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Compression behaviour of an extremely lightweight structure with a gyroid core used for bridge bearings

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A R T I C L E I N F O

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A B S T R A C T

This article reports an extremely lightweight structure used as a sandwich core for bridge bearings due to their superior mechanical properties, such as uniform stress distribution with no concentration stresses at the intersection of the structure, lightweight, rigidity, and energy absorption. The structure is based on triply periodic minimal surfaces (TPMS) conceived by observing the scales of butterflies' wings. The compression behaviour of this innovative structure used in these typical bearings is not well-known and has never been fully investigated. Therefore, it is important to comprehend their compression behaviour and also to identify a failure mode of these bridge bearings under compression. A gyroid unit cell finite element model used in the sandwich core for bridge bearing application is examined with a computational method. The numerical investigation shows the compression mechanisms and provides the failure mode, which is important in establishing relationships between its mechanical performance and geometry. The results have shown that the model exibits a stretch-dominated and uniform stress distribution behaviour under compression. These results can be implemented to better generate informed lightweight structure designs for bridge bearings which are subjected to different compression conditions.

1. Introduction

Over the past 50 years, multiple base isolation systems have been developed. Commonly, they consist of an elastomeric bearing and energy dissipators, for example, steel plates, lead-plugs, etc. In some cases, these bearings are a combination of sliding bearings and re-centre devices. In terms of bridge design, elastomeric bearings used as bridge bearings play a crucial role, which provides the longer fundamental period of free vibration of a structure.

Another function of bridge bearings is not only to facilitate lateral or torsional displacement induced by temperature variations and vibrations, but also to withstand and transfer vertical forces from the superstructure to the substructure of a bridge. Over the past 80 years, bridge bearings have been examined and their current design requirements are based on a study [1–4]. This study reports the better understanding of compressive behaviour of bridge bearings.

Recently, steel/fibre-reinforced elastomeric bridge bearings, also referred to as steel/fibre reinforced laminated ones, have been presented to be used in bridge system, in order to better perform with increasing vertical stiffness [5,6]. However, they seem to occur bulging behaviour under compression as shown in Fig. 1 and to result in the stress concentrations at the edges of steel/fibre shims as well as the failure of delamination between the reinforcements and the elastomer due to low adhesive bond for plain and steel/fibre-reinforced elastomeric bridge bearings, respectively.

According to our previous works related to the development of a common bridge bearing under different loading in [7–11], we have efforted to eliminate their drawbacks by using a lattice structure as a sandwich structure in typical bridge bearings for bridge system. This is because a lattice structure is likely to provide a better performance to ratio when compared to an elastomeric bearing [8].

To the best of our knowledge following a critical review of the available literature, there is no extant research on the compression behaviour of a gyroid unit cell used as a core for a bridge bearing. This study focuses on the development of a novel unit cell model using a gyroid structure for bridge bearing applications. The

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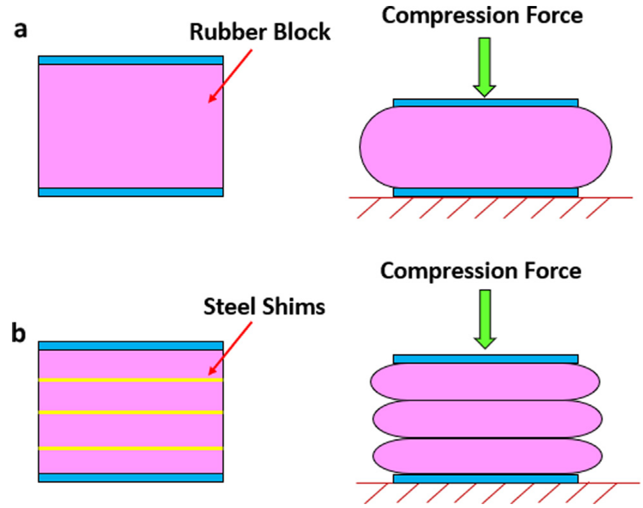

Fig. 1. (a) Massive bulging behaviour of an elastomeric bridge bearing, (b) layer-by-layer bulging behaviour of a steel/fibre-reinforced bridge bearing under compression.

force–displacement relationship and normal stress distribution at a 50 per cent strain of the model in compression are investigated and obtained through finite element method using Abaqus software. In the further section, a material and method for this paper will be presented, followed by numerical results of the gyroid unit cell model under compression.

2. Methodology strategy

The key concept of this paper is to better understand the compressive behaviour of a gyroid unit cell used as a sandwich core for bridge bearings, also to reduce the computation time for its simulation. According to a review in [12], Ashby mentions that there are three key factors affecting the mechanical properties of porous structures, which are arrangement pattern, materials, and density. Elastic finite element (FE) analysis is employed to investigate the idea behaviour of the proposed gyroid unit cell model to obtain its force–displacement and stress distribution.

