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COMPUTATIONAL MODELLING AND DIGITAL TWINS

Interpenetrating Composites with Enhanced Stiffness, Desired Poisson's Ratio and Superior Conductivity

Fibre matrix debonding, fibre pullout, delamination and mechanical anisotropy are the main common disadvantages of most fibre-reinforced composites. Interpenetrating phase composites (IPCs), however, do not have these problems because both their matrix material and their reinforcement fibre materials are self-connected networks, and interpenetrate each other. Moreover, IPCs could be designed to have an almost isotropic Young's modulus much larger than the Voigt limit, and a Poisson's at a desired value (i.e. positive, or negative or zero). In addition, they could have an isotropic thermal or electrical conductivity very close to the theoretical upper limit (i.e. the Hashin—Shtrikman's upper limit). This paper will introduce the relevant theoretical, simulation and experimental results on the elastic properties and thermal/electrical conductivities of some IPCs and compare their properties with those of other types of composites.

Keywords:
Interpenetrating phase composites, elastic properties, Poisson's ratio, conductivities.

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INTRODUCTION

Fibre composites are widely used in engineering applications, in which the fibres are usually much stronger and stiffer than the matrix material and used to reinforce the matrix material. To make the best use of the reinforcement material, it is very important that the reinforcement material is self-connected to form a network structure. For example, in modern buildings, bridges or water containing dams, the reinforcement steel bars are welded together to form a self-connected network, and the concrete material (i.e. the matrix material) is then casted into the porous space of the steel network. If the reinforcement steel bars are not self-connected, even if the same amount of the reinforcement steel material is used in buildings, bridges or dams, these structures could easily fall apart. Thus, in conventional fibre composites, the reinforcement fibres are in general not best used. Their common disadvantages include fibre matrix debonding, fibre pullout, delamination and mechanical anisotropy, etc [1]. In contrast, interpenetrating phase composites (IPCs) can avoid all these disadvantages because the reinforcement phase is a self-connected network. By theoretical analysis and computational simulations, Zhu et al. [2,3] and Zhang et al. [4,5] have found that IPCs could have an almost isotropic Young's modulus much larger than the Voigt limit, a Poisson's ratio at a desired value (i.e. positive, negative or zero), and a thermal or electrical conductivity close to the Hashin-Shtrikman's upper limit[6]. The aim of this paper is to highlight the advantages of IPCs over the fibre or particle composites.

MATERIAL MODELS

In our theoretical and simulation research works, the IPCs are reinforced by a self-connected periodic regular fibre network or a lattice structure. Thus, periodic representative volume elements (RVEs) and periodic boundary conditions can be used to obtain the elastic properties and thermal/electrical conductivities. Based on the geometric feature of the reinforcement network structure, the IPCs are classified into two main types: normal and auxetic. In the normal IPCs as shown in Fig. 1, the reinforcement fibre network is a normal network or lattice which has a positive Poisson's ratio. In the auxetic IPCs as shown in Fig. 2, the reinforcement fibre network is an auxetic network or lattice which has a negative Poisson's ratio. In theoretical analysis, the reinforcement fibre network and the matrix are divided into a number of blocks. In finite element simulations, both the reinforcement fibre network and the matrix are partitioned into a large number of tetrahedral elements.

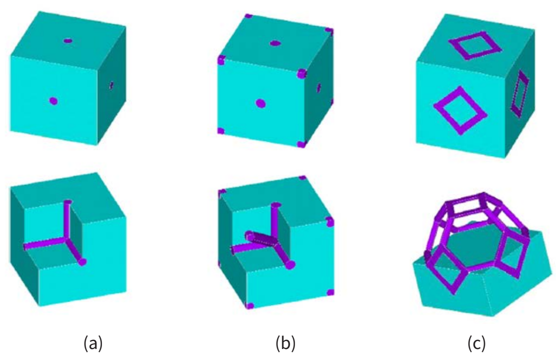

Fig. 1. Different types of normal IPCs: (a) type I, (b) type II, (c) type III.

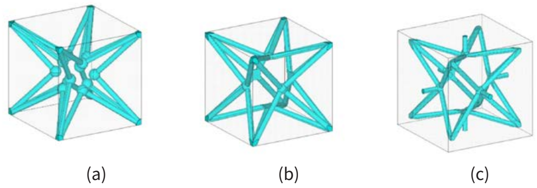

Fig. 2. Different types of auxetic IPCs: (a) type I, (b) type II, (c) type III.

