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Fracture behaviour of ceramic blocks with thin-walled cellular structures under dynamic loadings

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ABSTRACT

This paper lays the foundation for the development of a high-load bearing energy absorbing system with controlled deformation. Brittle ceramic blocks made of bricks with thin-walled cellular structures are presented and tested with impact loading. The authors demonstrate that such blocks are able to absorb impact energy because of the gradual brittle fracture process which occurs in the cellular structures. Full-scale specimens were subjected to laboratory impact tests: two non-deformable flat-nosed cart tests as well as two full-scale field crash tests involving passenger vehicles with crumple zones. The experiments were designed specifically to prove that block specimens are able to gradually absorb different levels of impact energy and to examine the applicability of using such blocks in the design of cross-drainage culverts. Based on a comparison of the two collisions with test culverts, the authors show that consequences of the collision can be significantly reduced by using brittle blocks with cellular structures in culverts. In fact, the crumple zone of the passenger vehicle which collided with a brittle block culvert was not crumpled; vehicle bounce off was eliminated and gradual deceleration of the vehicle was recorded.

1. Introduction

Most structures constructed around roads nowadays are non-deformable objects. Their inability to dissipate impact energy during car crashes can cause serious injuries or even deaths. This situation is alarming, with statistics indicating that one quarter of deadly traffic accidents are caused by the collision of vehicle with non-deformable objects [1]. Because of this, transportation hazards could be significantly decreased by using new energy absorbing systems as cushioning elements in structures which pose risks around traffic lanes. Cross-drainage culverts are a type of hazardous structure; collision with such culverts as currently designed is comparable to frontal impact with a rigid wall, because a car leaving a road with drainage ditches is directed—via the ditches—straight into a culvert face. It has been proposed [2] that an energy absorber with cellular structures might dissipate the impact energy because of deformation of the cells and have sufficient load bearing capacity in the direction perpendicular to the expected impact. The energy absorbing system should be designed in a way that the cells are impacted laterally with their walls serving as supporting elements.

Many authors [3–15] have reported that, while loaded laterally, an energy absorbing system composed of metallic tubes is able to dissipate impact energy because of plastic deformation of the structure. In addition to single tube systems [3,4,14,15], researchers have been working on improvement of the metallic tube system and proposed many modifications such as addition of exterior constraints [7,13], nested tubes [7–12], foam filled tubes [16], or a self-locked system [6].

Morris et al. [7], for example, studied nested metallic tube type energy absorbers consisting of three tubes of varying diameter placed within each other with their axes being parallel. The authors analysed its response under quasi-static loading with vertical and inclined side exterior constraints. It was shown that although the constraints increase the specific energy absorption of the system, crush efficiency suffers as a consequence and hence weight effectiveness is reduced. In follow-up works, the authors have presented two different modifications to the system. It was demonstrated [9] that an elliptical shape tube system has greater energy absorbing capacity than circular counterparts due to greater displacement stroke. It was also shown [10,11] that once the collapse load was reached, the crushing force could be kept relatively constant by adding cylindrical rods between the gaps of the tubes. Later, these two modifications were combined to create the nested oblong tube energy absorber [12] and the oblong tubes were subjected to crashworthiness optimization [13].

Chen et al. [6] presented a novel self-locked energy absorbing

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system composed of thin-walled tubes with a dumbbell-shaped cross section and demonstrated its ability to gradually decrease impact force. It was validated by experimental and numerical simulations that the self-locked system is able to prevent lateral splash from impact loading.

Recently, Baroutaji et al. [16] introduced an overview of the crashworthiness behaviour of tubular components including multi-cell tubes, functionally graded thickness tubes, and functionally graded foam filled tubes. Multi-cell configuration was found to improve energy absorption behaviour by controlling the number and shape of angle elements while functionally graded configuration was found to be a very promising solution for reducing the amount of material in less important zones and hence allowing for better distribution of material. Thin walled tubes filled with density gradient foam showed better crashworthiness response by increasing specific energy absorption without increasing the peak crush force.

This paper investigates blocks made of industrial ceramic bricks with thin-walled cellular structures originally designed as a load-bearing and thermal-insulating elements. The authors demonstrate how these blocks can dissipate impact energy because of brittle fracture of their cells. Responses of blocks to impacts with a non-deformable flat-nosed cart and two passenger vehicles with crumple zones are analysed. Both experiments verify the ability of cells to collapse progressively. In addition, an impact test with a non-deformable flat-nosed cart demonstrates that a specimen is able to gradually absorb different levels of impact energy.

Usually, car crash experiments or their numerical simulations are focused on the development or improvement of existing barriers and protecting sensitive structures, neglecting vehicle passenger safety. Namely, researchers have investigated the resistance of a barrier to impact loading [17]; effectiveness in reducing possible vehicle cross-overs [18,19]; protecting a perimeter around significant buildings or infrastructures and consequent reduction of blast and debris threats from vehicles bearing improvised explosive devices [20,21]. The effect of a crash on the safety of passengers has not, to our knowledge, been investigated in the aforementioned literature. The experiments presented in this paper were designed not only to demonstrate the ability of the target to stop the impact of a vehicle but also to determine the effect of a collision on vehicle passengers. The suitability of the tested specimens to be used as cushioning elements in cross-drainage culverts is determined and their load-bearing capacities are also verified.