3. Finite element modelling of a gyroid unit cell model

3.1. Unit cell design

Triply periodic minimal surface (TPMS) gyroid can be created through different methods. In this paper, the method to a gyroid three-dimensional modelling is based on the following level curvature equation [13].

$$sin\left(\frac{2\pi x}{h}\right) * cos\left(\frac{2\pi y}{h}\right) + sin\left(\frac{2\pi y}{h}\right) * cos\left(\frac{2\pi z}{h}\right) + sin\left(\frac{2\pi z}{h}\right) * cos\left(\frac{2\pi x}{h}\right) = k \tag{1}$$

where h denotes the size of a fundamental cell and k determines the cross section of the sheet, which affects the relative density of the structure.

After that, a CAD software is used for this method allowing to generate a three-dimensional surface by means of equation. Furthermore, this software can create a gyroid solid structure from this surface. Fig. 2 shows a gyroid unit cell model for a bridge bearing core. The dimensions of the unit cell model are 50 × 50 × 50 mm with a thickness of 2 mm.

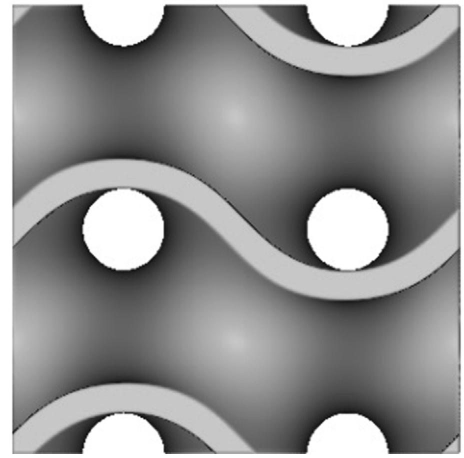

Fig. 2. A gyroid unit cell model in CAD software.

3.2. Applied force and boundary conditions

To observe the behaviour of an extremely lightweight structure for bridge bearings based on the investigation of the gyroid unit cell model, it is important to select proper boundary conditions. For compression simulation, the model is based on the isotropic material model in Abaqus software and compression displacement is applied to a reference point to move towards the base of the model. In terms of boundary conditions, the reference point in the middle of the upper faces of the model constraints all nodes on the upper faces and another reference point in the middle of the lower faces is fixed. Furthermore, the displacement loading for this compressive model is applied by using the static general FEA model on Abaqus software (see Fig. 3).

3.3. Material properties

The model material utilised for the finite element simulation in this paper is UV resin. The proposed UV resin material properties are provided in Table 1.

3.4. Data collection

Compression FEA model is run and force–displacement curve is plotted. A force is determined from the reaction force as vertical

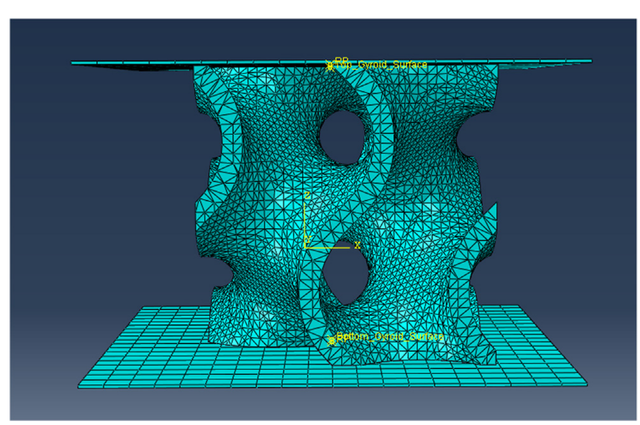

Fig. 3. The mesh of a gyroid unit cell model in Abaqus software.

Table 1
Material properties of UV resin material.

Parameter lists	Values	Units
Young's modulus	686.03	MPa
Shear Modulus	257.90	MPa
Density	1100	kg/m^3

deformation is applied to the middle reference point on the upper faces of the model. Also, the stiffness of the gyroid unit cell model is calculated by dividing force with applied displacement in the linear elastic region.

4. Results and discussion

Fig. 4 presents the force–displacement curve of the compressive behavior of the gyroid unit cell model used as a sandwich core for bridge bearings. It is clear that the graph presents the common stretch-dominated behavior of the gyroid unit cell model and its vertical stiffness is 1.71 kN/mm. The graph reaches its elastic limit at nearly 6.8 kN before a softening post yielding response, followed by a basin region which can be observed in the graph due to the continuous collapse of the gyroid sheets. Then, the structure of the gyroid unit cell model trends to carry more loads due to its densification. Furthermore, Fig. 5 shows the stress distribution visualization of the model obtained from the numerical results. It has shown that the model provides a uniform stress distribution which can eliminate a stress concentration.

