Compressive mechanical behavior and model of composite elastic-porous metal materials

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Abstract

This work presents the experimental characterization and theoretical modeling of composite elastic-porous metal materials (C-EPMM). C-EPMM is a novel porous metallic damping material made of wire mesh and wire helix. A series of quasi-static compressive experiments were carried out to investigate the stiffness and energy absorption ability of the C-EPMM with different mass ratios. The experimental results show that the mass ratios can significantly affect the stiffness and loss factor of C-EPMM. To efficiently predict the nonlinear mechanical properties of the C-EPMM a theoretical model of C-EPMM was proposed for the first time, the model was based on the manufacturing process. A comparison between the predicted data and the experimental data was conducted. The results show that the theoretical model can accurately predict the mechanical performance of C-EPMM. The conclusions derived from this work can provide a new method for adjusting the mechanical performance of EPMM in applications.

1. Introduction

Elastic-porous metal material (EPMM) is made by tangling or weaving various metal wires and compressing them in a target mold. EPMM has a broad application prospect in passive vibration control because its stiffness and damping characteristics do not degrade in extreme environments. EPMM has been used in high-temperature pipelines [1], railways [2], spacecraft [14–18], and turbo-machinery [6, 7]. When the EPMM is deformed by external excitation, the internal wire slips relatively at the contact point and dissipates vibration energy in the form of friction.

Common porous structures are: a ceramic-metal functionally graded sandwich plate [8]; FG microplates embedded by polymeric nanocomposite patches [9]; the imperfect sandwich higher-order disk with a lactic core [10]; viscoelastic multi-phase reinforced fully symmetric systems [11]; nonlocal porous nanobeams made of functionally graded material [12] reinforced porous sandwich plate using energy principle(FG-CNT) [13]; functionally graded porous plates [14–18] functionally graded beams [19].

EPMM is sometimes referred to as ‘metal rubber’ [20–22], ‘entangled metallic wire material’ [23], ‘metal mesh’ [24], ‘wire mesh’ [25], ‘metal cushion’ [26]. The mechanical properties of EPMM are affected by the type of metal wire used and microstructure, which is mainly determined by the preparation processes [27]. Previous researches have classified this kind of material as the same material. However, their preparation processes are different. There are two different preparation processes (tangling and weaving) to prepare the rough porous base material of EPMM. Therefore, EPMM can be subdivided into T-EPMM (tangled elastic-porous metal materials) and W-EPMM (waved elastic-porous metal materials).

There have been many studies on the capacity absorption theory and model of composite materials and metal structures. Hoo Fatt et al reported the analytical solution of the transient deformation response of the sandwich panels, and given the initial analysis and prediction of the impact damage [28]. A Riccio et al studied the mechanical behavior of composite fuselage barrel vertical drop test through numerical analysis [29].

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acanfora et al investigated the feasibility and effectiveness of novel thin additive manufactured hybrid metal/composite lattice structures by the new thin additive are studied, and the results showed that the structure maximizes the energy absorbed through plastic deformation and coating [30]. Francesco Di Caprio et al reported the impact aircraft metallic sandwich leading-edge subjected to a bird strike, and use the model to analyze its energy consumption characteristics [31]. D H Laananen et al established a performance analysis of the energy-absorbing seat configurations for aircraft [32]. Kwang Bok Shin et al performed a low-velocity impact test on the panel to verify its impact resistance [33].

The energy dissipation mechanism [34], mechanical model [35–37], mechanical properties, and influence parameters [38, 39] of EPMM have been widely studied. The analysis of the preparation process of T-EPMM and W-EPMM shows that there are significant differences in their internal spatial network structure. Thus, T-EPMM and W-EPMM are not directly equivalent, and their mechanical properties may be different. The previous studies only focus on the analysis of T-EPMM or W-EPMM, and the performance difference between them has not been studied.

The first aim of this paper is to compare the mechanical properties of T-EPMM and W-EPMM. The second aim is to develop an improved process to prepare new composite elastic-porous materials (C-EPMM) and investigate their mechanical properties. The third is to establish and verify a mechanical model of the new composite elastic-porous metal materials (C-EPMM).

