Sustainability, Agri, Food and Environmental Research, (ISSN: 0719-3726), 11(X), 2023:
http://dx.doi.org/10.7770/safer-V12N1-art2776

Behaviour of additively manufactured concrete cellular columns under axial loading conditions.

Comportamiento de columnas alveolares de hormigón fabricadas de forma aditiva en condiciones de carga axial.

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ABSTRACT

Additive manufacturing techniques have gained significance during the recent years. Most of the traditional construction techniques are more or less subtractive or in other words, they involve the machining away of extras to achieve the final product and hence their performance will be limited to the availability of moulds. Additive manufacturing methods tend to be more efficient and economical as it reduces the wastage of construction material, time and manpower by enabling the freeform printing of parts. This paper focuses on the behaviour of numerical models of simple additively manufactured concrete cellular columns when subjected to axial loading. The three unit cellular topologies adopted were square, triangular and hexagonal in shape. The numerical model was developed using Ansys Design Modeller and validation was carried out using the experimental data available from previous literature. The parametric study was then conducted on the validated models to obtain the optimum unit cellular shape, as well as study the effect of column height and thickness of walls of unit cells on the ultimate load carrying capacities of column. Strength to weight ratio of the cellular models was obtained to be 47-62% of that of solid columns with the optimum results for square concrete cellular columns. The load carrying capacity of columns decreased with increase in height as expected but the rate of decrease in strength was seen to be about 61% and 86% lesser in triangular and square columns respectively when compared to their solid counterpart. The load carrying capacity was seen to increase with increase in wall thickness of cells of column for all models.

Keywords— additive manufacture, 3D printing, cellular columns, unit cell shape, numerical analysis, finite element analysis, energy efficient.

RESUMEN

Las técnicas de fabricación aditiva han ganado importancia durante los últimos años. La mayoría de las técnicas tradicionales de construcción son más o menos sustractivas o, en otras palabras, implican el mecanizado de los extras para lograr el producto final y, por tanto, su rendimiento se limitará a la disponibilidad de moldes. Los métodos de fabricación aditiva tienden a ser más eficientes y económicos, ya que reducen el desperdicio de material de construcción, tiempo y mano de obra al permitir la impresión de piezas de forma libre. Este artículo se centra en el comportamiento de modelos numéricos de columnas celulares de hormigón fabricadas aditivamente simples cuando se someten a cargas axiales. Las topologías celulares de tres unidades adoptadas fueron de forma cuadrada, triangular y hexagonal. El modelo numérico se desarrolló utilizando Ansys Design Modeller y la validación se llevó a cabo utilizando los datos experimentales disponibles de la literatura anterior. A continuación, se realizó el estudio paramétrico en los modelos validados para obtener la forma celular unitaria óptima, así como también estudiar el efecto de la altura de la columna y el espesor de las paredes de las celdas unitarias sobre las capacidades de carga máxima de la columna. La relación resistencia / peso de los modelos celulares se obtuvo en un 47-62% de la de las columnas sólidas con los resultados óptimos para las columnas celulares cuadradas de hormigón. La capacidad de carga de las columnas disminuyó con el aumento de altura como se esperaba, pero se observó que la tasa de disminución de la resistencia era aproximadamente un 61% y un 86% menor en las columnas triangulares y cuadradas, respectivamente, en comparación con su contraparte sólida. Se observó que la capacidad de carga aumenta con el aumento del grosor de la pared de las celdas de la columna para todos los modelos.

Palabras clave: fabricación aditiva, impresión 3D, columnas celulares, forma de celda unitaria, análisis numérico, análisis de elementos finitos, eficiencia energética.

