PREDICTING ENERGY ABSORPTION PARAMETERS OF ALUMINUM LATTICE STRUCTURES FILLED TUBES VIA ARTIFICIAL NEURAL NETWORKS

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Abstract

In this paper, the energy absorption parameters of aluminum body centered cubic lattice structures filled thin-walled tubes under axial loading are predicted via artificial neural networks (ANNs). Different tube thickness, lattice member diameters and number of lattice unit cells are considered as design variables, the total amount of energy absorption (EA), the specific energy absorption (SEA), the mean crush force (MCF) and the peak crush force (PCF) are considered as design criteria (energy absorption parameters). The proposed approach is based on finite element simulations for construction of the sample design space and verification, ANNs for predicting the energy absorption parameters. The results showed that the proposed ANN approach is able to predict the energy absorption parameters with high accuracy.

Keywords: Artificial neural networks, energy absorption, lattice structures, energy absorption, finite element method

1. Introduction

Thin-walled tubes are the most conventional passive safety elements in vehicles in order to prevent loss of life and property due to their superior energy absorption capabilities [1,2]. Hence, extensive numerical and experimental researches have been carried out to improve the energy absorption performance of thin-walled tubes in past decades. At this point, various materials such as aluminum and composite, cross-sections such as circular and square, patterns such as windowed and grooved, semi-apical angles such as straight and tapered are proposed to enhance the crashworthiness performance of the tubes [3–6]. Compared to each other, all types of tubes have some advantages and disadvantages in terms of strength, weight, cost etc. Among them, aluminum tubes are the most widely used due to their production easiness, good deformability, high specific strength, low density and cost effectiveness [4-6].

In the last decades, researchers have been tried various ways to enhance the crashworthiness performance of thin-walled tubes with the least possible mass. At this point, filler or covering materials such as foams, honeycombs and composites enable to improve energy absorption performances [6]. The researches show that the thin-walled tubes enhanced by filler or covering materials could considerably increase the energy absorption capacities of the tubes.

Additive manufacturing technologies in other words 3D printing techniques provide an unprecedented opportunity to researchers to create novel parts due to their ability to easily manufacture complex parts. Thanks to this feature, various types of structures have been already used in the literature. Among them, the body-centered cubic (BCC) structures are the most preferred structures due to ease of design. Several researches investigated the energy absorption performances of BCC lattice structure. Mines et al. [7] and Shen et al. [8] investigated experimentally the low-velocity impact behavior of sandwich panels with BCC micro-lattice structures. Gümrük et al. [9] carried out an experimental study on the static behavior of BCC lattice structures under different loading conditions such as compression and tension loading conditions. Merkt et al. [10] studied on the mechanical characteristics of the BCC lattice structures under quasi-static and dynamic tests. Similarly, McKown et al. [11] executed quasi-static and blast tests for BCC lattice structures. Maskery et al. [12] investigated the effect of number of cells and cell size on the mechanical performance of the BCC structures subjected to tensile loading. Recently, Cetin and Baykasoğlu [13] proposed a novel structure consisting of BCC lattice structure and thin-walled tube, and the new hybrid structure showed superior crashworthiness performance.

The use of prediction methods has been gradually increasing in the literature since performing numerical simulations and experimental measurements for each cases is unaffordable due to excessive cost and time. In this study, the energy absorption parameters are predicted via ANNs. The proposed ANN approach is based on the finite element analyses for construction of the sample design space and validation. The datasets are generated through finite element simulations [13] that is used to model EA, SEA, MCF and PCF. The simulation results showed that ANN models is able to predict with high accuracy the energy absorption parameters of tubes filled with lattice structures under axial loading.

2. Problem description

2.1. Description of geometric features

The energy absorbing performance of aluminum square tubes enhanced by BCC lattice structures are investigated and crashworthiness parameters are predicted by ANNs in this study. At this point, body centered cubic lattice structures filled thin-walled tubes with different lattice member diameters ($1 \leq d \leq 5$ mm), different number of lattice unit cells ($3 \leq n \leq 7$) and different tube thickness ($0.5 \leq t \leq 1.5$ mm) are considered as design variables. A total of 75 different variable combinations are tested with finite element simulations, which also constitutes the data set

(design space) for ANNs. The schematic view of the evaluated structures are presented in Fig 1.