The rest of this paper is organized as follows: the comparison of compressive mechanical behaviors between T-EPMM and W-EPMM is investigated in section 2. In section 3, a new manufacturing method for C-EPMM is proposed, the effect of maximum external load, density, and the proportion of wire mesh in C-EPMM on the mechanical properties is investigated, a nonlinear mechanical model is developed to predict the mechanical properties of C-EPMM, and experimental validation of the developed nonlinear numerical model is described. Conclusions obtained from this work are presented in section 4.

2. Elastic-porous metal material specimens

In this work, to investigate the influence of the fabrication process on the compressive mechanical behaviors of EPMM, three kinds of EPMM specimens were made by the same grade 304 stainless steel wires (06Cr19Ni10) with a nominal wire diameter of 0.15 mm. Figure 1 presents the manufacturing processes of three kinds of EPMM.

The fabrication process of the T-EPMM is as follows: ① the straight metal wire is processed into a dense wire helix; ② a rough porous base material of EPMM is prepared by fixed-pitch stretching and cross-weaving of the tight wire helix; ③ the base material is molded in a specific mold [40].

The fabrication process of the W-EPMM is as follows: ① the straight metal wire is processed into a wire mesh by a knitting machine; ② a rough porous base material of EPMM is prepared by wrapping the wire mesh on a mandrel; ③ the rough porous base material is molded in a specific mold [41].
The manufacturing process of C-EPMM can be divided into the following five steps: first, the straight metal wire of a certain weight is weighed and processed into a wire mesh by a knitting machine; second, the straight metal wire of a certain weight is weighed and processed into a dense wire helix; third, a semi-rough base material of C-EPMM is prepared by wrapping the wire mesh on a mandrel; fourth, a rough base material of C-EPMM is prepared by fixed-pitch stretching and cross weaving of the tight wire helix on the outside of the semi-rough base material of C-EPMM; fifth, the base material is molded in a specific mold.

Figure 2 shows two of the fabricated T-EPMM and W-EPMM samples. The fabricated specimens have the same density. The outer diameter, inner diameter, height, and preset mass of the EPMM specimen is 24 mm, 10 mm, 15 mm, and 11.21/14.01 g, respectively.

For investigating the influence of the manufacturing process and density on the mechanical properties of EPMM, a series of C-EPMM with different mass ratios and densities was manufactured. The mass ratio (C) can be defined as

\[ C = \frac{M_w}{M} \]  

where \( M_w \) is the mass of the wire mesh, \( M \) is the mass of the C-EPMM. When \( C = 0 \), the C-EPMM is T-EPMM; when \( C = 1 \), the C-EPMM is W-EPMM.

Figure 3 shows one of the C-EPMM specimens considered in this work. Table 1 lists the parameters of all specimens.

3. Experimental methods

3.1. Quasi-static test methodology
In this research, the compressive mechanical properties of each EPMM specimen were tested by computerized electronic universal testing equipment (WDW-T200, Jinan Tianchen Testing Machine Manufacturing Co., Ltd, China) [42].
The WDW-T200 was used in displacement control mode with a constant speed (0.5 mm/min). To analyze the effect of the preparation process on the mechanical properties of specimens, the maximum loads set are 200 N, 400 N, and 600 N, respectively. To minimize the test uncertainty, a 5 N pre-compression load is applied to each specimen to decrease the influence of uneven contact between the specimen and WDW-T200 and make sure that every specimen has the same prestress. At the same time, the cyclic displacement range is reset and the results of the fifth test are analyzed to reduce the influence of contact local relaxation. The mechanical quasi-static test system of the EPMM in the forming direction is shown in figure 4.

