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Impact behaviour of plate-like assemblies made of new and existing interlocking bricks: A comparative study

A. Rezaee Javan[a], H. Seifi[a], S. Xu[a], X. Lin[a], Y.M. Xie[a,b,*]

[a] *Centre for Innovative Structures and Materials, School of Engineering, RMIT University, Melbourne, Victoria 3001, Australia*
[b] *XIE Archi-Structure Design (Shanghai) Co., Ltd., Shanghai 200092, China*

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ABSTRACT

This paper presents an extensive numerical study on the impact behaviour of plate-like assemblies made of interlocking concrete bricks. In the proposed 3D finite element model, a damage based concrete model is employed with considerations of strain rate effect and concrete failure criteria. Boundary conditions are appropriately defined to simulate various initial loading scenarios. The impact responses of both monolithic and assembly plates are investigated, and the numerical model is validated by comparing the predicted results with experimental data. Compared to the monolithic plate, the structural flexibility, energy absorption capacity and the tolerance to local failure are improved in the assembly plates made of interlocking bricks. A comparative study is also carried out on the assembly plates made of two types of interlocking bricks including osteomorphic brick with two curved side surfaces and newly designed interlocking brick with four curved surfaces. It is found that the plate made by the newly developed interlocking brick exhibits less deflection and absorbs more energy than the existing osteomorphic brick.

1. Introduction

Topology interlocking is an innovative and modern method for developing new materials and structures with improved performance. This method has made significant progress in the past decades. The principle of topological interlocking is based on segmenting a monolithic plate into a number of identical elements which could interlock with adjacent elements through kinematic constraint introduced by their special shapes, topologies and arrangements [1]. The out-of-plane movement resistance distinguishes the interlocking structural components from the components made of traditional regular bricks which intrinsically do not have any out-of-plane resistance with binder. Some studies were carried out [1–6] on the topology interlocking concept and shape configurations of interlocking elements (platonic elements and osteomorphic element). Besides, experimental studies were conducted to identify the mechanical behaviour and characteristics of assembly structures made of interlocking elements. For example, the assemblies made of topologically interlocked cube-shaped elements were tested under point load (indentation test) in several studies [7–9], which showed unusual negative stiffness. A series of indentation tests were carried out on a type of plate-like assembly using interlocked tetrahedral in 2015, which demonstrated that the tested plate could provide a desired out-of-plane stiffness and energy absorption characteristics [10]. Since Dyskin et al. [11] proposed the concept of osteomorphic brick in 2003, various experiments were conducted to investigate the special characteristics of the structural components made of this brick. Moreover, a series of experimental studies were conducted on plate-like assemblies made of osteomorphic brick [12–16] to investigate the bending stiffness, load bearing capacity, energy absorption capacity, capability to prevent crack propagation, and the tolerance to missing blocks. Carlesso et al. [17] reported the sound absorption properties of segmented structures using Dyskin's brick in 2012. Sandwich panels with a core of osteomorphic bricks were investigated by Molotnikov in 2013 [18]. In 2016, the study on the mechanical performance of hybrid material utilizing this topological interlocking geometry was conducted [19].

Interlocking features are achieved through a pair of curved faces of the element in the existing osteomorphic brick, in which each face prevents the out-of-plane displacement along either direction normal to the assembly plate [2]. Due to the existence of a pair of flat side faces in the osteomorphic brick (Fig. 1(a)), the mechanical response of the plate-like assembly made of this brick is different in the in-plane directions. The shape of the osteomorphic brick is also different on both top and bottom sides (Fig. 1(a)). Thus different patterns will be shown on different sides of the assembly plate, which may lead to different impact resisting performance on the two sides. Most recently, the

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[*] Corresponding author at: Centre for Innovative Structures and Materials, School of Engineering, RMIT University, Melbourne, Victoria 3001, Australia.
E-mail address: mike.xie@rmit.edu.au (Y.M. Xie).

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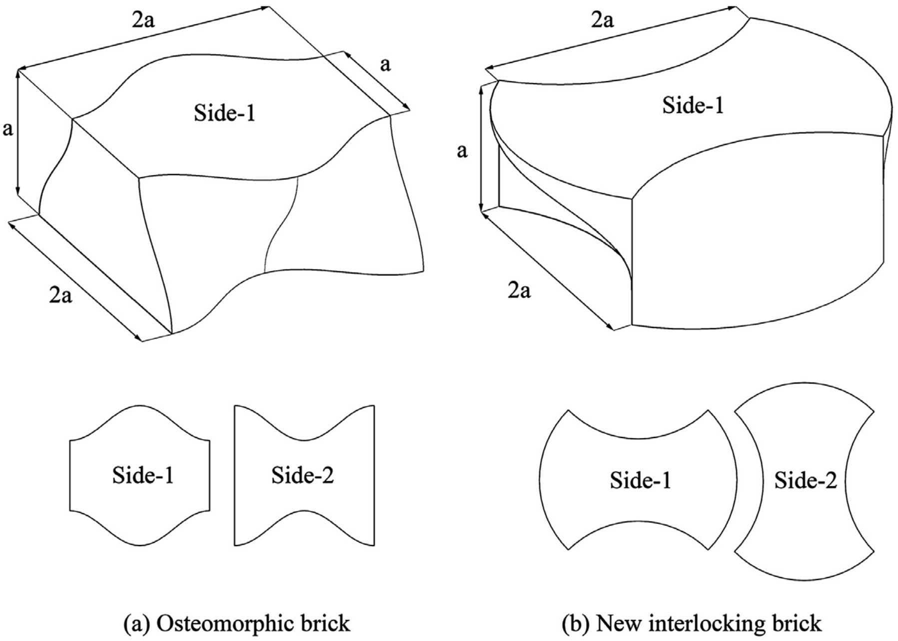

