MECHANICAL BEHAVIORS OF A NEW WIRE-WOVEN CELLULAR METAL

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Keywords: *Cellular metal, WBK(Wire-woven Bulk Kagome), WBD(Wire-woven Bulk Diamond), WBC(Wire-woven Bulk Cross)*

1 Introduction

A few years ago, a cellular metal named wire-woven bulk Kagome (WBK) was introduced. WBK is composed of helically formed wires and has multiple layers of Kagome-truss-like cells. It has been reported that the mechanical strengths under compression, shear, and bending are as high as those estimated theoretically for a corresponding ideal Kagome truss [1-4]. Recently, another metal named wire-woven bulk diamond (WBD) was introduced [5]. In WBK three wires pass by one another at each cross point, whereas in WBD four wires do. For a given slenderness ratio, WBD has the relative density, strength, stiffness about twice as high as those of WBK. Therefore, it is expected that WBD is more suitable to heavy duty applications compared to WBK. In this study, The third cellular metal named wire-woven bulk cross (WBC) is introduced. The basic analytic solutions for geometrical properties, relative density, strength and stiffness are presented and verified by experiments and finite element analysis (FEA).

2 Geometry and Basic Properties

2.1 Geometrical characteristic

Fig. 1 shows configurations for unit cells of WBD, WBK, and WBC. The minimum helical radius of WBC is substantially smaller than the other two, because two wires cross at each cross point in WBC, as shown in Fig. 2. Ignoring the effect of waviness of struts composing the structures, the relative density of WBK, WBD, and WBC are expressed as a function of the slenderness ratio, *d/c* as follows:

$$\rho_{rel} = C_1\left(\frac{d}{c}\right)^2 \qquad (1)$$

respectively.

2.2 Analytic solution of compression strength and stiffness

Equations for the compressive strength and stiffness of WBK, WBD, and WBC are derived for the unit cells shown in Fig. 3 under the assumption that they are composed of straight struts.

$$\sigma_y^c\Big|_{elastic\,buckling} = C_2 kE\left(\frac{d}{c}\right)^4, \qquad \sigma_y^c\Big|_{plastic\ yielding} = C_3\sigma_0\left(\frac{d}{c}\right)^2, \qquad (2)$$

$$\overline{E}_c = C_4 E\left(\frac{d}{c}\right)^2 \qquad (3)$$

The constants in Eqs.(1) to (3) are listed in Table. 1, where the strengths are given for elastic buckling and plastic yielding.

3 Experiments

3.1 Specimen preparation

The material for the core wires and face sheets is stainless steel SUS 304. The diameter of the wires is d=0.78, 0.98 and 1.18 mm, respectively. The pitch, which is twice the strut length, c, is $2c$=16.2mm and the helical radius is r_h=0.39mm. Fig. 4 shows the assembling process of WBC. The filler metal used to fix the assembly is BNI-2, which was applied by spraying aqueous mixture of paste (Nicobraz LM BNI-2, Wall Colmonoy Corp., USA) and The vacuum brazing was carried out for 225min in the brazing furnace at 10^{-4}~10^{-5} torr. During first 90min, the furnace was heated from room temperature to 930℃ and maintained at the same temperature for

15min. then, the temperature was increased to 1040℃ for 15min and maintained for 15min. Finally, the furnace was cooled down to room temperature for 90min. Two face sheets were attached to the top and bottom surfaces of a WBC core for the compression test. SUS 304 plate 3mm thick for face sheets, which was the same material for the core, was selected. The epoxy(AXIA EP-04 of Magnolia Plastic INC.) was used as an adhesive to attach the face sheets and cores

3.2 Compression test

The universal test machine Instron-Satec TC-55 was used for the uniaxial compressing test. As shown in Fig. 5, all the specimens were compressed between two steel circular compression platens, whose diameter, D=200mm, was sufficiently larger than the specimen sizes. The displacement rate of 0.005mm/s was applied on the bottom surface of each specimen as an external loading. The displacement was recorded by a data acquisition (DAQ) system. All specimens were loaded up to 40% of the strain to obtain their compressive behavior. For measuring the effective elastic modulus of each specimen, the unloading process was carried out before the measured strength reached to the peak strength, and the linear interval in the stress-strain curve obtained under the unloading process was used. The specimen displacement was measured a clip gauge installed between the two steel circular compression platens

4 Numerical Analysis

4.1 Finite element model

To explore the behavior of WBC core under compression, FE analyses were performed using the commercial code, ABAQUS version. The models were made with a CAD code, PATRAN 2008. 15-node quadratic triangular prism elements and 8-node quadratic brick elements were used for the WBC cores and the face sheets, respectively. We used a about total of 315,900 cores and 1600 face sheets elements, which were determined after the mesh dependency check of the computed results. As shown in Fig. 6 for FEA model, Brazed filler metals and the helically formed wires were separately and precisely modeled and combined to represent the core. The material properties of the brazed filler metal were assumed to be the same as those of the wires. The yield strength is σ_y=193MPa, the elastic modulus is E=200MPa, and Poisson's ratio is ν=0.3.

