ARTICLE IN PRESS

Cement and Concrete Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Cement and Concrete Research

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

3D printing using concrete extrusion: A roadmap for research

R.A. Buswell[a,*], W.R. Leal de Silva[b], S.Z. Jones[c], J. Dirrenberger[d,e]

[a] School of Architecture, Building and Civil Engineering, Loughborough University, UK
[b] The Concrete Centre, The Danish Technological Institute, Denmark
[c] Engineering Laboratory, National Institute of Standards and Technology, USA
[d] Laboratoire PIMM, Arts et Métiers-ParisTech, Cnam, CNRS, Paris, France
[e] XtreeE, 18/20 rue du Jura, CP 40502, Rungis Cedex 94623, France

ARTICLE INFO

Keywords:
Concrete printing
Extrusion
3DCP
Rheology
Hardened properties
Measurement
Geometric conformity

ABSTRACT

Large-scale additive manufacturing processes for construction utilise computer-controlled placement of extruded cement-based mortar to create physical objects layer-by-layer. Demonstrated applications include component manufacture and placement of in-situ walls for buildings. These applications vary the constraints on design parameters and present different technical issues for the production process. In this paper, published and new work are utilised to explore the relationship between fresh and hardened paste, mortar, and concrete material properties and how they influence the geometry of the created object. Findings are classified by construction application to create a matrix of issues that identifies the spectrum of future research exploration in this emerging field.

1. Introduction

Large-scale, cement-based additive manufacturing processes, often referred to as 3D concrete printing (3DCP), have been under development for the last 10 years and more than 30 groups world-wide are currently engaged in research. 3DCP disposes of the need for conventional moulds by precisely placing, or solidifying, specific volumes of material in sequential layers by a computer controlled positioning process. The manufactured component is a facsimile of a 3D model from which the machine control is derived in the same way as conventional Additive Manufacturing/Rapid Prototyping: see either [1] or [2] for an overview of these processes and their operation. Fig. 1describes the growth in activity since the seminal work of Pegna [3], a recent contemporary review of the literature is offered in [4].

A distinction is made here between automation methods for mould making and material shaping [5,6] and methods that 'build' using discrete layer deposition. A further distinction is made between the discrete layer deposition processes that are based on a particle bed approach [3,7] (and Lowke et al. [8] in this issue) and those based on extrusion.

Over half the processes under development employ extrusion, typically a small (∼6 mm to ∼50 mm diameter) continuous filament, pumped through a nozzle often mounted on a gantry or robotic arm that positions the material during the build process. The material is typically a high cement content mortar, with a maximum particle size in the order of 2 mm to 3 mm, although larger aggregates have been used. The shape of the extrusion varies and is either circular, ovular or rectangular and linear rates of extrusion are in the range of 50 mm/s to 500 mm/s. Fig. 2 offers examples of the component types, print orientations and geometrical features that have been demonstrated and can be classified into the three application families:

- Components, either stand alone (c) or for assembly (d and e);
- Walls and columns printed in-situ (f); and,
- Permanent shuttering where the shutter is printed and the structural element is cast conventionally (a and b).

The orientation of manufacture also varies and is either predominantly vertical (Fig. 2b, c, d and f) or horizontal (Fig. 2a and e). Components can be predominately planar (Fig. 2a, b, d, e and f) or volumetric (Fig. 2c). The creation of overhanging features may also be desirable and can be produced through corbeling (Fig. 2d) or by the additional application of a removable material to create support during printing, as has been used to create Fig. 2e. Voids can also be created to form shafts in vertical prints, such as those to the left hand end of the bench in Fig. 2c.

Research to date has been ad-hoc, focused on demonstrating viability [1,9-11]. Currently 3DCP manufacturing processes are inconsistent and unreliable, requiring expert machine operators and extraordinary care in the preparation and formulation of materials.

* Corresponding author.
E-mail address: r.a.buswell@lboro.ac.uk (R.A. Buswell).

https://doi.org/10.1016/j.cemconres.2018.05.006
Received 27 October 2017; Received in revised form 4 May 2018; Accepted 7 May 2018

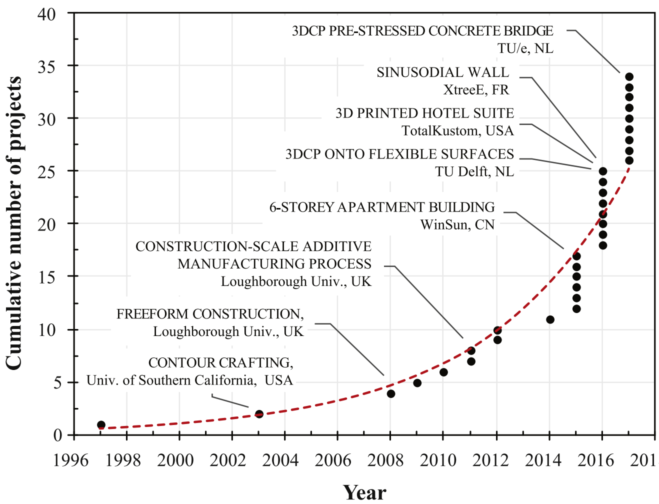


Fig. 1. The rise in large-scale additive manufacturing for construction applications since the concept inception in 1997.

Inconsistencies and unreliability arise from the dependency of material properties on the process apparatus, the operational parameters, and the generation of machine instructions from an algorithm to create the desired geometry. The material is required to flow and extrude through a nozzle, bond with the previous layer and maintain its shape under increasing hydrostatic pressure generated by subsequent layer deposition. Disturbances during printing, caused by changes in the material or problems with the process, are detrimental to the success of a build and can influence the performance of the component.