### 3.2. Characterization of mechanical properties of EPMM

In this work, the loss factor and secant stiffness were used to characterize the damping and load-bearing properties of EPMM respectively.

| Specimens | a/mm | b/mm | h/mm | Mass of wire mesh / mass of wire helixes (g) | C | \(\rho/\text{g} \cdot \text{cm}^{-3}\) |
|-----------|------|------|------|---------------------------------|---|-----------------|
| T-EPMM-1  | 9.97 | 24.07| 15.04| 0/11.20                         | 0 | 2.0             |
| T-EPMM-2  | 10.11| 24.12| 15.10| 0/14.11                         | 0 | 2.5             |
| C-EPMM1-1 | 9.89 | 24.10| 14.95| 2.18/9.00                       | 0.2|2.0             |
| C-EPMM1-2 | 9.93 | 24.06| 14.92| 2.82/11.16                      | 0.2|2.5             |
| C-EPMM2-1 | 10.08| 24.11| 15.06| 4.55/6.66                       | 0.4|2.0             |
| C-EPMM2-2 | 10.15| 24.24| 15.16| 5.56/8.44                       | 0.4|2.5             |
| C-EPMM3-1 | 9.95 | 24.08| 14.99| 6.68/4.59                       | 0.6|2.0             |
| C-EPMM3-2 | 10.21| 24.14| 14.89| 8.55/5.60                       | 0.6|2.5             |
| C-EPMM4-1 | 10.02| 24.15| 15.03| 9.03/2.20                       | 0.8|2.0             |
| C-EPMM4-2 | 9.96 | 24.13| 14.86| 11.07/2.86                      | 0.8|2.5             |
| W-EPMM-1  | 10.03| 24.19| 15.12| 11.34/0                         | 1.0|2.0             |
| W-EPMM-2  | 10.08| 24.17| 14.88| 13.89/0                         | 1.0|2.5             |

Figure 4. Photograph of the quasi-static compression test system.

Figure 5. Sketch of the hysteresis loop for EPMM.
Figure 5 presents the sketch of the force-displacement hysteresis loop of EPMM. The loading curve and the unloading curve do not coincide. This phenomenon is caused by the dry friction between the adjacent metal wires at the contact point. The dashed curve represents the nonlinear elastic force of the EPMM. The difference between the loading curve and the dashed curve is the damping force of the EPMM during the loading process, and the difference between the unloading curve and the dashed curve is the damping force of the EPMM during the unloading process. The energy dissipated by EPMM in each loading-unloading cycle is the area surrounded by loading and unloading curves ($\Delta W$). The maximum deformation energy stored in one test cycle ($U$) can be calculated as equation (1). Then, the loss factor of EPMM can be defined as equation (2).

$$U = W - \frac{\Delta W}{2}$$  

$$\eta_s = \frac{\Delta W}{\pi U}$$

The actual stiffness of the EPMM is the tangent slope of each point on the curve [44]. To facilitate the analysis of the influence of the fabrication process on the stiffness of the EPMM, secant stiffness is used to indicate the load-bearing property of EPMM. The secant stiffness ($K$) is the ratio of the maximum force ($F_{\text{max}}$) and the maximum deformation ($x_{\text{max}}$).

$$K = \frac{F_{\text{max}}}{x_{\text{max}}}$$
4. Results and discussion

4.1. Comparison of compressive mechanical behaviors between T-EPMM and W-EPMM

Figure 6 presents the experimental results of the quasi-static test for T-WPMM and W-EPMM. According to formula (3) and (4), the stiffness \( K \) and loss factor \( \eta \) of T-EPMM and W-EPMM can derive from the results (see table 2). The T-EPMM can bear a higher load than W-EPMM, in the case of the same deformation. At the same time, T-EPMM also has better damping and energy dissipation characteristics.