INTRODUCTION

3D printing, also known as additive manufacture, is a technique which involves the modelling of the structure to be created, followed by the layer by layer deposition of the structural material using printers leading to the construction of an actual part or structure. The last decade has witnessed the 3D printing technology growing at a very impressive rate. One of the major concerns regarding the finished product of additive manufacture is the attainment of sufficient strength at the interface between the layers. The concrete layers will be deposited one over the other during the time of printing. Hence if not adequately reinforced or supported it tends to collapse under its own weight. The improvement of the mechanical properties of printed concrete, so that they can be deposited without formworks and still promise stability, is an important topic of great prevalence. In other words the concrete should be stiff and stable enough to support its self weight as well as the weight of the above layers while sustaining minimum or no deformation. Owing to the difficulty in fabricating precise and complicated formworks, the manufacture of concrete members of hollow section is usually rare. However with the help of 3D printing, complex geometries can be printed out for concrete structures too. The prefabrication of such members can hence optimize material consumption through shape efficiency. Such sections are preferred for the construction of oversized structures which are lightweight. Hollow sections have a number of advantages. One of them being their lesser self weight compared to their solid counterparts. By saving material we can effectively bring down the cost of construction. Lattice members tend to have superior sound and thermal insulation properties. They are also said to possess better shock resistance and energy absorption capabilities. The objectives of this study were to compare the axial load carrying capacities of additively manufactured cellular concrete columns against solid ones and to find the optimum unit cell shape for a cellular concrete column by finite element analysis. It also identifies the effect of variation of height of cellular & solid concrete columns on their ultimate load carrying capacity.

MATHERIAL AND METHODS

This paper focuses on the numerical study of additively manufactured concrete cellular columns and their behaviour under axial loading when compared to solid concrete columns of same nature. The analysis was carried out using the finite element software package Ansys 19.2 and the geometrical model was prepared in the Design Modeller software which is a part of the Ansys Workbench. The engineering data required was obtained from Ye et al., (2021) [10]. The compressive stress strain graph for printed specimens loaded in the same axis as that of the present study was adopted. Hence the work is for ultra high ductile concrete. The properties gave satisfactory validation results for the models based on the work conducted by Wang et al., (2020) [8]. The numerical model which was successfully validated was then adopted for further parametric studies. Initially the models for each square, triangular, hexagonal as well as solid printed concrete columns where subjected to axial loading and their load deflection graphs were obtained. The next step involved the modelling of all columns of each cellular configuration for the various heights.

NUMERICAL STUDY-VALIDATION: The geometric model for the beam specimens to be used for validation process was modelled in ANSYS Design Modeller for the dimensions of 100 x 100 x 400 mm. Three beams were modelled that is, one for each square, triangular and hexagonal unit cell shapes. The models were designed in correspondence to the specimens used by Wang et al., (2020) [8] in their experimental setup. As the values obtained from experimental test results are comparable (as seen in Table 1) to the analytical results, the axial load carrying capacities of cellular hollow concrete columns of similar geometry can be obtained with sufficient accuracy using the developed numerical model. The validation based on the cube specimens of each cellular topology was also further carried out and the load deflection graph obtained from analysis was graphically compared against the experimental graph obtained by Wang et al., (2020) [8] in their study. The graphical comparison of results is shown in Fig. 1.

