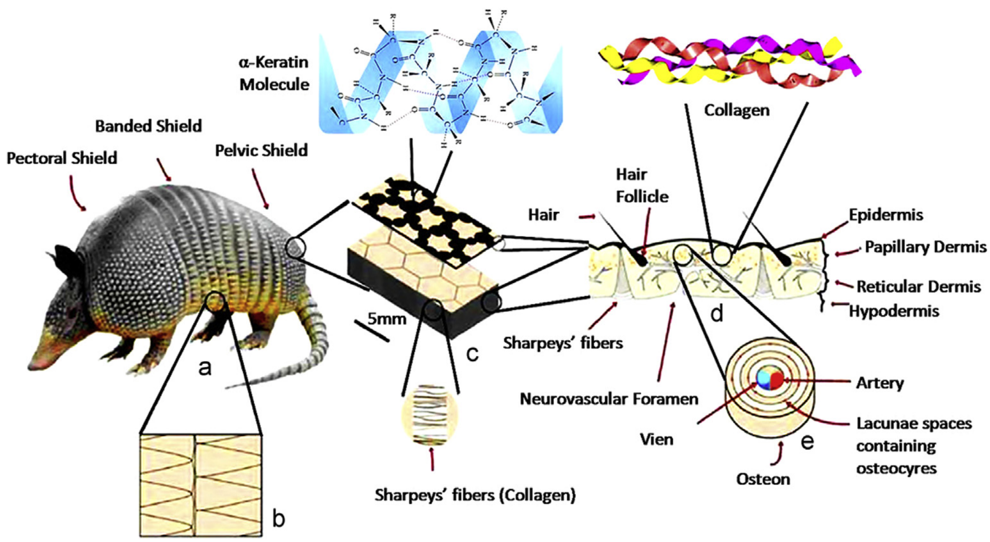

Fig. 1. Juxtaposed hexagonal plates of an Armadillo's armour, separated by flexible collagen. Source: [2].

1.2. Usage of hexagonal tiles

The use of hexagonal tiles for ballistic protection has been seen in the products of LAST-ARMOR®- aircraft slap-on cellular armour solutions for military applications, NEVZ-CERAMICS, KYLIN, and LITAI- technical ceramics for ballistic protection, and very recently studied by Chintapalli et al. [3] who laser-engraved hexagonal segments onto glass mounted on rubber substrate, and reported penetration improvements of up to 70%. This design has also been used extensively in architectural works in pavements and ceramic floor tiles for ease of construction and assembly. (See Fig. 2). However, the application of this design for projectile impact resistance for high strength mortar systems have not been given extensive treatment yet, and the use of cementitious materials have potential for large scale applications due to economic considerations compared to technical ceramics.

1.3. Scope of study

Inspired from the armadillo's natural armour, it is intended to develop a cellular system comprising of 7-hexagonal cells adjacent to each other (See Fig. 3) to study the effect of mutual confinement on the center cell which is subjected to projectile impact. The 7-cell assembly is placed in fitting steel mould to simulate a larger semi-infinite system of hexagonal tiles, and test this cellular system for its ballistic performance. This design has two distinct mechanical features:

(1) Zero-lateral displacement. It is intended to use adjacent tiles to impose an almost zero-(lateral)-displacement boundary condition on the impacted tile so as to increase its impact resistance by delaying failure due to volumetric dilation in the lateral direction.
(2) Impedance mismatch. The introduction of an impedance mismatch has the effect of confining the majority of radial cracking to within the impacted tile. The deliberate introduction of media discontinuity also relieves the stress concentration at the crack tip as cracking progresses towards the boundary, thereafter, arresting the crack propagation. Moreover, the introduction of a higher impedance boundary has the effect of reflecting the incident compressive wave as a compressive wave rather than a tensile wave. This leverages on the compressive strength of concrete, and mitigates its weak tensile strength.

1.4. Research significance

The development of a hexagonal cellular mortar system is original and has the potential for macro-scale applications, particularly in revolutionalising the construction design of surface facilities such as runways and critical roads which may be subjected to bomb runs by enemy aircraft or land-based weapon systems. In rapid runway repair (RRR) operations, the size of craters, and the distance between them is of great concern to the civil engineer as these two factors limits the choice of a minimum operating strip,[1] and increase the repairs required. By increasing the spacing between craters, and reducing the crater size, vibrations imparted from one repaired crater onto the aircraft can be allowed to dampen out before it hits another repaired crater. Decreasing the crater size in turn increases the area suitable for the sitting of a minimum operating strip. See Fig. 4 for an illustration.

2. Experimental approach

2.1. Materials and test matrix

Table 1 shows the test matrix for this phase of the research. Three types of specimens were cast and assembled for this test. For the cellular specimens, two types of cellular specimens were experimented. The thickness of the cells were 50 mm (nominal) throughout for all specimen sizes.

(1) Monolithic Mortar specimens of similar size and weight but without cellular construction were used as controls. For each configuration, 150 mm (50 mm cell), 210 mm (70 mm cell) and 270 mm (90 mm cell) specimens (measured flat-to-flat) were cast to investigate the size effects.

[1] A runway which meets the minimum requirements for operating assigned and/or allocated aircraft types on a particular airfield at maximum or combat gross weight (Dictionary of Military and Associated Terms. US Department of Defense 2005). In other words, the minimum length and width of a portion of a runway that is required to allow an aircraft of a certain size and weight to land and takeoff.