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A design tool for resource-efficient fabrication of 3d-graded structural building components using additive manufacturing

F. Craveiro[a], H.M. Bartolo[a,b], A. Gale[c], J.P. Duarte[a,d], P.J. Bartolo[a,c,*]

[a] Research Centre for Architecture, Urbanism and esign, University of Lisbon, Portugal
[b] School of Technology and Management, Polytechnic Institute of Leiria, Portugal
[c] School of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK
[d] Stuckeman Center for Design Computing, Penn State University, USA

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ABSTRACT

The construction sector is under increasing pressure to improve its efficiency and effectiveness, reducing environmental impacts, material use and costs. A computational tool was developed to design and fabricate functionally graded building components. The material composition was defined based on voxel determination in order to design building elements with varying material stiffness. A cement-based conceptual building wall was investigated with a varied material composition, using two different lightweight aggregates, a granulated cork one and the other with expanded clay. This functionally graded material concept applied to lightweight building components will allow producing resource-efficient graded building components tailored to specific loading conditions, minimizing waste generation, emissions and resource consumption.

1. Introduction

The European Comission is committed to reducing the environmental impact of buildings by improving resource efficiency, as the construction industry is responsible for one third of the Earth's resource consumption, generating huge amounts of solid waste [1]. Annually, the world's production of cement accounts for approximately 7% of CO_2 global emissions, while portland cement is responsible for a large amount of greenhouse gases (GHG) [2]. The production of a ton of portland cement requires 4 GJ of energy, while the manufacture of the clinker accounts for 1 ton of CO_2 released into the atmosphere [3]. Therefore, more sustainable construction strategies, enabling to improve energy efficiency and contributing to reduce GHG emissions, are required. On the other hand, a resource efficient construction sector with lightweight structural components will help to reduce waste generation, emissions and global resource consumption [4].

Additive Manufacturing (AM) technologies, a class of manufacturing processes, in which a part is built by adding layers of material upon one another [5–8], has been exploited for the construction sector. Khoshnevis [9] developed a concept for the automatic fabrication of a house called Contour Crafting. This system consists of the automatic fabrication of building walls layer by layer, until the creation of a formwork filled with mortars mainly composed by cement. Lim et al. [10] developed a concrete printing strategy based on the extrusion of cement mortars to produce 3D customized products. Gosselin et al. [11] developed a system based on an extrusion print head mounted on a 6 axis robotic arm, in which the fabrication process includes a mortar premix and an accelerating agent to accelerate the setting of mechanical properties after extrusion. Dini [12] developed binder jetting technology called "D-Shape", using sand and a binder to create stone-like structures to build medium size structures. The Dutch company DUS Architects developed an extrusion-based printer to produce a canal house in Amsterdam [13]. Real scale prototypes were developed to print homes, namely by the Chinese company Yingchuang [14], and the World's Advanced Saving Project [15]. In the construction area, AM processes can be used for both off-site and on-site applications, for the production of construction components or repairing applications (Fig. 1).

Current Additive Manufacturing (AM) technologies are commonly used to fabricate physical elements with homogeneous material properties [16,17], and not to produce physical elements with spatially varying compositions, characterized by a gradual spatial change in composition and microstructure. Such structures were defined by [18] as Functionally Graded Materials (FGM).

Craveiro et al. [19,20] proposed a fabrication system, called "RapidConstruction", to produce multi-material structures using several materials (cement, polymers and clay). This fabrication system comprised a computer controlled gantry crane integrating multi-deposition

* Corresponding author at: School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, UK
E-mail address: paulojorge.dasilvabartolo@manchester.ac.uk (P.J. Bartolo).

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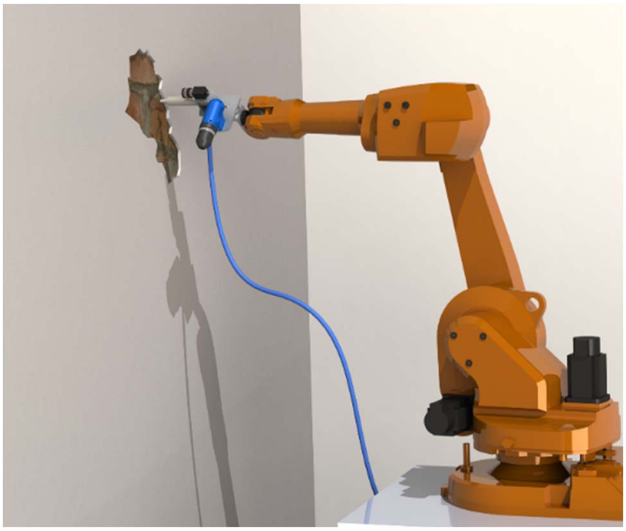

Fig. 1. CAD model concept for AM for repairing applications.

heads with various degrees of freedom. A functional prototype was developed with three extrusion heads. The the first extrusion head was used to process different composite materials (clay with natural fibers) and composite concrete for contour paths, smoothed by lateral trowels. A second head created composite meshes and the third one extruded filling material, both producing polyuretane polymers with different compositions [21–24].

