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Proceedings of the First MoHESR and HCED Iraqi Scholars Conference in Australasia 2017

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5- 6 December 2017

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Preface

Under the sponsorship of the Iraqi Ministry of Higher Education and Scientific Research 'MoHESR' and the Higher Committee for Education Development in Iraq 'HCED', a large number of postgraduate scholars are currently engaged in doctorate and masters degree programs in Australia and New Zealand. The scholars are from different fields of study including engineering, science, social science, law, agriculture and medicine. The First MoHESR and HCED Iraqi Scholars Conference in Australasia 2017 'ISCA-2017 was held at Swinburne University of Technology in Melbourne, Australia from 5 to 6 December 2017. The purpose of the conference was to celebrate the achievements of the Iraqi scholars and give them the opportunity to showcase their research outcomes to peers and the wider community of Iraqi scholars in Australia and New Zealand.

The proceedings contain four keynote and fifty general abstracts and fifty general papers. The four keynote speakers were A/Professor Salah Al-Fatlawi, Dr Daniel Mansfield, Professor Ahmed Al-Jumaily and Professor Riadh Al-Mahaidi. Reviewers, who were drawn from a specialist pool of International Advisory Committee members and other experts, peer reviewed all general abstracts and general paper submissions. The contribution of all keynote speakers and peer reviewers is greatly valued and appreciated.

ISCA2017 would not have been made possible without the support of numerous individuals and organisations. Resources provided by the host organisation Swinburne University of Technology is gratefully acknowledged. Support provided by the sponsors RMIT University, The University of Queensland and the University of New England is most appreciated. The Local Organising Committee provided extremely valuable contributions to the handling of the technical papers and the peer review process, as well as the compilation of the proceedings and book of abstracts. They also provided an excellent service in developing and maintaining the conference website. Thank you to Cristian Rojas of Red Box Communication Design who skilfully designed and produced the book of abstracts and proceedings. Thank you to Maria Han of Swinburne for providing administrative support to the conference.

Riadh Al-Mahaidi, Alaa Al-Mosawe and Mohamed Al-Younis

Editors, ISCA2017

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Numerical simulation of the compressive behavior of functionally graded lattice structures

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Keywords: Lattice structure, functionally graded, finite element analysis, deformation behaviour.

Lattice structures have attracted attention of a large number of applications such as personal protective equipment and packaging due to their distinctive properties, in particular combining the lightweight and high strength. Previous work on the mechanical properties and energy absorption capability of lattice structures has been experimentally investigated. In this research study, finite element models have been developed using LS-DYNA code of ANSYS© software to investigate the compressive properties and energy absorption capability of cubic lattice structures. The investigated lattice structures were uniform and functionally graded lattice structures with corresponding relative density. Both uniform lattice and functionally graded lattice models were meshed using 3D solid element and subjected to quasi-static compressive loads. Finite element analysis results were found to agree well with previous empirical findings of the functionally graded lattice structure. The functionally graded lattice structures exhibited distinctive deformation behavior than uniform one, where by the collapse of layers starts sequentially, starting with a lower density layer to higher density one in sequence. In contrast, uniformly dense lattice structures were homogeneously deformed under compressive loads. The results also showed that the energy absorption behavior was distinct and increased with increased compressive loads in the functionally graded lattice. These results increase the potential that the functionally graded lattice structures or other models of density gradient would be more desirable for an application that required high energy absorption capability.

