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Auxetic nail: Design and experimental study

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ABSTRACT

Under uniaxial compression (tension), auxetic materials would shrink (expand) laterally. It has been speculated that the auxetic property could be used to design superior nails for easier push-in and harder pull-out. In this study, the first auxetic nails are designed, fabricated and experimentally investigated. Pine timber and medium-density fibreboard are selected as testing materials. The push-in and pull-out performance of auxetic and non-auxetic nails is compared by using two key parameters of the maximum compressive force and the maximum tensile force. It is found that the auxetic nails do not always exhibit superior mechanical performance to non-auxetic ones. Also, the small auxetic deformation of one typical designed auxetic nail is revealed by the experimentally validated finite element model. The experimental and numerical results illustrate the limitations of exploiting the auxetic property in the nail application. Some suggestions are provided for more effective designs of future auxetic nails.

1. Introduction

Auxetic materials exhibit uncommon deformation behaviour, e.g., under uniaxial compression (tension), rather than expanding (shrinking) in the lateral direction as conventional materials, auxetic materials would shrink (expand) [1–9]. Along with this counter-intuitive behaviour, auxetic materials are regarded to possess many desirable properties, e.g., shear resistance [10,11], indentation resistance [12–15], fracture resistance [16–19], synclastic behaviour [20,21], variable permeability [22,23] and energy absorption [24,25].

As one of the pioneers in the field of auxetic materials, Lakes [16] fabricated and reported the first re-entrant foam structure with negative Poisson's ratio in 1987. Since this early contribution, significant efforts have been made towards investigating the novel materials with negative Poisson's ratio. Friis et al. [26] reported the first metallic re-entrant foam with negative Poisson's ratio in the year after. Theoretically, for further investigating the underlying mechanism of auxetic behaviour, various auxetic cellular models were proposed and analysed. Re-entrant model, as a traditional cellular structure was firstly proposed by Gibson et al. [27] in 1982. Grima et al. [28] put forward a novel mechanism to achieve negative Poisson's ratio, which was based on an arrangement with rigid squares connected together at their vertices by hinges. Pozniak et al. [29] investigated the planar auxeticity from elliptic inclusions. Wojciechowski [30,31] first put forward the two-dimensional auxetic chiral system. Later on, Lakes [32] reported a simplified chiral hexagonal microstructure with auxetic behaviour. Similar micro-structures were also discussed by [33]. The theoretical and experimental investigations on a two-dimensional chiral honeycomb were conducted by Prall et al. [34]. A crumpled sheet model was also reported which could be adjusted to demonstrate auxetic behaviour [35]. As a typical type of perforated sheets model, conventional materials containing diamond or star shaped perforations could demonstrate auxetic behaviour both in compression and tension [36]. In addition, other models were also reported to have auxetic behaviour, e.g., nodule-fibril model [37], missing rib model [38,39], egg rack model [40], tethered-nodule model [41], hexatruss model [14] and entangled wire model [42].

The contraction behaviour of auxetic materials and structures against compressive loadings makes them potential candidates for the protective structure and defence applications [25,43–47]. Researchers have compared the dynamic behaviours between auxetic and conventional foams and demonstrated that auxetic foams present higher yield strength, lower stiffness and better energy absorption. The auxetic structures and materials have also shown enhanced static indentation resistance and stiffness improvement. In the studies [25,43,44], sandwich panels with auxetic cores have also been investigated against the impulsive loading, e.g., blast-induced shockwave and low-velocity impact. It has been evidently shown that the deformation, localised damage and structural flexure of the auxetic panels could be reduced

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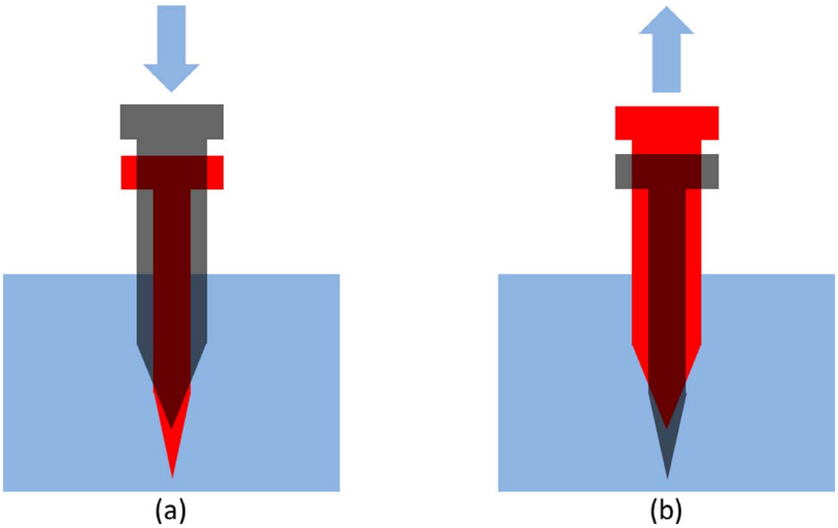

Fig. 1. Illustration of auxeticity for auxetic nails: (a) during push-in; (b) during pull-out. (The nails in grey and red colour represent the configurations of the nails before and after deformation, respectively).

noticeably.