5. Results and discussion

5.1 Relative density and its limit

Fig. 7 shows variations of the relative densities of WBK, WBD and WBC with respect to the slenderness ratio of the struts composing the three structures. The relative density of WBC increases more rapidly, as the slenderness ratio increases. The horizontal lines show the upper limits of geometrically permissible region which are governed by interference among the wires composing each structure. The limits of relative density for WBK, WBD and WBC are 6.3%, 12.8% and 42.5%, respectively.

5.2 Compressive behavior of WBC

The stress-strain curves obtained by compression test for each specimen are shown in Fig. 8. From the curves, the effective elastic modulus and effective strength determined and they were compared with the results from Eqs. (2),(3) and FEA. From the compression test, the yield strengths for d/c=0.096, 0.121 and 0.146 are 2.92MPa, 3.6MPa and 5.2MPa, respectively. For slenderness ratios d/c=0.096 and 0.121, the results are all similar to from theory, test and FEA. But for d/c=0.141, that from test are less than theory and FEA.

5.3 Comparison with and WBD, WBK and WBC

From the stress-strain curves for three slenderness ratios at Fig. 8, The compressive behavior of WBC show different trends with WBK and WBD. The curves decrease slowly after the pick points in case WBC and appear like uneven shapes in case WBK and WBD. As shown in Fig. 9, theoretical specific strengths (Max strength per unit weight) $\sigma^c_{Max} / \sigma_0 \rho_{rel}$ are all constant values of about 0.33, but the measured specific strengths of WBD and WBK from experiments increase linearly and them of WBC almost constant as increase of slenderness ratio. As shown in Fig. 10, The specific stiffnesses $E_c / E_0 \rho_{rel}$ of theory and experiment are very different in WBC.

5.4 Discussion

For all the cases, it was found that slenderness ratio affected compressive strength a lot. As shown in Fig. 2. The minimum helical radius for WBD, WBK and WBC is $\sqrt{2}/2d$, $\sqrt{3}/3d$ and $0.5d$, respectively. Thus, the helical radius of WBC is the least among them. Because the eccentricity effects get decreased by the small helical radius, compressive strength of WBC is higher than WBD. Because the waviness effects of wire have no consideration, theoretical results differ them experiment. Fig. 11 show the deformed shape of specimen for slenderness ratio *d/c*=0.146 at the peak strength. It clearly shows de-bond between the wire and filler metal in the circled regions. That is, the maximum strength is governed by the break at the brazed joints when slenderness ratio is *d/c*=0.146. the reason stems from the low interference among wires at each cross point. The low interference induces the higher stress concentrated at the brazed joints.

6. Conclusion

The WBC truss core, which is a new type of Wire-woven cellular metal, was introduced. Mechanical behaviors of WBC specimens were tested under compression. The conclusions are as follows:

(1) The relative densities of WBK, WBD and WBC are limited upto 6.3%, 12.8%, 42.5%, respectively.
(2) As slenderness ratio increases, generally the normalized strength of WBK and WBD increase linearly but that of WBC suddenly decreases at the slenderness ratio (d/c= 0.146).
(3) The normalized stiffness of WBC is smaller than WBK, bigger than WBD, and The result Showed the difference between experiment and theory. Because theoretical solution is not considered the waviness effect of wire.
(4) A good agreement between FEA and experimental results proves the validity of theory.

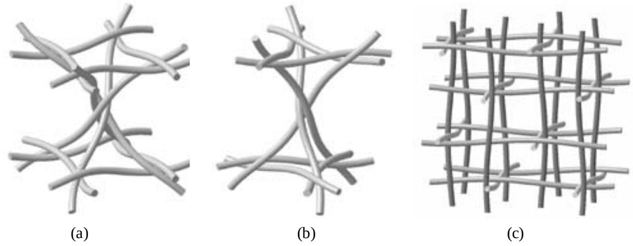

Fig. 1 Unit cell of (a) WBD (b) WBK (c) WBC

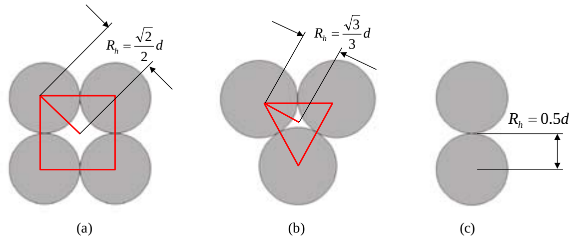

Fig. 2 Helical radius of unit cell : (a) WBD (b) WBK (c) WBC.

