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Dynamic Modal Parameters of an Extremely Lightweight Structure using a Gyroid Core for Bridge Bearings

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Abstract:

This article reports an extremely lightweight structure used as a sandwich core for bridge bearings due to their superior mechanical properties, such as sound and vibration attenuation, rigidity, and energy absorption. The structure is based on triply periodic minimal surfaces (TPMS) conceived by observing the scales of butterflies' wings. The vibration behaviours of this innovative structure used in these bearings are not well-known and have never been fully investigated. Therefore, it is important to comprehend their vibration behaviours and also to identify dynamic modal parameters of these bridge bearings. Two gyroid sandwich panel finite element models with different unit cell sizes used as bridge bearings are examined with a computational method. The numerical investigation shows the vibration mechanisms and provides the dynamic modal parameters important in establishing relationships between its mechanical performance and geometry. Finite element predictions of the vibration behaviours of the two models with different unit cell sizes under free vibration provide good results. These results can be implemented to better generate informed lightweight structure designs for bridge bearings, which are subjected to different vibration conditions.
Keywords: bridge bearings; triply periodic minimal surfaces (TPMS); gyroid, vibration behaviours

1. Introduction

In contemporary bridge system, base isolation with elastomeric bearings also well-known as laminated rubber bearings (LRB) has been widely employed for attenuating the influence of seismic loads (vibrations) by reducing the loads transferred to the substructure [1-3]. These seismic loads can lead to the failure of a bridge and its components due to natural frequency resonance. The key functions of these bearings are not only to experience the compressive loads, transmitted from the deck, but also to facilitate deformations in horizontal and rotational direction. On the other hand, in some cases, LRBs, which are fixed between the superstructure and the substructure via bolted connections, are likely to face tensile displacements (uplift) induced by the rotation of a pier cap during earthquakes [4-6]. This results in internal local failures in the rubber as a well-known cavitation phenomenon [7-10].

In term of materials used in LRBs, they are a combination of rubber layers and steel shim plates which are laminated together alternately. Steel shim plate is a solid material that provides high vertical stiffness. Unlike rubber layer, it is a mainly incompressible material which offers high horizontal flexibility [11, 12]. Thus, LRBs possess an extremely high vertical stiffness, whilst remaining high horizontal flexibility which is needed to extend the period of a structure under seismic loading condition. This response is required for isolation of a civil engineering structure.

Nevertheless, there is an optional structure like a lattice structure which is possible to be used in an elastomeric bearing as a sandwich-structured composite, in order to show better mechanical properties than common structures provide currently, due to their high-performance and weight ratio. Lattice sandwich structures do not only offer benefits in lightweight, but also vibration attenuation, superior energy absorption, as well as thermal dissipation when compared to general structures (foam and honeycomb sandwich structures) [13-18]. Therefore, the lattice structures could potentially be the ideal core of sandwich structures for bridge bearing applications.

A common sandwich plate consists of a lightweight core connected to two relatively thin, dense, high-strength and stiffness face sheets. In this work, the idea of a novel extremely lightweight structure called a porous structure is inspired by butterfly wings due to their specific design with several features [19, 20]. The wings consist of a lightweight structure core with an infinitely connected triply periodic minimal surface (TPMS) geometry called gyroid and reinforced on their outer areas with a series of ribs. Thus, the architecture of the porous structure used in butterfly wings can lead to a well-known porous structure (gyroid), which is a member of a TPMS family [21]. TPMSs are minimal surfaces with mean curvature of zero and periodic structures in three coordinate directions [22].

In term of great benefits of using a TMPS structure, a TMPS can locally minimise its region (uniform stress distribution) and free it of self-intersections [23]. Additionally, it possesses high manufacturability of additive manufacturing (AM) process because of its geometrical characteristics [24-26]. Gyroid structures can be designed, but it is difficult to produce them until the advantages of AM technologies [27]. The main advantage of AM is that it allows the design and fabrication of more complex components by their features than conventional manufacturing processes [28, 29], with a certain benefit in enhancing performances of components [30, 31].