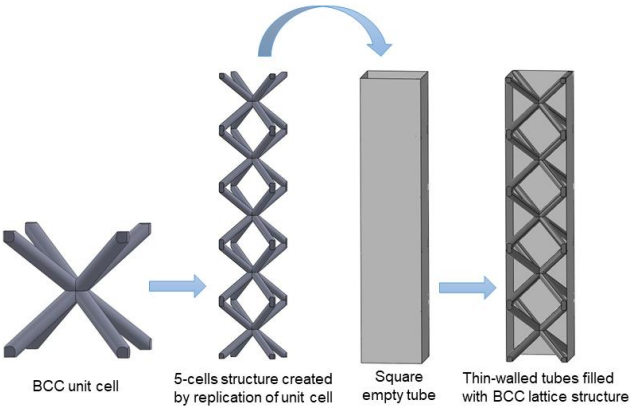

Figure 1. The schematic view of a 5-cell structure

The BCC lattice unit cells are designed to fit exactly into the square tube and the cells are replicated to the vertical direction depending on the requested number of lattice unit cell. Designed lattice structures are placed inside the tubes as shown in Fig. 1. It should be noted that the lattice structures have idealized structural geometry. The initial length of all structures is considered as 120 mm. On the other hand, width of the structures varies depend on the number of unit cells, and the width of the structures having 3, 4, 5, 6 and 7 lattice unit cells are 40, 30, 24, 20 and 17.14 mm, respectively.

2.2. Numerical modeling and validation

The BCC lattice models are formed in SolidWorks platform, and numerical simulations are carried out by using Abaqus finite element (FE) software. In all analysis, the tubes enhanced by lattice structures are situated between a fixed and moving rigid plates as shown in Fig 2. The moving rigid plate with 10 m/s initial velocity and 250 kg impacting mass is allowed to moves only in the vertical direction, while the fixed rigid plate is fixed in all directions for translation and rotation. All of the interactions between the tubes, lattice structures and rigid plates are specified via general contact property, and penalty formulation is used to model the contact behavior in the tangential direction. The friction coefficient is considered as 0.25 for all contacts similar to [13,14]. In order to take geometric imperfections into account, the eigenvalue buckling simulations are carried out before the crash simulations, and the magnitudes for the first buckling modes are considered as 0.02 of the tube thickness [13]. The rigid plates, lattice structures and thin-walled tubes are modeled using four-node linear quadrilateral R3D4 elements, four-node linear tetrahedron C3D4 element and four-node S4R shell elements with reduced integration, respectively. In order to prevent penetration between the tube and lattice structures, the square tubes are designed by taking into account mid-surface finite element shell formulation. At least three elements are used through diameter of the lattice structures in order to obtained acceptable results. 1 mm and 2 mm are selected as global element size for the tube and lattice structures, respectively [13].

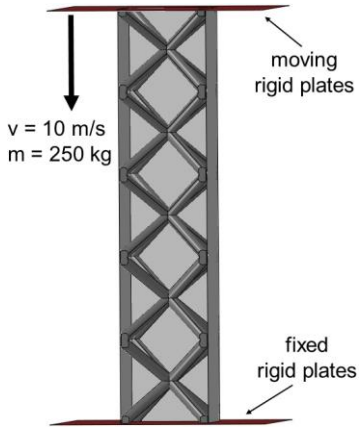

Figure 2. The finite elements model and boundary conditions of the structures

The material of square tubes is Al6063-T5 with the modulus of elasticity of 68.2 GPa, yield strength of 187 MPa, density of 2700 kg/m^3 and Poisson's ratio of 0.3. On the other hand, the BCC lattice structures are made of the AlSi10Mg with the modulus of elasticity of 69.3 GPa, yield strength of 160 MPa, density of 2700 kg/m^3 and Poisson's ratio of 0.3. In order to validate the proposed finite element model, the BCC lattice structures are produced from AlSi10Mg with particle size of 30 μm using EOS M 290 direct metal laser sintering (DMLS) machine. Next, the manufactured BCC lattice structures are placed inside the Al6063-T5 square tube. Then, experimental axial crushing tests are performed to check the validity of the proposed finite element models. The results of the experimental test and finite element models are shown in our previous study [13], and it is revealed that the elastic, elastic-plastic, plateau and densification region of finite element model results are considerably compatible with the experimental results. The experimental test procedure, the material models and validation results are given in detail in ref. [13].

2.3. Crashworthiness parameters

Different performance parameters such as EA, SEA, MCF and PCF are used in order to investigate the energy absorption performance of thin-walled tubes. The parameters are obtained from their load-displacement responses.