2. Material and methods

2.1. Design

Ground bricks (commercially available HELUZ 50 Family) were chosen for the specimens considered in this study (Fig. 1). These bricks are made primarily of clay mixed with saw dust and papermaking sludge as aeration agents. Ceramic bricks are manufactured structural elements, making them easily and inexpensively obtainable in large quantities and ideal for the purpose of this study. Such bricks have thermal-insulating structural elements containing hollow cells with a designated volume (58%) to ensure thermal insulation properties but still provide sufficient load-bearing capacity. These cells are hexagonal and are distributed regularly; each row is offset by the half the cell spacing. These cellular structures do not contain any walls which could brace impact. Their ability to collapse progressively was preliminary verified using a reduced-scale specimen and high speed camera recording. The reduced-scale specimen was tested using an impact pendulum machine with a 37 kg flat-nosed impactor travelling in a circular trajectory and hitting the specimen in the bottom-return point [22]. According to footage recorded (Fig. 2), cells collapsed systematically with brittle fracture. This led to gradual deceleration of the impactor.

According to the manufacturer, the mass of the grinded brick is 19.7 kg; and width, height, and depth 247 mm, 249 mm, and 500 mm, respectively. Thickness of the wall is 3.7 mm. The mean compressive strength, secant modulus of elasticity, and Poisson's ratio were determined experimentally using conventional procedures. Bricks were transferred to the laboratory 14 days before experimental measurements to ensure constant properties. Temperature in the laboratory was 19–19.5 °C and relative humidity was 45–49%. Mean compressive strength was measured for seven specimens in a hydraulic loading machine using monotonic increments of load at speed 0.36 MPa/s up to brittle failure of the brick. Tests were performed using a DSM 2500-100 testing apparatus. The apparatus consists of a stiff loading frame with loading capacity of 2500 kN. The loading frame has a hydraulic servomechanism that allows both force increment and close-loop feedback deformation loading. The secant modulus of elasticity and Poisson's ratio were determined based on results for five specimens. The modulus of elasticity and Poisson's ratio were measured using two strain gauges attached vertically to the sides of each specimen and another two strain gauges glued horizontally to the longitudinal sides of specimens at the middle of their heights. In the first step, specimens were loaded to 1/3 of expected maximal compressive strength for 60 s. Following this, specimens were unloaded to 0.5 MPa. This procedure was repeated three times. The secant modulus of elasticity and Poisson's ratio were calculated during the third unloading cycle. The results of the experiments are summarized in Table 1.

Bricks with two different modifications were considered in this study. When a brittle specimen was required, the longitudinal sides of the brick were trimmed (Fig. 3) to eliminate tongue and groove joints. When a stiffer specimen was required, cells of brick were filled with polystyrene.

2.2. Impact of a non-deformable flat-nosed cart

Two impact experiments using a 1000 kg non-deformable flat-nosed impact cart were conducted, varying only in impact energies. During one experiment, the impact velocity was 30 km/h (8.33 m/s); during the other, velocity was 50 km/h (13.89 m/s). Impact energies were 34.7 kJ and 96.5 kJ, respectively. The tested specimen had soft and semi-stiff parts. The soft part was comprised of 45 trimmed bricks, 5 wide and 3 tall/long. The semi-stiff part was wrapped in plastic foil and comprised of 36 bricks filled with polystyrene, 4 wide and 3 tall/long. Dimensions of the entire specimen were approximately 750 mm × 1000 mm × 3000 mm (height × width × length). The back face of the specimen was placed against a rigid wall (Fig. 4). The progressive collapse of the cellular structure was recorded with a high speed camera

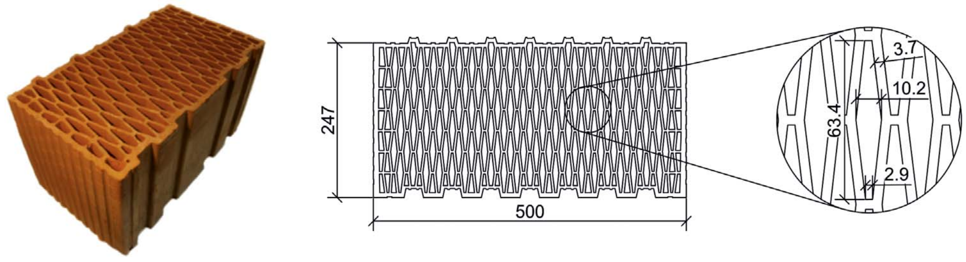

Fig. 1. Grinded ceramic brick; its cellular structure and detailed sketch of one cell; dimensions in mm.

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