As aforementioned, bridge bearings can fail in resonance when the frequency of a periodically applied load is close or equal to a natural frequency of a bridge system on which it behaves. Hence, it is crucial to comprehend the dynamic modal parameters of bridge bearings for designing and predicting their vibration responses. Lots of research works have been performed on the stability of laminated rubber bearings imposed to vertical and horizontal loading [32-34], the buckling load capacity of LRBs [35], and also the instability of LRBs influenced by cavitation [36]. There are our previous works on the development of a common bridge bearing using lattice structures, which focus on their compressive and modal behaviour under compression and vibration, respectively [37-42]

On the other hand, to the best of our knowledge, there is no existing research on identifying dynamic modal parameters of an extremely lightweight structure with a gyroid core for bridge bearing applications. As these parameters obtained, an effective seismic base isolation system can be designed. In this paper, we aim to determine the dynamic modal parameters of the gyroid sandwich panel used as a bridge bearing (BB) subjected to free vibration, in terms of natural frequencies, mode shapes through numerical modal analysis.

2. Materials and methods

2.1 Design of an extremely lightweight structure

A computer-aided design (CAD) model of the gyroid structure is created by using Rhino 6 software. The software allows users to design a gyroid structure by plotting an implicit function presented in the following equation (1). This function reproduces a structure closely similar to the three-dimensional pattern of the gyroid topology.

$$\sin x * \cos y + \sin y * \cos z + \sin z * \cos x = 0. \tag{1}$$

The unit cell is 10 mm in size and the gyroid cell is patterned on the 3D space to the desired core shape (3x3x2 unit cells) with a width of 30 mm, a length of 30 mm, and a height of 20 mm. As presented in Fig. 1, it illustrates the gyroid structure with a unit cell size of 10 mm and a thickness of 0.75 mm created with Rhino 6 software. The unit cell size is one of the parameters investigated in this paper.

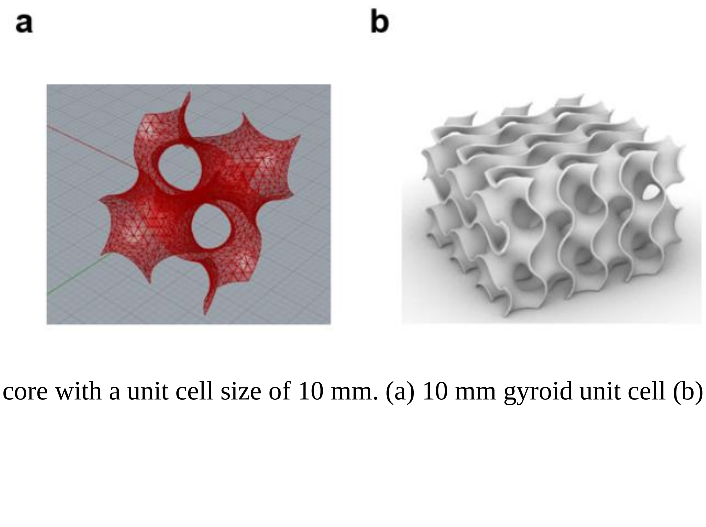


Figure 1: A gyroid core with a unit cell size of 10 mm. (a) 10 mm gyroid unit cell (b) 30 x 30 x 20 mm array.

The two metallic facets with a thickness of 1.5 mm are connected to the upper and lower surface of the gyroid core, illustrated in Fig 2. The connections are designed by employing Siemens NX 12.0 software.

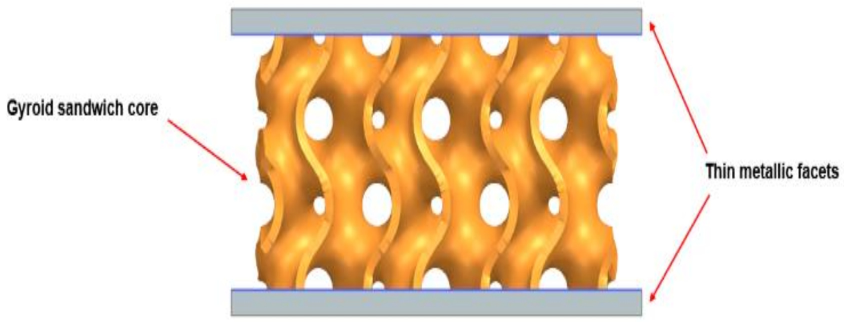


Figure 2: Gyroid sandwich panel used as a bridge bearing.