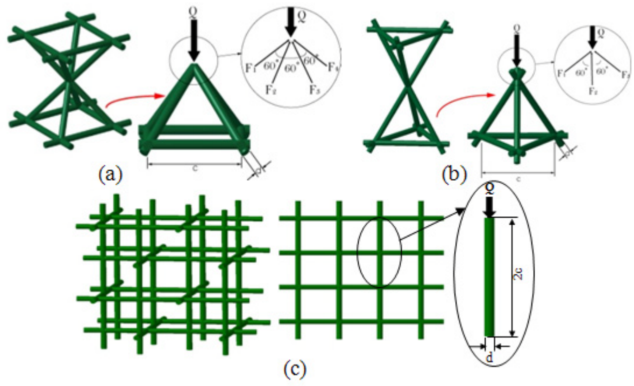

Fig. 3 Idealized unit cells of WBK, WBD, and WBC used to derive analytic solutions of their strengths and stiffness under compression.

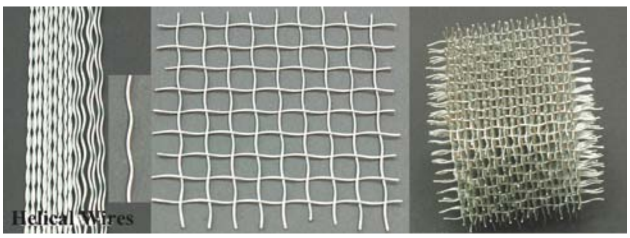

Fig. 4 Helical wires and assembled multi-layered WBC core.

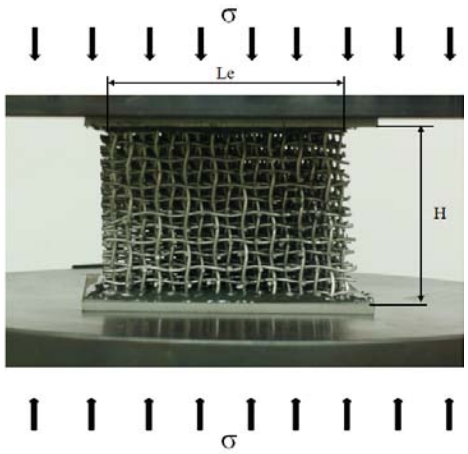

Fig. 5 Compression specimen of sandwich plate with Wire-woven Bulk Cross(WBC) truss core.

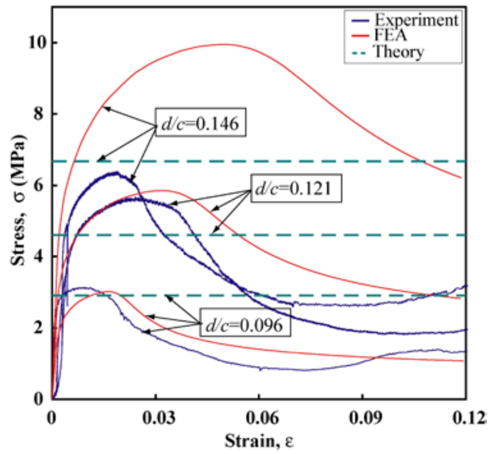

Fig. 8 The stress-strain curves measured by compression.

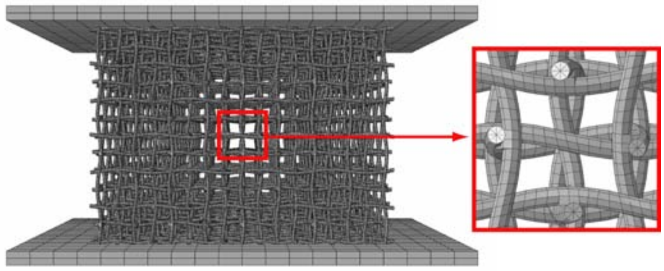

Fig. 6 FEA model for Brazed filler metals and the helically formed wires.

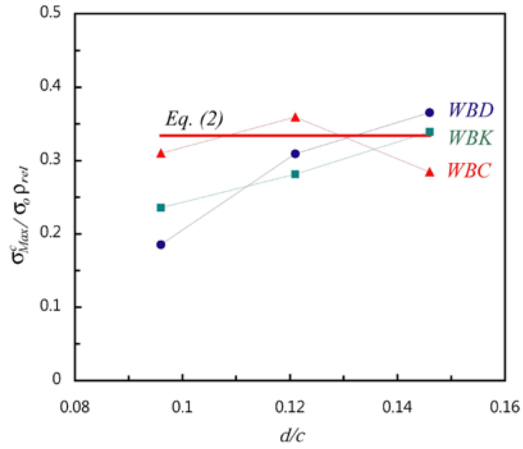

Fig. 9 Normalized Max strength versus slenderness ratios.