1. Introduction

Lattice structures or cellular structures have been widely used in various applications such as personal protective equipment and packaging, structural lightweight, thermal insulation, energy absorption and bio-medical implant due to their unique properties. Cellular structures have received intensive studies to investigate their mechanical and physical properties in last few decades. The most important research work is that performed by Gibson and Ashby[1]. They have conducted a comprehensive study on investigating the deformation behaviour and mechanical properties of the different cellular models such as honeycomb, metallic foam and natural cellular structures with a range of volume fraction. In general, different manufacturing methods that have been traditionally used to produce the metallic lattice structures, for example melt gas injection has been used to form a metallic foam and then machine it to the desirable shape [1]. For the same purpose, investment casting [2], stacking and joining the laminar plates in a periodic manner [3, 4], physical vapour deposition (PVD) have been employed. However, these conventional fabrication methods have some limitations. For example, they are costly and unable to produce lattice structures with a complex shape for advanced uses [5]. Their effectiveness to the

shape complexity [6] and discrepancy in properties of fabricated cellular structures are also some of the main limitations.

Recently, additive manufacturing technology opens new window to manufacture the lattice structures for a wide range of applications due to its ability to overcome the limitations of the conventional techniques [5, 7-9]. Several attempts have been experimentally conducted to study and investigate the mechanical compressive behavior and energy absorption capability of cellular structures made of additive manufacturing [5, 10-14]. The drawbacks associated with additive manufacturing processes are high cost and slow fabrication process, but these are expected to get better with continued development in this technology [9, 15].

Accordingly, conducting the numerical simulation, which can predict the mechanical properties of lattice structures, can decrease the required experimental works as well as the manufacturing cost. In addition, finite element analysis is able to simulate and verify the experimental work, which increases the recognition of the deformation response and mechanical properties of a new designing approach of the lattice structures due to the ability to identify the stress distribution and high stress concentration regions before the fabrication step. Smith et al. [13], Lee et al. [16], Zargarian et al. [9] and Zhong et al. [17] developed the finite analysis models to investigate the mechanical properties, and to verify the experimental results of different types of uniform lattice structure.

In this study, the mechanical properties and energy absorption capability of uniform as well as functionally graded lattice structures are investigated numerically. No previous works have been reported on investigations the mechanical characteristics and energy absorption property of the functionally graded lattice structures with continuous and smooth density change using finite element analysis. Most researches have focused on an experimental study in investigations the functionally graded lattice structures with abrupt, step-wise and pore size density changes in every layer [5, 8, 10]. A quasi-static compression test was simulated to study the deformation behaviour under the compressive loads of both types of lattice structures numerically using LS-DYNA export code of ANSYS© software.

2. Methodology

2.1 Design of the lattice structure

The investigated lattice structures in this study measuring (30×30×30 mm) were designed using PTC CreoTM Parametric ©3.0 software. The lattice structures were built of F2BCC unit cell. The F2BCC lattice unit cell consists of 12 solid struts with circular cross-section by which they intersected at 45° angle to vertical, four at the cell centre, and eight at the four faces of the cell (two struts at each face) as shown in Fig 1 (a). It was duplicated in three directions (X, Y, Z) in order to build whole lattice structure, thus providing lattice structures contain six layers. In this study, investigation the mechanical performance and energy absorption capability of functionally graded lattice structures and assess and compare with uniform lattice structures based on identical relative density is the main purpose. The relative density was assigned to both lattice structures 0.185. In meeting this value, functionally graded lattice structures were designed with density increase continuously gradually from top to bottom throughout the structure layers at 35% constant rate. This was achieved by design cell struts diameters varying from (0.38 - 1.113 mm) for the structure. The cell struts diameters were changed in one direction with linear and continuous change, thus resulting in smooth density change at the boundaries of the lattice structure layers. Fig 1 (a) shows the CAD model and schematic of the unit cell, and (b) CAD model of the

designed functionally graded and uniform lattice structures. In lattice structures with uniform density, this was achieved through the design of uniform cell struts with 0.7 mm diameter.