2.2 Numerical modal analysis

Modal analysis is a tool which is one of the most widely used methods to characterise and identify the properties of systems in the frequency domain. In this paper, we aim to determine the dynamic modal parameters of extremely lightweight structure components with a gyroid core, in terms of fundamental frequencies and mode shapes via finite element (FE) modal analysis. The dynamic equation under free vibration for a single degree of freedom system without damping can be described as [43].

$$[\boldsymbol{m}]\{\ddot{\boldsymbol{s}}\} + [\boldsymbol{k}]\{\boldsymbol{s}\} = \{\boldsymbol{0}\}. \tag{2}$$

Free vibration solution is mathematically considered as a non-trivial solution. It should take the form as:

$$\{\boldsymbol{s}\} = \{\boldsymbol{S}\}\,\mathbf{sin}\,\boldsymbol{\omega t}. \tag{3}$$

By substituting Eq. (3) into Eq. (2), the equation becomes a simple algebraic matrix equation:

$$([\boldsymbol{K}] - \boldsymbol{\omega}^{\mathbf{2}}[\boldsymbol{M}])\{\boldsymbol{S}\} = \{\boldsymbol{0}\}. \tag{4}$$

As $\{S\}$ cannot be zero in Eq. (4), therefore:

$$\boldsymbol{det}|[\boldsymbol{K}] - \boldsymbol{\omega}^{\mathbf{2}}[\boldsymbol{M}]| = \{\boldsymbol{0}\}. \tag{5}$$

Where, ω^2 represents the eigenvalue which identifies the natural frequency of the system and $\{S\}$ denotes the eigenvector which identifies the mode shape of the system.

Two gyroid sandwich panel finite element models with different unit cell sizes are generated and analysed using Siemens NX 12.0 software. Modal analysis is proposed as the mode of analysis employed to investigate these panels. For gyroid core, TPU which is used in the core for the simulations is a rubber-like material (hyperplastic) with very high bulk modulus but having low shear modulus. Whilst two thin steel facets are assigned to be linear elastic materials. Their properties are shown in the following table. Also, the materials are meshed using 238,813 and 210,819 tetra10 elements with 0.5 and 1 mesh size for 10 mm and 20 mm unit cell size presented in Fig 3, respectively. Simulations are employed to reveal the dynamic modal behaviours and to conduct a parametric study. It is important to mention that the two gyroid sandwich panels in this paper are modelled with a small scale to reduce computational time.

Table 1: Engineering properties of a gyroid sandwich core and two steel facets.

Properties	TPU	Steel	Unit
Density	1,235	7,829	kg/m3
Poisson's ratio	0.39	0.29	-
Young's modulus	2,491	206,940	MPa
Yield strength	21.00	137.90	MPa
Ultimate tensile strength	38.40	276.00	MPa