(a) Osteomorphic brick (b) New interlocking brick

Fig. 1. A schematic demonstration of (a) osteomorphic brick and (b) new interlocking brick.

authors of the present paper proposed a new design of interlocking brick [20,21], in which the curved surfaces of the same profile on all sides of the interlocking brick (see Fig. 1(b)) lead to the symmetrical in-plane behaviour of the assembly plate in the two principal directions. Besides, additional curved side surfaces of the new brick provide more resistance against out-of-plane movements because of increased friction and shear resistance. Moreover, the patterns appeared on both sides of the assembly plate made of the new interlocking bricks are similar (Fig. 1(b)).

Impact resistance of protective structures has gained increasing interest. Extensive research has been reported on various types of systems subjected to impact loads, including steel plates, fabric panels, concrete structures, brick structures and so on [22–27]. However, very limited experimental and numerical investigations can be found from literature on studying the dynamic behaviour of interlocking structures under impact loads [28,29]. The potential applications of these novel structures (assembly plates made of interlocking bricks) can be protective walls in resisting the collision of fragments produced in explosion, or road side crash barrier [20]. In 2012, Khandelwall et al. [29] conducted drop weight tests to study the dynamic behaviour of the topologically interlocked material (TIM) created using identical tetrahedral elements made of brittle base material. Numerical modelling of the same TIM assembly conducted by Feng et al. [28] demonstrated that TIM could absorb more impact energy than conventional solid plates. Recently, the authors of the present paper carried out a series of drop weight tests on both monolithic plates and the assembly plates made of the newly designed interlocking brick [20,21] under different loading scenarios, i.e., different incident energies and different levels of lateral confinement [20]. It was shown that, similar to TIM with tetrahedral elements, the new interlocking assembly plate absorbed more energy than monolithic plate. Furthermore, the increase of the confining load enhanced the energy absorption capacity of the assembly plate [20].

In the present study, a 3D finite element model is established to simulate the dynamic responses of assembly plates made of new interlocking bricks under impact loads. The numerical model is developed using the explicit finite element program ANSYS/LS-DYNA. The Continuous Surface Cap Model (CSCM, MAT 159) is used for modelling concrete, which considers the effect of strain rate on the dynamic material properties of concrete. To simulate the crack development and propagation, appropriate erosion criteria are selected in the proposed finite element model. The structural flexibility, energy absorption capacity and the tolerance to local failure of the interlocking assembly plates are studied. The proposed numerical model is validated by comparing the predicted results with the experimental data from drop weight tests in reference [20]. The developed numerical model is then applied to investigate the effects of incident energy and initial confining loads on the dynamic responses of assembly plates made by both new interlocking brick and existing osteomorphic one.

2. Numerical modelling and comparison with test data

2.1. Material model for concrete under impact loading

In this study, concrete is modelled using the Continuous Surface Cap Model in LS-DYNA (MAT 159), which can model the damage-based softening and modulus reduction, shear dilation, shear compaction, confinement effect and strain rate effect. It is capable of predicting the failures in compression, tension and shear [30]. It also allows automatic generation of parameters based on the three basic input parameters in material card: the unconfined compression strength ($f'c$), the maximum aggregate size and the units [31]. A comprehensive model review and validation can be found in reference [31]. The input parameters used in this study are shown in Table 1 and other parameters are automatically generated in CSCM.

The mass density, unconfined compressive strength and the maximum aggregate size are selected based on the test data [20]. Element erode is a control parameter. Erosion will not occur if this parameter is not specified (ERODE = 0.0) or set less than one (ERODE $\leq$ 1.0). The recommended coefficient of erosion is 5 to 10 percent of the maximum principal strain, i.e. 1.05 $\leq$ ERODE $\leq$ 1.10 [31]. In this paper, an eroding coefficient of ERODE = 1.10 is employed for all the simulations which allows erosion of concrete elements when damage exceeds 0.99

Table 1
Key parameters for concrete material model CSCM (MAT159).

Mass density (g/mm^3)	NPLOT	Rate effect	Element erode	Unconfined compression strength (MPa)	Maximum aggregate size (mm)
2.1E-3	1	1	1.10	28.6	2.0