These issues hamper the *robustness* of 3CDP, a critical milestone for commercial viability, of which rheological properties of 3DCP materials are fundamentally important. It is, however, the hardened properties and conformity to design geometry that give the manufactured component value. Indeed, if these processes are to become common construction practice, engineers will need to understand how to design structures to be manufactured with printed materials, leading to new design codes and standardised methods of testing.

2. Method and approach

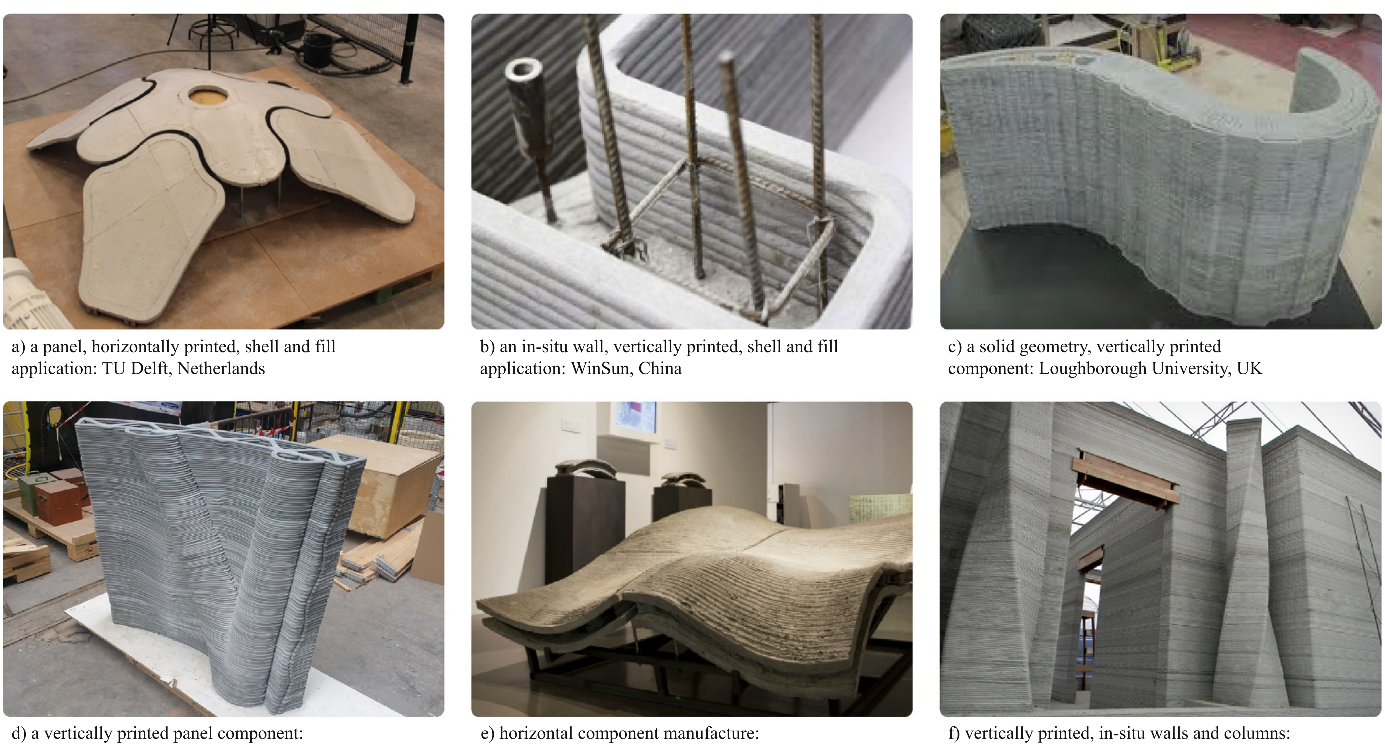
This paper provides a structured insight into the technical issues and solutions surrounding 3DCP and discusses:

- Properties of wet materials used in 3DCP prior to solidification;
- Hardened properties of 3DCP materials;
- Achieving geometric conformity; and,
- Factors affected by application.

A thorough literature review in the area of 3DCP resulted in 50 to 60 topically relevant papers that were filtered by removing review papers and work that did not focus on mortar extrusion-based 3DCP. The remaining papers were then reviewed to establish whether they commented on or provided evidence of technical issues. Observations were either based on structured investigation or experience and both were included to form an evidence base of about 22 papers.

Reflecting on the key challenges outlined by Wangler et al. [12], the issues highlighted by these publications are supplemented with new insights from recent international work undertaken at Loughborough University (UK), The Danish Technological Institute, the National Institute of Standards and Technology (USA) and Conservatoire National des Arts et Métiers (France). Reflective discussion is provided throughout, touching on issues relating to the measurement and testing of rheology and hardened material properties.

The work aims to provide a state-of-the-art review that can be readily evidenced and related to key areas of material research, signposting the latest publications in this special issue. At the same time, it identifies the interdependent factors effecting, and effected by, the component design and the mechanics and control of the process. These issues and their interrelationships, are then collated to create a matrix of research and development issues that are dependent on the



a) a panel, horizontally printed, shell and fill application: TU Delft, Netherlands

b) an in-situ wall, vertically printed, shell and fill application: WinSun, China

c) a solid geometry, vertically printed component: Loughborough University, UK

d) a vertically printed panel component: XTreeE, France

e) horizontal component manufacture: Loughborough University, UK

f) vertically printed, in-situ walls and columns: Total Kustom, USA

Fig. 2. Examples of 3DCP application type and orientation of the manufactured components.