The EA is defined as total energy absorption during crushing distance (δ) and can be defined as:

$$EA = \int_0^{\delta} F(\delta) d\delta \tag{1}$$

The SEA is total amount of energy absorption per total mass (m) of the structure, and is calculated as:

$$SEA = \frac{EA}{m} \tag{2}$$

The MCF is defined as the ratio of energy to displacement and is defined as follows:

$$MCF = \frac{EA}{\delta} \quad (3)$$

The PCF indicates the maximum force value throughout the crushing displacement. Extremely high PCF values lead to undesirable results for passenger safety due to sudden large deceleration, while the EA, SEA and MCF are expected to be as high as possible.

3. ANN modelling and analysis

ANNs are very often used in predicting key parameters of industrial processes/materials including crashworthiness parameters due to their very high prediction abilities [16]. ANNs have too many parallel working non-linear computing entities like biological neurons in the brain. In executing an ANN, all input data feed progressively into input neurons (nodes). The input data disseminates along the connections (weighted links) to the other sections of the ANN. As they spread, they are combined at common nodes and updated based on the predefined computational procedures. This process is repeated iteratively in order to train the ANN by using a suitable learning algorithm. Results (predictions) obtained from the output neurons (nodes) institute the numeric results that are utilized for the specific application. There are many software platforms to design and utilize ANNs for practical applications. In the present study, the well-known MATLAB's Neural Network Tool Box is employed for developing an appropriate Generalized Feedforward ANN for predicting crashworthiness parameters (total energy absorption, EA (J), specific energy absorption, SEA (kJ/kg), mean crush force, MCF (kN) and peak crash force, PCF (kN)) of square tubes filled with lattice structures under axial impact loading. The datasets are produced through finite element simulations (as mentioned in the previous section [13]) is used to model *EA, SEA, MCF* and *PCF*. Detailed explanations about the datasets and their generation and the related finite element simulations can be obtained from our recent work [13]. The ultimate goal is to discover a well-trained ANN, which connects input variables, namely, number of lattice unit cells (*n*), lattice member diameter (*d*), and tube thickness (*t*) to the output variables, *EA, SEA, MCF* and *PCF*.

A suitable ANN configuration (number of hidden layers and number of neurons in each hidden layer) need to be determined which results in high training performance. Unfortunately, there is not a universally agreed practice for determining optimal ANN configurations. Generally, trial-and-error procedures are utilized for this purpose. In this research, a feedforward ANN with one hidden layer and 25 neurons in this hidden layer is employed for body centered cubic (BCC) lattice structure in predicting *EA, SEA, MCF* and *PCF*. Levenberg-Marquardt training algorithms that is known to be very effective in ANN training is selected to train selected ANN configuration. Average prediction result after 20 independent runs is R=0.9877 (correlation coefficient). The best test result is R=0.98833. Results indicate that there is significantly high correlation between the actual and predicted outputs. Computational results for the selected ANN configuration is shown in Figs 3-7.