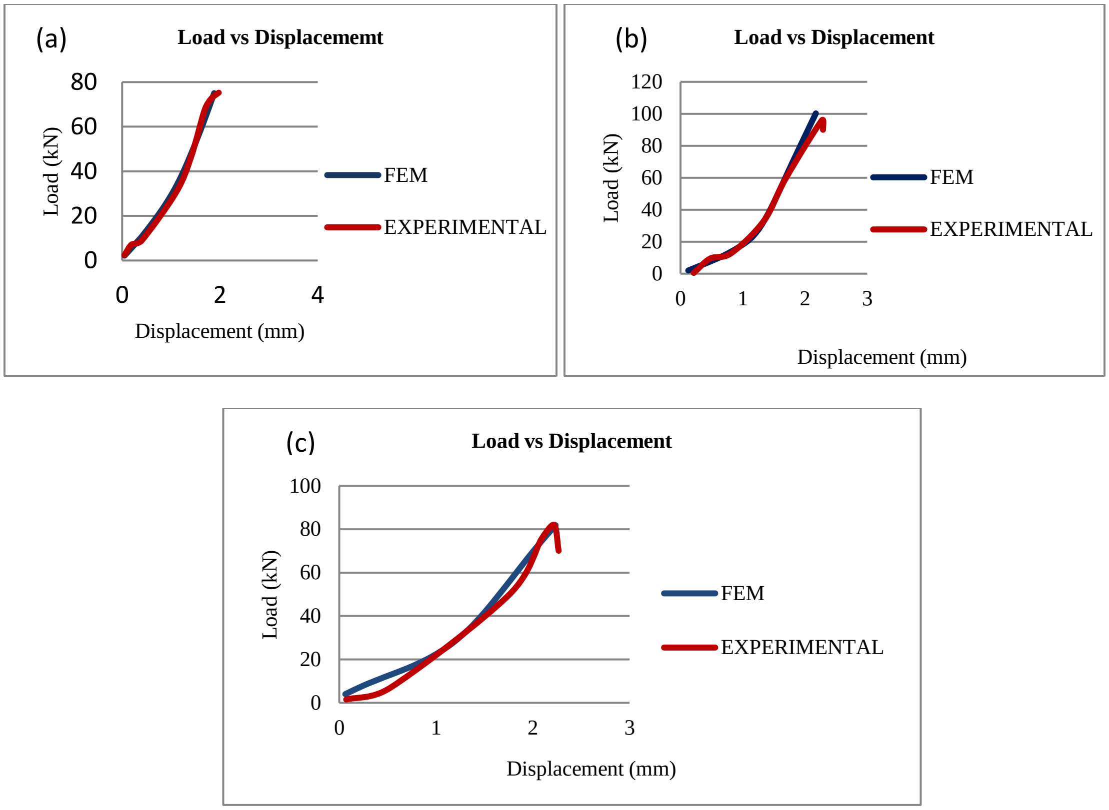

Fig. 1 Validation results comparing FEM and experimental compression test results of (a) square; (b) triangular and (c) hexagonal unit cellular cubes

Table 1 Validation results of the models of concrete cellular beams

Unit cell shape	Peak displacement in mm (Flexure test) Wang et al., (2020) [8]	FEM RESULTS	% VARIANCE
Square	0.52	0.5288	1.48
Triangle	0.75	0.7477	0.31
Hexagon	0.58	0.5773	0.47

PARAMETRIC STUDY: A comprehensive parametric study was carried out using the validated model to decide upon the optimum unit cellular configuration that can be adopted for additively manufactured cellular columns. The columns were obtained by reorienting the axis of the validated beam specimens. The cross section of the column was kept a constant of 100 x 100 mm and the length of the column was initially same as that of beam specimen that is 400 mm. The wall thickness was chosen to be 12 mm which is same as that of the validated beam specimens. Multilinear isotropic hardening property was used to provide the plasticity characteristics for the model and the stress strain values required for isotropic hardening property was obtained using the data obtained by Ye et al., (2021) [10]. The large deformation settings were also kept on. The bottom face of the models where kept fixed and the top face displacements and rotations other than Y axis displacement were set to be zero. The axial compressive load was applied to the top face as remote displacement in increments of 2 mm/min. The models used for study as shown in Fig. 2.

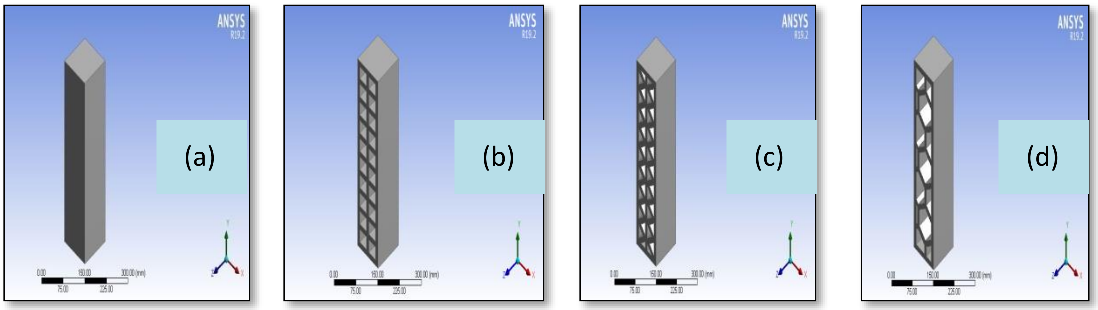

Fig. 2 (a) Solid Concrete Column; (b) Square cellular column; (c) Triangular cellular column (d) Hexagonal cellular column

