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Mechanical properties of three variations of a wire-woven metal subjected to shear

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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

In this study, two variations of WBC (Wire-woven Bulk Cross), named semi-WBC and straight-WBC, are introduced. In the variations, helically formed wires in an ordinary WBC are partly or totally replaced with straight wires to obtain higher shear strength and modulus, and the fabrication processes are modified to enhance productivity. Analytic solutions of the relative density, shear strength and modulus for the three variations of WBCs including the ordinary WBC with X-orientation are derived. And CAD modeling, shear tests and FEA were performed to prove the analytic solutions. The effects of the curviness of the struts loaded or floating between face sheets, and the offset at the joints are evaluated. The semi- and straight WBCs had equivalent shear strengths and moduli comparable to those of typical aluminum honeycombs, and all the three variations of WBCs maintained their strengths at low densities down to 1%.

1. Introduction

Recently, periodic cellular metals (PCM) have drawn attention because of their high strength and stiffness for a given weight. The truss PCM is a clear example. The high strength of truss PCMs is derived from the regular structure composed of straight struts which leads their strength 'stretching-dominated' rather than 'bending-dominate' as stochastic foams are (Deshpande et al., 2001). Furthermore, due to their open architecture, truss PCMs can be used for multi-functions such as heat transfer (Tian et al., 2004; Wadley, 2006), catalyst support (Choi et al., 2009), and even actuation (Lucato et al., 2004) as well as load-bearing. Truss PCMs can be fabricated by investment casting (Chiras et al., 2002), crimpling of perforated sheets (Sypeck and Wadley, 2002; Wadley, 2006) or crimpling of expanded metal (Wadley et al., 2003; Zok et al., 2004; Lim et al., 2009). For engineering applications such as sandwich cores, multi-layered truss PCMs with fine cells are preferred because of their enhanced material homogeneity, resistance against face sheet buckling, and vibration suppression capability. However, most fabrication techniques are not suitable for multi-layered truss PCMs with fine cells. Therefore, they are fabricated by merely stacking up multiple single-layered PCMs.

Wire-woven metals are a kind of PCMs with truss-like structures composed of wires. In fact, wires have several merits as raw materials in the fabrication of PCMs. Namely, wires provide high strength without defects, can be produced at low cost, and can be handled easily during the fabrication process. Textile core (Sypeck and Wadley, 2001), WBK (Wire-woven Bulk Kagome) (Lee et al., 2007), Strucwire (Kieselstein et al., 2009), WBD (Wire-woven Bulk Diamond) (Lee et al., 2012), and WBC (Wire-woven Bulk Cross) (Lee et al., 2013a) are the representative wire-woven metals that have been introduced over the past decade. Except for the textile core, all the wire-woven metals are inherently multi-layered and assembled with helically formed wires. Consequently, the struts are curved so as to assemble into truss-like structures. Fig. 1(a)–(d) shows the configurations of WBK, Strucwire, WBD, and WBC, respectively. In the figures, one of the helical wires composing each structure is highlighted with red-color to show curviness of the wires, which result in the curved struts in the truss-like structures of the wire-woven metals. Studies of the mechanical properties of the wire-woven metals have revealed that the curved struts of the structures substantially degrade the strength and stiffness of the wire-woven metals (Lee et al., 2013a,b). This means that the strengths of the wire-woven metals with the more curved struts are more likely to be "bending-dominate" than "stretching-dominate" as a typical truss PCM is to be. The curviness of the struts in each wire-woven metal is determined from the helical radius of the wires used to fabricate it. The minimum helical radii, R_h, of the wires are ranked in order of WBC, WBK, WBD, and Strucwire as follows;

$$R_h = 0.5d < 0.577d < 0.707d < c, \quad \text{respectively}. \tag{1}$$

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Here, d and c are the diameter of wires and a half of the pitch, respectively. Hence, WBC is expected to have the least strength degradation due to the smallest helical radius.

On the other hand, the textile core is fabricated by simply stacking multiple plain-woven meshes. The textile core, which is not inherently multi-layered, is easy to fabricate with traditional textile technology, not requiring the development of a new weaving process. The structure is composed of struts curved in a 2D wavy pattern, and the eccentricity due to the curved struts is $0.5d$, which is as small as that of WBC. According to Queheillalt et al. (2007), the curved struts result in about 20% reduction in the stiffness and strength of the textile cores compared to the corresponding collinear cores composed of straight struts. Fig. 2(a) and (b) depict the textile core and collinear core. Textile cores have additional disadvantages. First of all, they have severe material anisotropy; that is, a textile core is loose on the woven plane, but dense in the stacking direction. Consequently, a textile core with a low density has to have thin and long struts, which makes it vulnerable against elastic buckling of struts. Hence, a practical lower limit of relative density is around $\rho_{rel} = 0.07$, which is higher than that of aluminum honeycombs most commonly used for light sandwich panels in typical aerospace applications, i.e., $\rho_{rel} = 0.01–0.05$ (Bitzer, 1997).