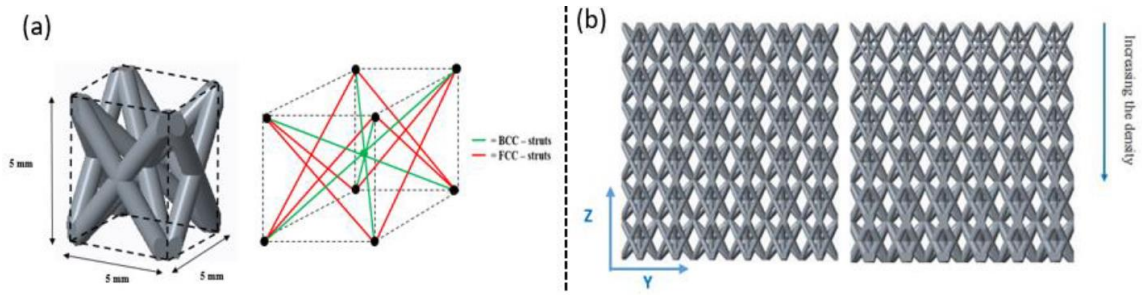

Figure 1. CAD model and schematic of unit cell (a), CAD model of uniform (left) and (b) graded lattice (right)

2.2 Finite element analysis of mechanical properties

To simulate the compressive behaviour of the lattice structures, LS-DYNA code of ANSYS© software was used to generate the model and solve the equations of finite element analysis. For both lattice structures uniform and graded, 3D solid elements were employed to mesh lattice models with six degrees of freedom. During the numerical analysis, the FE models were assigned with material properties based on Alomarah's study [18] that shown in table 1, which is supposed to be a bilinear material response under compression tests. Since the lattice structures have separated small areas (nodes) on the top and bottom of the models Fig 1 (b), which may cause some errors during the applying boundary conditions, two connected plates were modelled on top and the bottom to overcome this issue. The boundary conditions were applied to simulate exactly what had happened in experimental test [5, 8, 10], in which the top plate was freely moved in Z direction at the constant velocity and fixed in other directions, and the bottom one was fully fixed in all degrees of freedom Fig 2. In addition, the type of contact between the rigid plates and the model was used an automatic node to surface contact, while the automatic single surface contact was used to define the interaction between the connected solid struts of the cells [7]. For clarification, no boundary constraints were used to the sides of the lattice models during the all simulations.

properties	Density ($g\ m^{-3}$)	Young's modulus GPa	Poisson ratio	Yield strength MPa	Tangent modulus GPa	Ultimate strength MPa
AlSi-12	2.7	15	0.33	165	3.3	220

Table 1. Properties of aluminium alloy material [18]

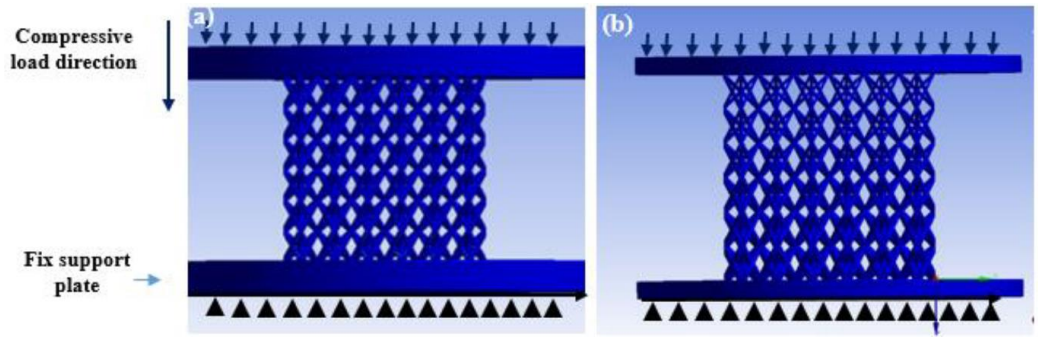

Fig 2. Boundary conditions of FEA models of compression test for (a) uniform, (b) graded lattice