To analyze the reasons for the differences in mechanical properties of the two EPMM, they were magnified in mesoscale by Quanta 250 (see figure 7). Figure 7 reveals that the contact forms of the adjacent wires inside the T-EPMM are point contact or line contact, while the internal W-EPMM is only in the form of point contact. For ease of observation, figure 8 and figure 9 show the three contact states in the case of line contact and point contact respectively. It can be seen from figure 5 that there are three types of interaction (non-contact, slip, and stick) between the adjacent wires in the EPMM during compression [44, 45]. When the EPMM is deformed by an external force, the interaction (non-contact, slip, and stick) between the adjacent wires will change (non-contact becomes slip or stick; slip becomes stick). The adjacent wires slip relatively at the contact area (point or line) dissipates the vibration energy in the form of dry friction. Line contact means that the adjacent wires have a larger contact area for energy dissipation. Therefore, the loss factor of T-EPMM is larger than that of W-EPMM. For these wires in the line contact stage, for wire wires in line contact, they can be regarded as multi-strand springs in parallel. While the wires of W-EPMM can be regarded as slender curved rods between two contact points. The shape of the internal wire causes T-EPMM to have a higher load-bearing capacity.

| Table 2. Mechanical properties derived from tests of T-EPMM and W-EPMM. |
|---------------------------------------------------------------|
|                   | T-EPMM | W-EPMM |
| Secant stiffness (N/mm) | 196.39 | 171.76 |
| Loss factor         | 0.1701 | 0.1278 |

Figure 8. Three types of contact states between the wires in the case of line contact.

Figure 9. Three types of contact states between the wires in the case of point contact.
4.2 Mechanical properties of C-EPMM

A series of quasi-static tests of the EPMM samples, which are listed in table 1. To facilitate the analysis, the loss factor and stiffness of the EPMM can be derived from the test results according to equations (3) and (4) and are listed in table 3.

4.2.1 Effect of maximum load

A series of quasi-static compression tests of the C-EPMM specimens with density 2 g cm\(^{-3}\) and different mass ratios were carried out with different maximum load forces (200 N, 400 N, and 600 N). Figure 10 presents the test results of the C-EPMM with a mass ratio of 0.8, specimen number is C-EPMM4-1. The influence of the maximum load force is similar in the specimen, thus take a specimen as an example. The stiffness and loss factor of C-EPMM with different mass ratios varying with the load is drawn (see figure 11).

### Table 3. Mechanical properties of the EPMM specimens.

| Specimens   | C  | \(\rho\) / (g·cm\(^{-3}\)) | Maximum load / N | Average stiffness and standard deviation / (N/mm) | Average loss factor and standard deviation |
|-------------|----|-----------------------------|-------------------|-----------------------------------------------|------------------------------------------|
| T-EPMM-1    | 0  | 2.0                         | 200               | 104.76/ 3.67                                  | 0.19689/0.033                           |
| T-EPMM-1    | 0  | 2.0                         | 400               | 152.66/ 2.15                                  | 0.18012/0.041                           |
| T-EPMM-1    | 0  | 2.0                         | 600               | 196.39/ 4.24                                  | 0.17012/0.035                           |
| T-EPMM-2    | 0  | 2.5                         | 600               | 243.96/ 2.02                                  | 0.16874/0.027                           |
| C-EPMM1-1   | 0.2| 2.0                         | 200               | 101.51/ 3.65                                  | 0.19463/0.023                           |
| C-EPMM1-1   | 0.2| 2.0                         | 400               | 149.53/ 2.87                                  | 0.17510/0.041                           |
| C-EPMM1-1   | 0.2| 2.0                         | 600               | 192.93/ 3.61                                  | 0.16763/0.025                           |
| C-EPMM1-2   | 0.2| 2.5                         | 600               | 236.25/ 2.56                                  | 0.16572/0.037                           |
| C-EPMM2-1   | 0.4| 2.0                         | 200               | 98.34/ 4.11                                   | 0.18418/0.039                           |
| C-EPMM2-1   | 0.4| 2.0                         | 400               | 147.72/ 1.33                                  | 0.17064/0.024                           |
| C-EPMM2-1   | 0.4| 2.0                         | 600               | 186.27/ 2.58                                  | 0.16301/0.019                           |
| C-EPMM2-2   | 0.4| 2.5                         | 600               | 228.14/ 5.05                                  | 0.15073/0.040                           |
| C-EPMM3-1   | 0.6| 2.0                         | 200               | 95.56/ 2.31                                   | 0.17496/0.035                           |
| C-EPMM3-1   | 0.6| 2.0                         | 400               | 143.78/ 1.89                                  | 0.16484/0.042                           |
| C-EPMM3-1   | 0.6| 2.0                         | 600               | 181.46/ 2.25                                  | 0.15020/0.027                           |
| C-EPMM3-2   | 0.6| 2.5                         | 600               | 220.32/ 3.12                                  | 0.13463/0.019                           |
| C-EPMM4-1   | 0.8| 2.0                         | 200               | 93.57/ 4.78                                   | 0.16338/0.044                           |
| C-EPMM4-1   | 0.8| 2.0                         | 400               | 140.01/ 5.74                                  | 0.15083/0.038                           |
| C-EPMM4-1   | 0.8| 2.0                         | 600               | 179.30/ 3.36                                  | 0.13792/0.027                           |
| C-EPMM4-2   | 0.8| 2.5                         | 600               | 216.03/ 5.80                                  | 0.13120/0.034                           |
| W-EPMM-1    | 1.0| 2.0                         | 200               | 87.42/ 4.08                                   | 0.14267/0.058                           |
| W-EPMM-1    | 1.0| 2.0                         | 400               | 136.81/ 5.49                                  | 0.13468/0.047                           |
| W-EPMM-1    | 1.0| 2.0                         | 600               | 171.76/ 4.55                                  | 0.12784/0.039                           |
| W-EPMM-2    | 1.0| 2.5                         | 600               | 203.84/ 4.97                                  | 0.12330/0.050                           |