Although a considerable progress has been made in the field of negative Poisson ratio metamaterials in the last three decades both theoretically and experimentally, most of the previous work focused on two-dimensional auxetic materials and structures. Attributed to the rapid development of 3D printing technique in the past years, manufacturing the 3D auxetic models with complicated geometrical configuration was no longer a technical constraint and resulted in several successful fabrications of 3D auxetic materials and structures [3,4,48–51]. Unfortunately, the real application of auxetic materials is still in its infancy and more pioneering works of utilising auxetic materials towards practical application are in need.

Choi et al. [52] reported that an auxetic fastener could be easier to insert and harder to pull out. Later on, Grima et al. [53] stated that auxetic nails were a potential application for auxetic materials based on the concept that auxetic nails become thinner when knocked in and become fatter when pulled out, as shown in Fig.1. Inspired by their work and based on our previous work of auxetic tubular structures [3], the first auxetic nails were designed, fabricated and experimentally investigated.

2. Design of auxetic and non-auxetic nails

Based on our previous work of auxetic tubular structures [3], four groups (A, B, C, D) of nails with three categories of nails in each group were designed. The three categories of nails included an auxetic nail (AN) with alternatingly patterned ellipse-like holes (rectangles with semicircles in two ends in their planar view), a non-auxetic nail with circular holes (CN) and another non-auxetic nail of the solid nail (SN) without holes. The geometrical configurations of the three categories of nails in different perspectives are shown in Fig.2. The nail bodies of ANs and CNs were hollow. Also, the number of holes and superficial area of the holes between ANs and CNs were kept the same.

It should be noted that the work of Bertoldi et al. [54] indicated that the two-dimensional rubber-like plates with circular holes exhibited auxetic behaviour under compression. Hence, it seems that the nails with circular holes are auxetic. However, in our design, the auxetic behaviour of CN will not occur because the buckling-induced mechanism is not valid when the base material is metal. This statement is one of the main conclusions in our previous works [3,4].

In total, twelve different nails were designed. The geometric parameters of these nails are shown in Fig.3, where H is the overall length, h is the length of the nail head, L is the length of the nail body, D_1 is the diameter of the nail head, D_2 is the outer diameter of the nail body, T is the wall thickness of the nail body, θ is the angle of the nail bottom, N is the number of the rows of holes in the longitudinal direction. It should be noted that the three categories of nails which belong to the same nail group (A, B, C, D) have all the identical parameters shown in Fig.3 except for the parameter of T based on the fact that the nail type of SN was solid, but the parameter of T for the AN and CN was still identical.

In order to make our experiments more convincing, the effects of six parameters of H, h, L, T, θ and N were investigated. Two parameters of D_1 = 8 mm and D_2 = 6 mm were fixed to satisfy the acceptable range of the clip of the Shimadzu machine, i.e., from 4 to 9 mm. The specific parameters for the four groups of nails (A, B, C, D) are listed in Table 1. For the simplicity of labelling the nails, three capital letters were used to represent one of the twelve nails with different nail group and nail type. The first two represent the nail type and the third one represents the nail group, i.e., ANA is the auxetic nail in group A, CNA is the nail with circular holes in group A, and ANC is the auxetic nail in group C. It should be noted that most of those parameters were selected due to the manufacturing capacity of the available 3D printing machine.

3. Fabrication of the designed nails

The 3D printing technique (Shapeways, New York) was employed to fabricate the designed twelve types of nails. The designed twelve types of nails were not only printed using stainless steel but also printed using brass due to the high ductility of brass was beneficial for demonstrating larger auxetic deformation, as shown in Fig. 4. The nails with gold colour were printed using brass material and the nails with silver colour were printed using stainless steel. It should be noted that the minimal link length of the designed auxetic nail was only 1.1 mm and this value approached the limit (1 mm) of the 3D printing company (Shapeways, New York) for manufacturing brass and stainless steel production.

4. Experiments

4.1. Pine timber experiments

Considering the overall stiffness of the printed nails and the available materials, timber was selected as a candidate for carrying out push-in and pull-out tests. One piece of cuboid plantation pine timber with a length of 2.7 m and cross section of 88 × 88 mm was selected, as shown in Fig. 5a. Then the four rectangular timber surfaces were marked with different numbers of straight lines from one end to the other end. After that, the long timber was cut into many pieces of small cubic timbers with the same length of 50 millimetres, as shown in Fig. 5b. It should be noted that there is glue bond appears between the second and fourth pine timber surfaces as indicated by the dashed line in Fig. 5b. In order