5. Conclusions

In this study, a force–displacement curve and stress distribution behaviour of a gyroid unit cell model used for a bridge bearing core is observed to potentially predict the stretch-dominated behavior of a gyroid sandwich core under compression for bridge bearing applications considerably well [12]. As a result, the gyroid unit cell model would be practical for use when the model validation is carried out to compare its experimental results. Furthermore, additional work in the near future will be assessed on the bridge bearing lattice model with a combination of gyroid unit cells under compression loading.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

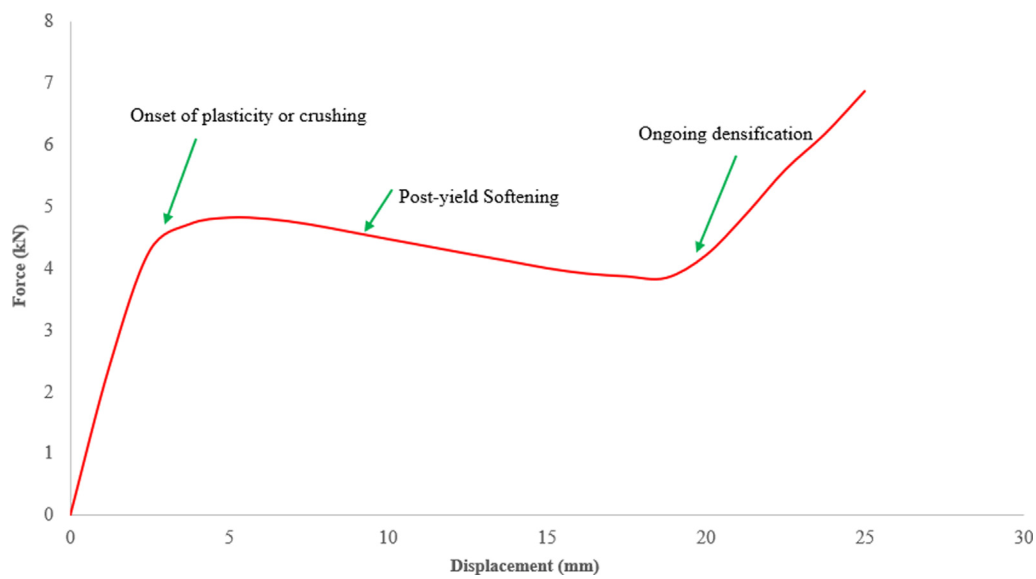

Fig. 4. Force-displacement curve of the gyroid unit cell model used for bridge bearings sandwich core at 25 mm enforced displacement.

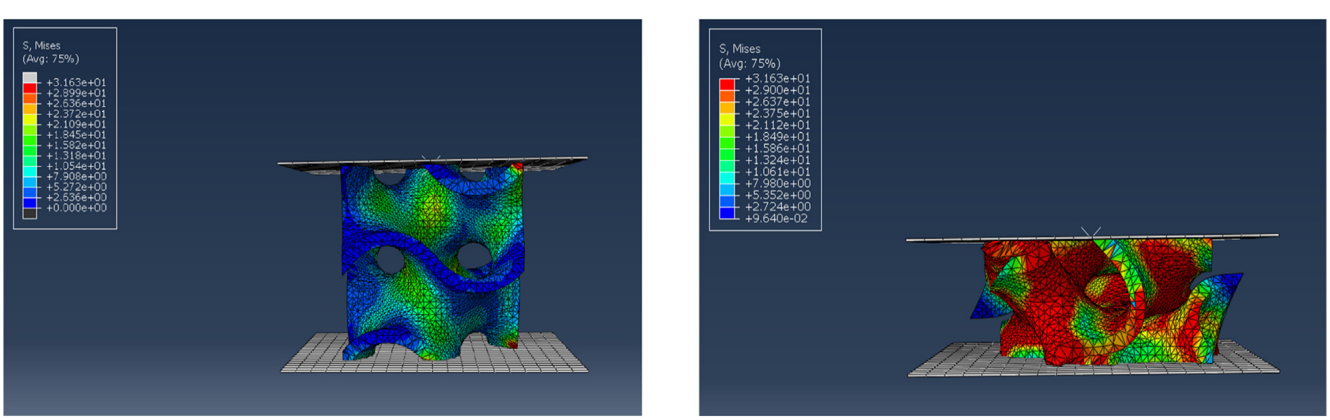

Fig. 5. Uniform stress distribution of the compressive behaviour of the gyroid unit cell model (a) at a strain of 25 %. (b) at a strain of 50 %.

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