Figure 10. Hysteresis loop at different maximum loads (C = 0.8).

4.2. Mechanical properties of C-EPMM

A series of quasi-static tests of the EPMM samples, which are listed in table 1. To facilitate the analysis, the loss factor and stiffness of the EPMM can be derived from the test results according to equations (3) and (4) and are listed in table 3.

4.2.1 Effect of maximum load

A series of quasi-static compression tests of the C-EPMM specimens with density 2 g cm\(^{-3}\) and different mass ratios were carried out with different maximum load forces (200 N, 400 N, and 600 N). Figure 10 presents the test results of the C-EPMM with a mass ratio of 0.8, specimen number is C-EPMM4-1. The influence of the maximum load force is similar in the specimen, thus take a specimen as an example. The stiffness and loss factor of C-EPMM with different mass ratios varying with the load is drawn (see figure 11).
It can be seen from figure 10 and figure 4 that the loading and unloading curves of T-EPMM, W-EPMM, and C-EPMM are nonlinear and form a closed hysteresis loop. It means that the EPMM manufactured by different processes has energy dissipation capacity. It also can be seen from figure 10 that under different load forces, the compression curve has a high coincidence. It indicates that the loading force has little effect on the initial stiffness of the EPMM.

The stiffness of EPMM increases with the increase of maximum load, as shown in figure 11(a) and table 3. With the increase of external load, the deformation of EPMM increases, and the contact state of the internal wire will change (non-contact becomes slip or stick; slip becomes stick). The effective stiffness for slip and stick is higher than that for non-contact [26]. Especially when the internal wire is in the stick state, the stiffness of EPMM increases sharply with the increase of load.

As shown in figure 11(b) and table 3, the loss factor of EPMM decreases with the increase of the maximum loading force. With the increase of the external load, the pores in the EPMM will become smaller and more wires will enter into the stick state. The wire in the stick state cannot slip to dissipate energy, thus the loss factor decreases with the increase of maximum load. Under the same load, the loss factor of C-EPMM decreases with the increase of the proportion of wire mesh. And this phenomenon is determined by the proportion of the wire in the C-EPMM in the line contact mode.

Figure 11. Mechanical properties of C-EPMM under different loads with different mass ratios (2 g cm$^{-3}$).

Figure 12. Hysteresis loop of C-EPMM with different mass ratios (2 g cm$^{-3}$).
Figure 13. Stiffness and loss factor of C-EPMM with different mass ratios.