In fact, WBC is the result of our efforts to improve the textile core in two respects. First, one pitch of wires in WBC is intersected four times by other wires; twice in one vertical direction and twice in the other vertical direction, while the wires in the textile core are intersected only twice per pitch. Consequently, WBC has higher resistance against the elastic buckling of struts than in textile cores. Second, WBC has the same structure in three orthogonal directions. Hence, its structure is loose in all three orthogonal directions, so its material anisotropy is relatively low. The details of the geometry are given in the authors' preliminary study (Lee et al., 2013a), which revealed that its strength under compression is maintained down to the relative density of $\rho_{rel} = 0.01$, owing to these two features. This means that WBC can be a good replacement of metallic honeycombs. The open cell structure of WBC can provide additional function as well as load-bearing. Note that the mechanical properties that are important for core materials of sandwich panels subjected to bending loads are shear strength and stiffness rather than compressive strength and stiffness.

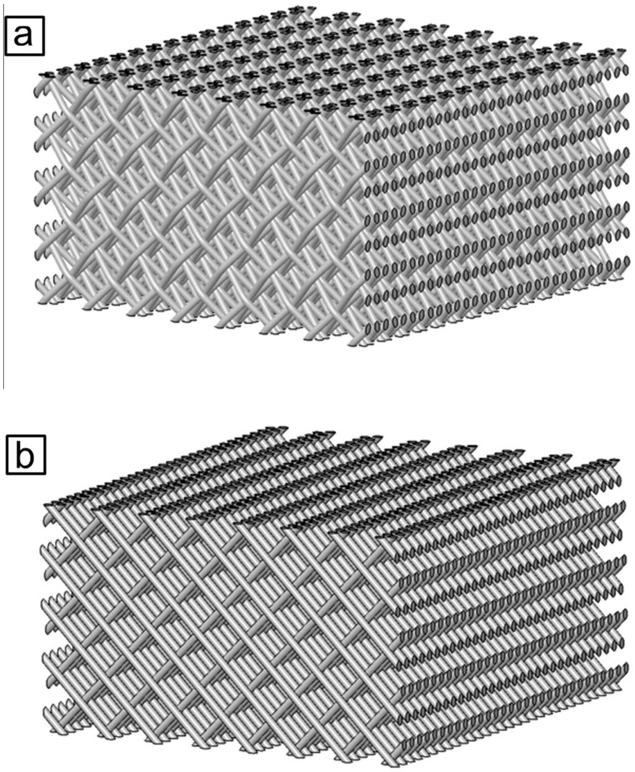

Fig. 2. Configurations of the textile core and a collinear core (Queheillalt et al., 2007).

The previous study (Lee and Kang, 2014) investigated the strength and modulus of WBC in two different orientations under shear load according to the slenderness ratio of the struts composing the structure. In WBC of X-orientation (the wires in two of the three orthogonal directions were at 45° with the top and bottom face sheets, and the wires in the other one direction were parallel to the face sheets), the resistance of the struts against axial elastic buckling was relatively high. Consequently, the lower limit of the relative density at which WBC resists shear loading could be as

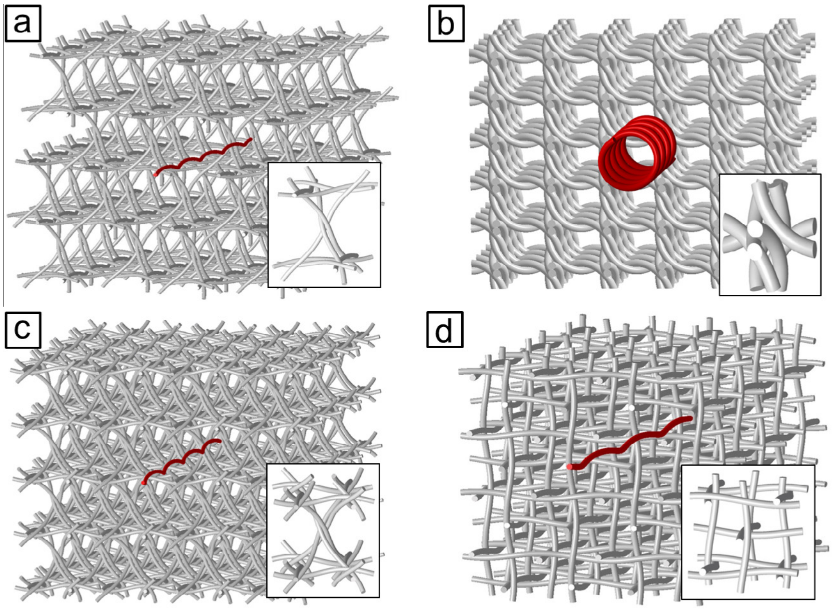

Fig. 1. Configurations of WBK, Strucwire, WBD, and WBC, in each of which one of the helical wires is highlighted with red-color to show the curviness of the wires. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)