3. Result and discussion

3.1 Deformation behavior of FEA models

Figure 4 shows the resulting data of the compressive stress-strain curves of FEA models. The predicted deformation behavior of FEA models under the compressive loads for both uniform and graded density models presents in Fig 3 (a, b) respectively. Unfortunately, the running simulation for whole structure could not be conducted due to facing some of the constraints. Computational time required and capability of available computers are the main constraints that we had faced during the finite element analysis. To overcome these issues, and by considering the symmetrical geometry of the designed lattice structure, one tower of the structure contains six layers with one cell in each layer was considered to conduct the numerical analysis. It is found that the deformation response of FEA model of uniform lattice found to be discrepancy with experiment collapse behavior [5, 8, 12]. The deformation process of FEA - uniform model was deformed in a corresponding manner and homogeneous as shown in Fig 3 (a), in which starts with buckling and bending in solid struts of the cell and is followed by full compaction due to contact of the cell struts with the next cell struts. The difference is due to the difficulty in simulating the mechanism of collapse, which is a combination of 45° shear, fracture and flake formation in some struts at the same time.

Compared to the FEA- uniform density model, the FEA model with gradual density exhibited close agreement with the empirical results of the previous work [5, 8, 10]. Fig 3 (b) elucidates the collapse behavior of FEA – graded model. It can be observed that the deformation process is entirely different from the collapse behavior of FEA - uniform model. The deformation behavior of FEA – functionally graded model exhibit a distinctive deformation behaviour by which commenced with low density cell at the top, and then, in sequence, the collapse of cell-after-cell continuously. However, it is worth mentioning that the gradually dense lattice structure exhibited distinct collapse behavior under the compressive loads than uniform lattice structures. These findings increase and support the potentials that the functionally graded lattice structures are more desirable for applications with high impact resistance [5, 8, 10].

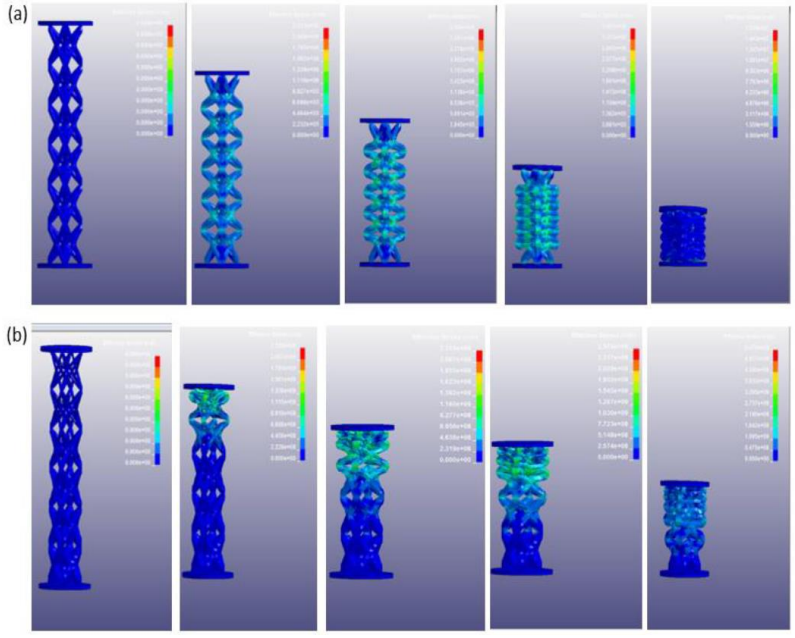

Figure 3. Predicted deformation behaviour of (a) uniform, and (b) graded lattice structure under compressive loads.

3.2 Energy absorption response of FEA models

The determined values of energy absorption of both FEA models provide in Table 2. The energy absorption capability for both FEA-uniform and FEA-graded lattice structures has been determined as the area under the compressive stress - strain curve using the numerical integration, which is represented by equation (1).

$$Wv = \int_0^{\varepsilon} \sigma\,(\varepsilon) d\varepsilon \qquad (1)$$

The cumulative energy absorption per unit volume versus the increase of compressive strain for FEA-uniform and FEA-graded lattice structures are plotted in Fig 5.