Figure 14. Hysteresis loop of C-EPMM with different densities.

Figure 15. Mechanical properties of C-EPMM with different densities.
4.2.2. Effect of mass ratio

Figure 12 presents the hysteresis loop of the C-EPMM with different mass ratios when the maximum loading force is 600 N. The stiffness and loss factor of C-EPMM are derived from these hysteresis loops and are presented in figure 13. The changing trend of all specimens is the same, as shown in figure 12. With the increase of mass ratio C, the force-displacement hysteresis loop gradually shifts to the right, and the corresponding maximum displacement is larger. It indicates that the load-bearing capacity of C-EPMM will gradually decrease with the decrease of mass ratio C. Figure 13 reveals that the stiffness and loss factor of C-EPMM decrease gradually as the mass ratio increases. The decrease in the proportion of T-EPMM indicates a decrease in the proportion of wires in the form of line contact within C-EPMM. Compared with point contact wires, line contact wires have a larger contact area and can dissipate more energy. Therefore, the stiffness and loss factor of C-EPMM decreases with the increase of mass ratio.

4.2.3. Effect of density

Figure 14 presents the hysteresis loop of C-EPMM with different densities (C = 0.4; C = 0.8). The stiffness and loss factor of C-EPMM with different densities are drawn (see figure 15).

It can be seen from figure 14 that the C-EPMM with a larger density has greater stiffness, but the loss factor is the opposite. The larger the density of the C-EPMM, the smaller the porosity inside. It means that there are more metal wires in the stick state. According to the above analysis, the metal wire cannot slip and dissipate energy in the stick state, and at the same time, there will not continue to deform elastically.

5. Mechanical model of composite elastic-porous metal material

The internal wire arrangement of W-EPMM can be divided into two types: transverse beam element and longitudinal rigid node element [46]. When the W-EPMM deformed under the compression load, the transverse beam element does not deform, and only the relative distance of the transverse beam element of different layers is reduced. The longitudinal rigid node element is produced by the interaction of wire contacts in the process of W-EPMM forming. When the W-EPMM is subjected to compression load, the axial force in the wire is very small and the longitudinal rigid joint element is subjected to bending deformation. Therefore, the internal model of W-EPMM can be simplified to the structure shown in figure 16(a). Figure 16(b) is a schematic diagram of longitudinal rigid joint elements.

Because the equivalent stiffness of the longitudinal rigid joint element between each layer of the unit grid is in series, the unit grid stiffness $k_i$ is equivalent to the stiffness of a single longitudinal rigid joint element. Thus, $k_i$ can be expressed as

$$k_i = \frac{P}{\Delta x}$$  \hspace{1cm} (5)

where $P$ is the longitudinal pressure on the element, $\Delta x$ is the longitudinal deformation of the element.

By using the integral method, $\Delta x$ can be obtained.

$$\Delta x = \frac{2}{3EI} \cos \frac{\alpha}{2} [Fl^3 + F \sin(\pi/2 - \alpha)l^3]$$  \hspace{1cm} (6)

where $l$ is half the length of the wire in the unit, $E$ is the elastic modulus of the wire, $I$ is the inertia moment of wire cross-section.

$$I = \pi d^4/64$$  \hspace{1cm} (7)
Thus, $k_1$ can be re-expressed as

$$k_1 = \frac{3\pi Ed^4}{64l^3 + 64l^3 \cos \alpha}$$

where $d$ is the diameter of the wire.

The length of the wire mesh ($L$) is proportional to the initial relative density of W-EPMM. Setting the proportional coefficient as $A$, the width of the wire mesh as $z$. The stiffness of the W-EPMM specimen is as follows

$$k_2 = k_1 \frac{2L}{z} = \frac{3\pi Ed^4}{52l^3(1 + \cos \alpha)z} = \frac{A\sigma_M d^4}{l^3 \cos \alpha (1 + \cos \alpha)}$$

5.1. Stiffness of T-EPMM

Take the force and deformation characteristics of the wire helix into consideration a cantilever curved beam model (as shown in figure 17) is selected as the basic mechanical model for T-EPMM [47].