RESULTS AND DISCUSSION

The comparison of load versus deflection graph for heights 400, 500, 600 and 700 mm are shown in Fig. 3. From Table 2, it is obvious that the axial load carrying capacity of cellular columns is about 56 to 76 % lesser than that of solid specimen. The highest load carrying capacity among the three concrete cellular columns is for triangular concrete cellular column and least for hexagonal concrete cellular columns. The strength of concrete cellular columns are seen to be around the range of 20-43% of the strength of the solid concrete columns for a material saving of 26-51% of that of solid columns. However, the cellular columns have about 47-62% of strength to weight ratio of that of solid columns. This point out the fact that compared to solid concrete columns, cellular columns being lightweight can make up for some of its lack in axial load carrying capacity.

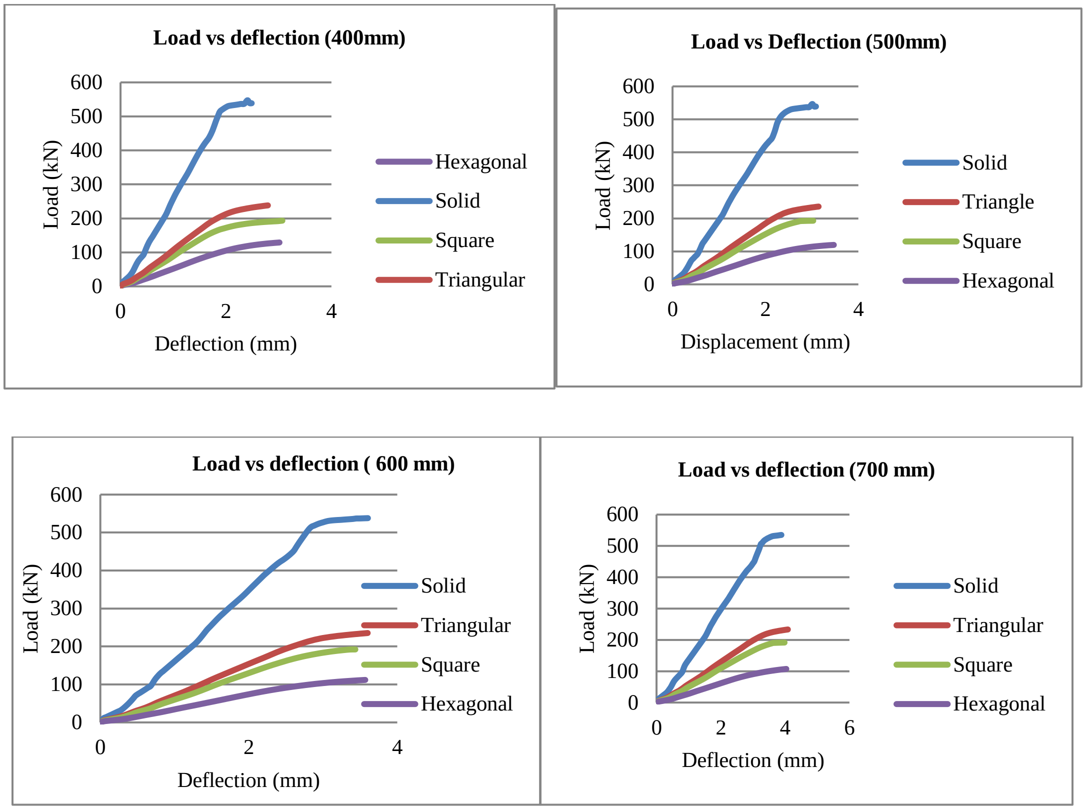

Fig. 3 Load vs deflection graph for the different heights of various cellular shapes