Cementitious materials, particularly concrete, are the most widely used materials in the world. Every year, more than 1 m^3 is produced per person worldwide, taking into account that vast quantities of cement and concrete produce 5–8% of CO_2 [25]. There is an increasing pressure for innovation and sustainability in the construction sector, and the use of alternative aggregates processed from waste materials or natural and renewable materials is a good solution to reduce the depletion of earth's natural resources [26]. To process functionally graded concrete, using cork and expanded clay, a printing head capable of metering the additives during emplacement of the concrete will be used [27]. A computational tool was developed to design and fabricate functionally graded building components made with cement-based aggregates, with different amounts of cork or clay, depending on structural and thermal constraints. This paper describes in detail this computational tool.

2. Design tool for functionally graded components

The computational tool was designed to control the material composition variation of conceptual building walls, using lightweight aggregates in specific areas to satisfy structural and environmental needs, in order to reduce its weight, and keeping its structural performance. The workflow overview is illustrated in Fig. 2.

The computational tool includes a parametric design tool and a structural analysis (Finite Element Analysis, FEA) to provide an integrated generative tool, allowing the definition of the material composition of the building components. A visual programming tool called Grasshopper (Rhinoceros plugin) is used to parametrically design the 3D construction elements using iconic components interactively manipulated by the user [28]. These components are boxes, representing shapes and operations, and connectors linking the boxes, creating dataflows between components, where the output of a component is the input to another. The parametric tool comprises two modules. The first

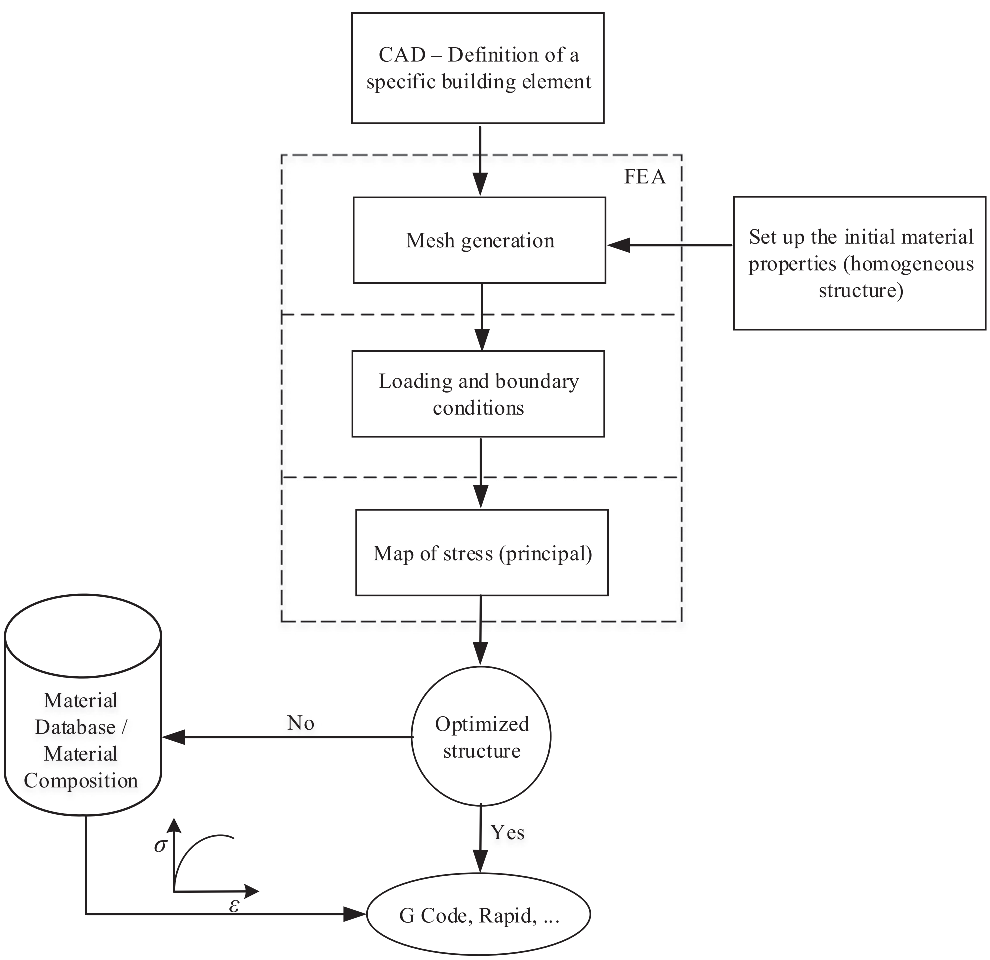

Fig. 2. Flowchart representing the strategy to produce FGM structures.