According to the characteristics of meso-deformation, the cantilever curved beam is simplified to an arc with a radius of $R$.

When the cantilever curved beam is subjected to load $F$, the bending moment at the central point $C$ of the section is as follows

$$T = FR \cos^2 \beta \sqrt{2(1 - \cos \gamma)}$$

$$F = FR \sin \beta \cos \beta \sqrt{2(1 - \cos \gamma)}$$

According to Castigliano’s theorem, the deformation of the curved beam along the load direction can be expressed as

$$\Delta z = \int_0^l \frac{\partial M}{\partial F} \frac{M}{EI} ds + \int_0^l \frac{\partial T}{\partial F} \frac{T}{Gt} ds$$

Figure 17. Mechanical model of cantilever curved beam.
where $G$ is the shear modulus, $I_t$ is the polar moment of inertia.

$$G = \frac{E}{2(1 + \nu)}$$

(13)

where $\nu$ is Poisson’s ratio.

$$I_t = \frac{\pi d^4}{32}$$

(14)

$$ds = Dd\gamma/2$$

(15)

Then $\Delta x$ can be re-expressed as

$$\Delta x = \frac{16FDuD^3 \cos \beta (1 + u \cos^2 \beta)}{\pi Ed^4} (\gamma - \sin \gamma)$$

(16)

To facilitate modeling, $(\gamma - \sin \gamma)$ is simplified to $\lambda \gamma^3$. $\lambda$ is a constant to be fitted. Therefore, the stiffness of the cantilever beam can be obtained as

$$k_3 = \frac{\lambda \pi Ed^4}{16FD^3 \cos \beta (1 + u \cos^2 \beta)} \gamma^3$$

(17)

For T-EPMM, the internal wire helix is mostly in the state of 4-segment contact [11]. The spiral coil can be equivalent to four curved beams, and in this case $\gamma = \pi/4$, the stiffness of a single spiral coil is

$$k_4 = \frac{16\lambda \pi Ed^4}{\pi^2D^3 \cos^2 \beta + u\pi^2D^3 \cos^2 \beta}$$

(18)

Assuming the T-EPMM is a continuous homogeneous body; there are $n$ spiral coils per unit area; $m$ layers of spiral coils per unit length. Then the stiffness of T-EPMM per unit volume is

$$k_3 = \frac{n}{m}k_4$$

(19)

$$\frac{n}{m} = \sqrt{\frac{4\pi M}{\pi^2 Dd^2}}$$

(20)

$$\rho_M = \rho / \rho$$

(21)

where $\rho_M$ is the density of EPMM, $\rho$ is the density of wire.

Therefore, the stiffness of T-EPMM is as follows

$$k_3 = \frac{VEu \left(\frac{d}{D}\right)^{10} \rho_M}{u \cos^4 \beta + \cos^2 \beta}$$

(22)

where $V$ is a parameter related to volume.

Figure 18. Comparison of the measured and predicted force-displacement curves for two C-EPMM specimens with different mass ratios.
5.2. Mechanical model and parameter identification

The C-EPMM is composed of T-EPMM and W-EPMM in parallel. Thus, the stiffness of C-EPMM can be defined as follows

\[ k = k_2 + k_3 \]  

(23)

The quasi-static test results show that the force-displacement relationship of EPMM is strongly nonlinear, which can be properly expressed by cubic polynomials. Combined with the analysis of stiffness, the mechanical model of C-EPMM can be obtained as follows

\[
F = \left[ \frac{A\bar{d}_d d^4}{l^3 \cos \alpha} \left( \frac{\alpha}{2} (1 + \cos \alpha) \right) + \frac{VE}{6} \left( \frac{d}{D} \right)^{10} \bar{P}_M \right] (C_1 x + C_2 x^2 + C_3 x^3) \]  

(24)

where \( C_1, C_2, \) and \( C_3 \) are the parameters to be fitted, which can be obtained from the experimental data.