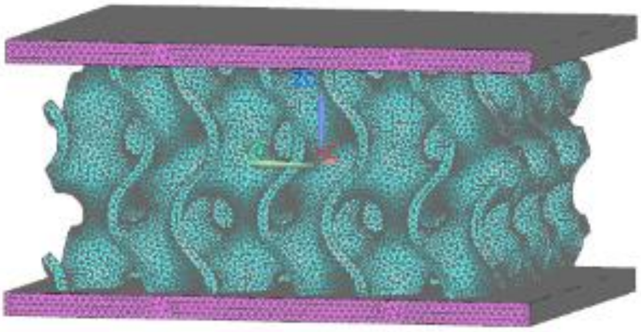
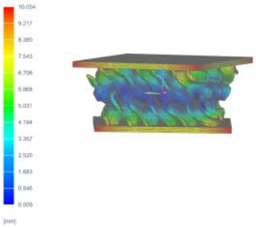
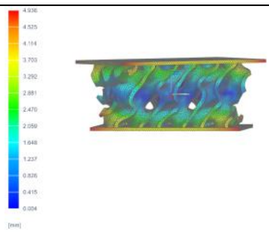
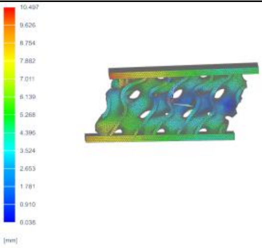
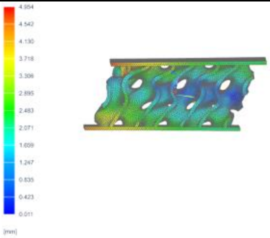
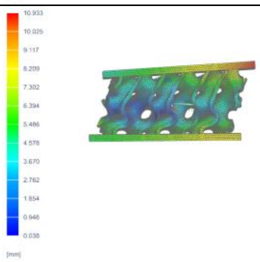
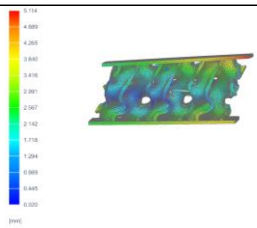
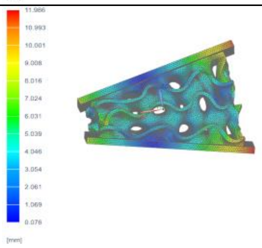
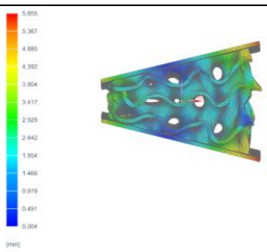


Figure 3: Finite element model of a gyroid sandwich panel for modal analysis.

3. Results and discussion

The dynamic modal parameters of a gyroid sandwich panel for bridge bearing applications are well-known as natural frequencies and mode shapes without damping. These parameters are obtained from finite element modal analysis. A comparison of dynamic modal parameters of both gyroid sandwich panels with two different unit cell sizes (10 mm and 20 mm) extracted from the numerical modal analysis is presented in Table 2. The natural frequencies and mode shapes from both analyses are compared for the first four modes. The results show that, for both panels, the first torsional deformation pattern is generated in the first mode, whilst the first and the second rollover deformation patterns are produced in the second and third mode, as well as the first uplift deformation occurred in the fourth mode. It is obvious that the difference of natural frequencies of FE models of gyroid sandwich panels with different unit cell sizes exhibits quite large discrepancies. On the other hand, the natural frequencies of the gyroid sandwich panel made of 10 mm unit cells are approximately 1.4 times the other ones of the gyroid sandwich panel with 20 mm unit cell size. This is because natural frequencies depend on geometry property and mass of a material.

Table 2: Results of modal analysis for both gyroid sandwich panels.

Mode No.	FE model with 10 mm cell size Mode shape	Frequency (Hz)	FE model with 20 mm cell size Mode shape	Frequency (Hz)	Δ%	behaviour
1		421.17		292.48	30.56	Torsion
2		603.25		407.86	32.90	Rollover
3		613.60		415.07	32.35	Rollover
4		649.63		446.71	31.24	Uplift

4. Conclusions

Modal analysis is completely conducted to examine the dynamic behaviours of two gyroid sandwich panels with different unit cell sizes for bridge bearing applications. These panels consist of a gyroid core confined between two thin steel facets which provide higher stiffness of their structure. The results show that the first natural torsion mode obviously controls the first resonant mode of vibration for both panels. Also, the gyroid sandwich panel with a bigger unit cell size can better experience vibrations than a one with a smaller one as the decreasing natural frequencies of all the modes. These insights will be useful to the performance benchmarking of bridge bearings as well as the development of the vibration-based design approach to predict their modal dynamic characteristics. Further work of model validation should be performed for practical use in reality.

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