Energy absorption	FEA models	
	Uniform	Graded
$Wv\ (MJ/m^3)$	5.06 ± 0.008	6.27 ± 0.006

Table 2. Energy absorption properties of FEA models

It is clear that the FEA-graded lattice structure was able to absorb energy higher than the FEA-uniform lattice structures, in which 6.27 MJ/m^3 and 5.06 MJ/m^3 are the values respectively. It has been observed that the energy absorption response of FEA-uniform lattice structure increases at a constant rate and in an almost linear relationship with the compression strain values. This is due to the homogeneous deformation of the uniform lattice under the compressive loads as shown in Fig 4. On the other hand, the energy absorption behaviour of the FEA-graded lattice structure was quite different as shown in Fig 5.

The graded lattice structure exhibits distinctive behaviour of energy absorption due to its deformation response under compressive loads as explained in the previous section. The gradual increase of absorbed energy was tied with the deformation behaviour of layer by layer starting with the top layer of low density one. These results and observations are found to agree with reported values of energy absorption experimentally from the literature that supports the functionally graded lattice structures [5, 8, 10].

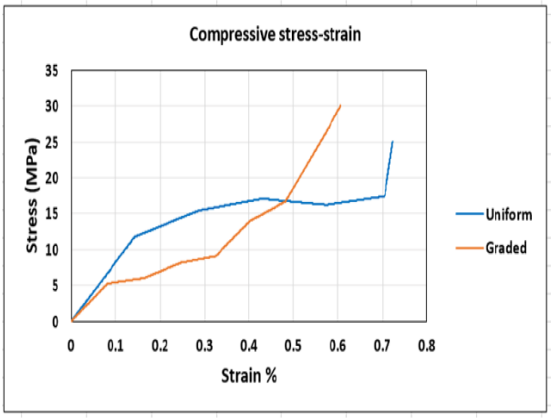

Fig 4. Compressive stress strain of FEA models

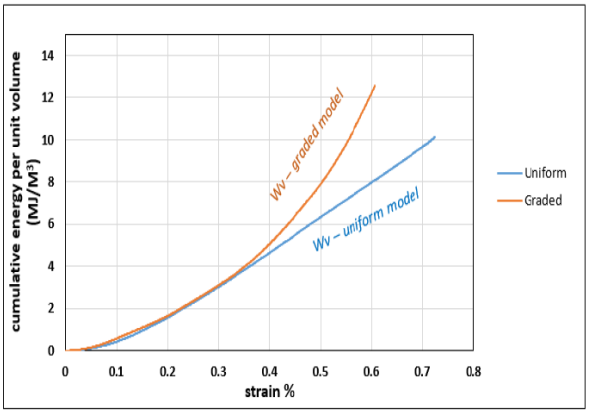

Fig 5. Cumulative energy absorption per unit volume against compressive strain curves of FEA models

4. Conclusion

It was demonstrated that numerical simulation of the compressive behaviour and energy absorption capability of uniform and functionally graded lattice structures can be performed successfully using LS-DYNA code of ANSYS software. The finite element analysis has proved that the functionally graded lattice structure exhibits distinctive characteristics in deformation under compressive loads. The collapse process of graded structure is a non-homogeneous layer by layer crushing beginning with the collapse of the lower density layer and then to higher density one in sequence, while the uniform lattice structure exhibited homogenous collapse in the whole structure. The energy absorption behaviour of the graded lattice structure increased continuously and gradually with increase in the strain value while the uniform lattice structure shows closer to a linear relationship. These results indicate that functionally graded lattice structures would be more attractive for applications that required high impact or shock resistance. Further investigations are needed on more advanced density gradient profile for various applications. In addition, combined finite element analysis and experimental study are recommended for optimising the design of new density gradient structures.

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