For C-EPMM, the mass ratio \( C \) is an important preparation parameter. The mechanical properties of C-EPMM are not a simple linear superposition of the mechanical properties of T-EPMM and W-EPMM according to the mass ratio. In this work, the mass ratio \( C \) is taken as a variable in \( C_1, C_2, \) and \( C_3. \)

By fitting the test data, \( C_1, C_2, \) and \( C_3 \) can be obtained. The variation law of \( C_1, C_2, \) and \( C_3 \) with the mass ratio can be known from table 4, and the coefficients \( C_1, C_2, \) and \( C_3 \) can be expressed as a polynomial series of the mass ratio.

\[
\begin{align*}
C_1 &= 144.2C^3 - 198.9C^2 + 20.14C + 99.25 \\
C_2 &= -125.6C^3 + 171.2C^2 - 52.6C - 33.77 \\
C_3 &= 16.47C^3 - 19.25C^2 + 1.55C + 21.69
\end{align*}
\]  

(25)

The mechanical model of C-EPMM including the preparation parameters and the mass ratio can be obtained by combining equation (24) and equation (25).

To verify the efficiency of the mechanical model of C-EPMM proposed in this research work, two C-EPMM specimens with a density 2 g/cm\(^3\) are prepared. Their mass ratios are 0.7 and 0.8, respectively. Two comparisons of the experimental and predicted force-displacement curves are shown in figure 18.

Use residual analysis to analyze the prediction results and test results of the model, the parameters and formulas are shown in formula 26, the error analysis results are shown in table 5.

\[
\begin{align*}
S_T &= \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \\
S_T &= \sum_{i=1}^{n} (y_i - \bar{y})^2 \\
R &= \sqrt{1 - \frac{S_T}{S_T}}
\end{align*}
\]  

(26)

\( y_i \) —measured results; \( \hat{y}_i \) —predicted results; \( \bar{y} \) —average value of.

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| Table 4. Fitting result. |
|-------------------------|
| Number | \( C \) | \( C_1 \) | \( C_2 \) |
|-------|-----|------|------|
| 1     | 0   | 99.3412 | -34.8450 |
| 2     | 0.2 | 94.9353 | -38.5646 |
| 3     | 0.4 | 85.0349 | -36.2270 |
| 4     | 0.6 | 70.3764 | -30.0449 |
| 5     | 1.0 | 63.5801 | -41.1901 |

| Table 5. The results of error analysis. |
|---------------------------------------|
| Sample | \( S_T(N^2) \) | \( S_T(N^2) \) | \( R \) |
|--------|----------------|----------------|-----|
| C-EPMM (C = 0.7) | 55104.87425 | 14962707.32 | 0.998 |
| C-EPMM (C = 0.8) | 429839.013 | 84498230.55 | 0.997 |
It can be seen from Table 5 that the values of R for the two specimens are close to 1, so the mechanical model of C-EPMM has a good agreement with the experimentally measured force-displacement curve. It indicates that the mechanical model proposed in this work can describe the mechanical properties of C-EPMM well.

6. Conclusion

In this work, the mechanical properties of T-EPMM and W-EPMM are compared, and a new preparation process is developed to manufacture composite EPMM (C-EPMM). The mechanical properties of C-EPMM were investigated with different maximum loading forces, densities and mass ratios. Based on the experiment, a mechanical model of C-EPMM was proposed and verified. To summarize, the main conclusions can be drawn as follows.

(1) The spatial structure of the metal wire inside the EPMM has a significant effect on its properties. The stiffness and damping of T-EPMM are larger than those of W-EPMM.

(2) A new composite elastic-porous metal material (C-EPMM) can be made of wire mesh and wire helix. With the increase in the proportion of wire mesh, the stiffness, and damping of C-EPMM decrease nonlinearly.

(3) A theoretical model based on the manufacturing process were developed. The theoretical model can effectively predict the mechanical properties of C-EPMM.

This work can provide experimental and theoretical inspiration for the engineering application of C-EPMM in the future.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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.

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