Table 2 Comparison of load carrying capacity of each sample of 400 mm height

Unit cell shape	Ultimate Load (kN)			
	400 mm	500 mm	600 mm	700 mm
Solid (Reference)	547.41	546.63	538	535.03
Triangle	238.26	235.74	235.42	233.3
Square	193.23	192.79	192.13	191.53
Hexagon	128.98	118.94	111.89	107.27

Table 3 Comparison of strength to weight ratio of each sample of 400 mm height

Unit cell shape	Strength to weight ratio	Percentage of reference model
Solid (Reference)	59.5	
Triangle	35.4	59.5
Square	36.8	61.8
Hexagon	28.1	47.2

Square cellular columns are seen to have 61.8% of the strength to weight ratio of solid columns and therefore concrete columns of square cellular configuration are optimum compared to their triangular and hexagonal counterparts. The evaluation of the load vs deflection graph for the remaining heights of 500, 600 and 700 show similar trend variation as that of 400 mm and hence it is safe to conclude that height variations do not lead to extreme changes in the load carrying capacity for solid columns as well as concrete cellular columns. Table 2 gives the ultimate load carrying capacity for solid, square, triangular and hexagonal concrete cellular columns for heights of 400, 500, 600 and 700 mm respectively.

EFFECT OF VARYING COLUMN HEIGHT: The increase in height of column leads to a decrease in value of the ultimate load carrying capacity values. However the decrease in strength values is not very predominant. From the data obtained it is safe to conclude that the ultimate load carrying capacity is seen to decrease with the increase in height for both solid as well as all the cellular columns. The rate of decrease in strength is maximum for concrete hexagonal cellular columns. Compared to columns of hexagonal unit cells, the rate of decrease in solid columns is 43% lesser and 92% lesser in square unit cellular column. The rate of decrease in axial load carrying capacity in hexagonal concrete cellular columns is exceptionally high and this is most likely due to high stress concentration at corners of the hexagonal unit cells since there are geometrically less vertical elements supporting their corner ends. The visible topological asymmetry in the arrangement of hexagonal cells compared to the other shapes can also be a cause of the loss in load bearing capacity of hexagonal cellular columns. Compared to solid columns, the rate of decrease in strength with height is about 61% and 86% lesser in triangular and square columns respectively. These points to the fact that cellular columns are more advantageous than solid columns, in saving load carrying capacity of columns with increase in height. The square unit cells are seen to be more stable under compression than triangular ones with increase in height as they show a lower rate of decrease in column strength as the height increases. Thus the choice of square topology as the optimum configuration for concrete cellular columns is further reinforced.

As conclusions, the present study is based on the performance of concrete cellular columns when subjected to axial loading alone. The process of 3D printing, otherwise named additive manufacturing which is a considerably novel construction technique, is considered for the manufacture of the cellular columns investigated in this project. The detailed numerical study has led to the following conclusions: Out of all the three cellular column configurations considered in this study (that is square, triangular and hexagonal), the triangular cellular columns show the highest load carrying capacity of 43% compared to the solid reference column. However, they save the least amount of material of only 27% of that of the solid column.The study of strength to weight ratio of concrete cellular columns revealed that, the square cellular columns have 61.8% of the strength to weight ratio of solid columns which was the highest among all three different column cellular configurations. The rate of decrease in strength with height is about 61% and 86% lesser in triangular and square columns respectively. The rate of decrease in strength with height is highest in hexagonal cellular concrete columns when compared to all other counterparts including the reference column. Taking into consideration all the factors studied (that is strength to weight ratio and effect of column) cellular columns of square topology are considered to be optimal. And the hexagonal cellular columns are least preferred. The column models are currently proposed to be used in open pillars and brick elements where the strength requirements of the structure are not much significant.

ACKNOWLEDGMENTS

Sincere thanks to all the faculty of Civil Department, College of Engineering Trivandrum for all the necessary help extended by them for the fulfillment of this work.

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Received: 03th November 2020; Accepted: 06th January 2022; First distribution: 06th November 2022.