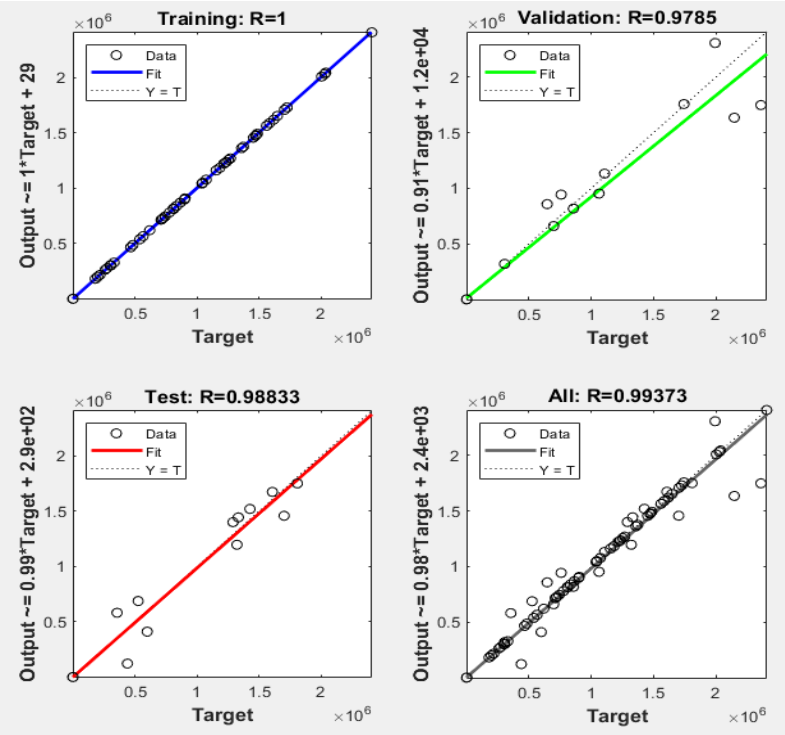

Figure 3. Correlation coefficients for the most suitable ANN for BBC structures

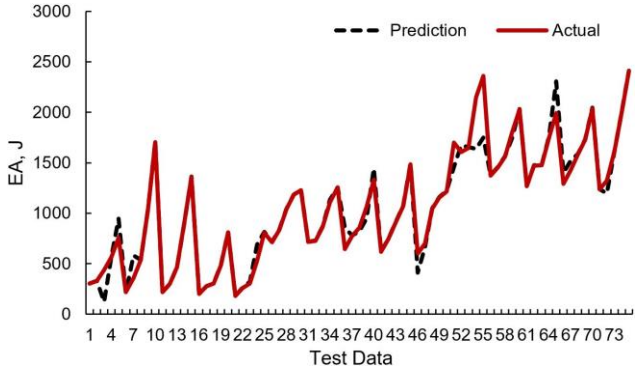

Figure 4. Test results for EA

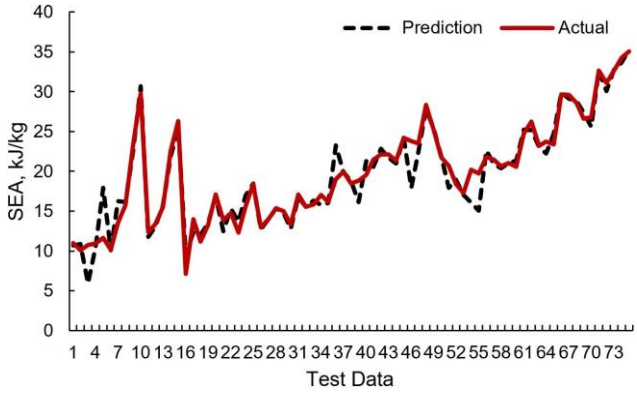

Figure 5. Test results for SEA

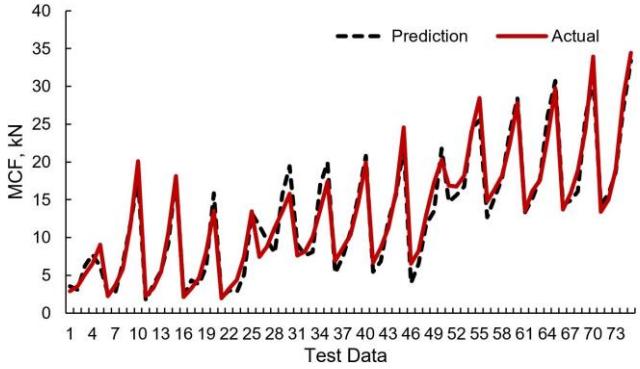

Figure 6. Test results for MCF

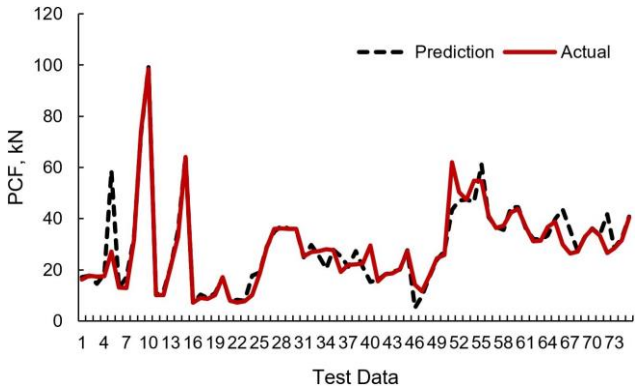

Figure 7. Test results for PCF

4. Conclusions

The energy absorption parameters of aluminum body centered cubic lattice structures filled thin-walled tubes under axial loading are predicted via ANNs in this study. Different number of lattice unit cells, lattice member diameter and tube thickness are proposed in designs, and EA, SEA, MCF and PCF are considered as energy absorption parameters. The proposed approach is based on finite element simulations for construction of the sample design space and verification. Feedforward type ANNs are employed for predicting the energy absorption parameters. The simulation results proved that the proposed approach is able to provide good solutions with very high accuracy. Having very high level of accuracy can motivate engineers/designers to employ ANNs and similar computational intelligence based learning algorithms in reducing number of physical experiments in design evaluation, which are very expensive, and time consuming. In future studies, the ANN approach is planned to be integrated with multiple objective optimization algorithms in order to determine the most suitable design variables that optimize the energy absorption performance of thin-walled structures.

Acknowledgment

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