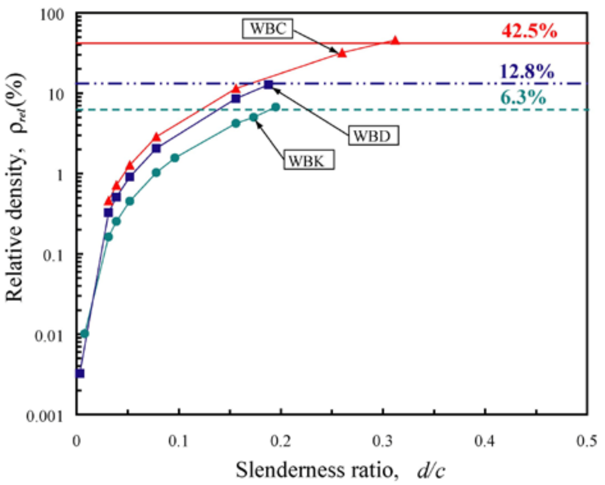

Fig. 7 Relative density variation with slenderness ratio of struts composing WBK, WBD and WBC

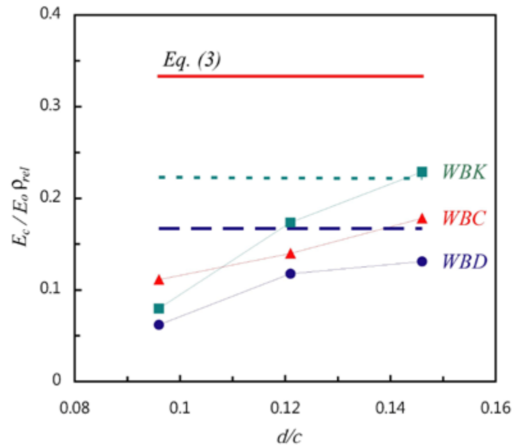

Fig. 10 Normalized stiffness versus slenderness ratios.

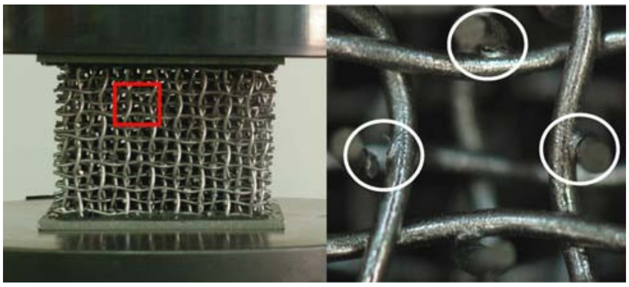

Fig. 11 The failure occurred in the brazed parts at each cross wires.

Table. 1 Constants in Eqs. (1)-(3) for the relative density, compressive strengths and stiffness, respectively, of WBK, WBD and WBC cores.

	WBK	WBD	WBC
C_1	$\frac{3\sqrt{2}}{8}\pi$	$\frac{3\sqrt{2}}{4}\pi$	$\frac{3}{2}\pi$
C_2	$\frac{\sqrt{2}}{128}\pi^3$	$\frac{\sqrt{2}}{64}\pi^3$	$\frac{1}{32}\pi^3$
C_3	$\frac{\sqrt{2}}{8}\pi$	$\frac{\sqrt{2}}{4}\pi$	$\frac{1}{2}\pi$
C_4	$\frac{\sqrt{2}}{12}\pi$	$\frac{\sqrt{2}}{8}\pi$	$\frac{1}{2}\pi$

Table. 2 Strength, Young's modulus, and relative density of WBD, WBK and WBC for three levels of slenderness ratios.

	Slenderness ratio (d/c)	Yield Strength σ^c_{ys} (MPa)		Max Strength σ^c_{Max} (MPa)	Young's Modulus E_c (MPa)		Relative Density ρ_{rel} (%)	
		Theory	Experiment	Experiment	Theory	Experiment	Theory	Experiment
WBC	0.096	2.91	2.92	3.13	2913	1123	4.37	5.05
	0.121	4.6	3.61	5.64	4599	2194	6.9	7.85
	0.146	6.67	5.2	6.39	6667	4001	10.0	11.23
WBD	0.096	2.048	-	1.72*	1032	574	3.08	4.64
	0.121	3.252	-	3.89*	1626	1480	4.88	6.29
	0.146	4.715	-	5.92*	2258	2123	7.08	8.10
WBK	0.096	1.03	-	0.834*	687	282	1.54	1.77
	0.121	1.63	-	1.559*	1084	962	2.44	2.77
	0.146	2.36	-	2.639*	1571	1781	3.54	3.89

* Peak strength in $\varepsilon \leq 0.1$

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