RESULTS

Enhanced Young's modulus

The Voigt limit has long been regarded as the upper limit for the Young's moduli of isotropic composites [1]. For composites composed of a reinforcement material with a Young's modulus of E_f and a matrix material with a Young's modulus of E_m, the Voigt limit is given as

$$E_{Voigt} = E_f V_f + E_m V_m \qquad (1)$$

where V_f and V_m are the volume fractions of the fibre and matrix materials in the composites, respectively, and $V_f + V_m = 1$.

To make the theoretical and the finite element simulation results of the IPC more useful, the Young's modulus of the matrix material is assumed to be 1, and the Young's modulus of the reinforcement fibre material is the value of E_f/E_m, i.e. the ratio of the actual Young's modulus of the fibre material to that of the matrix material. Further, the obtained Young's of the IPC is normalized by the Voigt limit given by Eq. (1).

For different types of IPCs reinforced by a normal fibre network shown in Fig. 1, the effects of the different combinations of the constituent material properties on the normalized Young's moduli of the IPCs are presented in Fig. 3.

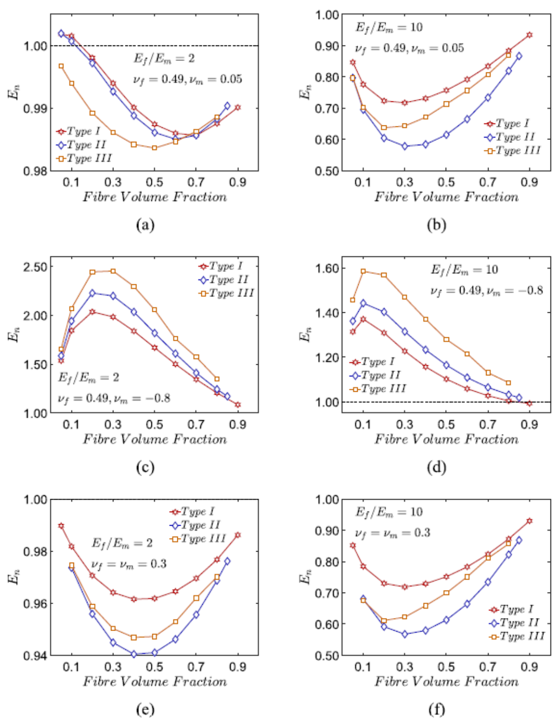

Fig. 3. Effects of the different combinations of the constituent material properties on the normalized Young's modulus of different types of normal IPCs [5], where ν_f and ν_m are the Poisson's ratios of the fibre and matrix materials, respectively.

Both the constituent materials, i.e. the fibre and matrix, are assumed to be isotropic. Thus, the possible range of their Poisson's ratio is (-1.0, 0.5). The theoretical [2] and finite element simulation [5] results indicate that the elastic properties of the IPCs are nearly isotropic. The results in Fig. 3(c) and 3(d) show clearly that the Young's moduli of the IPCs could be much larger than the Voigt limit, and therefore much larger than those of the conventional particle or fibre composites. In general, the larger the difference between the Poisson's ratios of the matrix and the reinforcement fibre materials, or the smaller the difference between the Young's moduli of the two constituent materials, the larger will be normalized Young's modulus of the IPCs. It is noted that for different types of IPCs [4] reinforced by an auxetic fibre network shown in Fig. 2, their Young's moduli are in general smaller that those of the IPCs reinforced by a normal fibre network, but still much larger than those of the conventional particle or fibre reinforced composites. It is also worth noting that for the same given amounts of the matrix and reinforcement materials, if the geometric structure of the reinforcement material is a perfect regular closed cell foam with a uniform wall thickness and the matrix material fills the identical cubic cells, the resultant composite [7] has the largest nearly isotropic Young's modulus. This is because among all the possible geometrical structures of the self-connected porous reinforcement material, the regular closed-cell foam structure with identical cubic cells and uniform wall thickness has the largest nearly isotropic stiffness. However, this type of composites is not IPC because its matrix material/phase doesn't form a self-connected network.

Desired value of Poisson's ratio

For different types of IPCs with different fibre volume fractions and reinforced by a normal fibre network shown in Fig. 1, the effects of the different combinations of the constituent material properties on the Poisson's ratio of the IPCs are demonstrated in Fig. 4. As can be seen, if both the matrix and the fibre materials have a positive Poisson's ratio, the Poisson's ratio of the IPCs would always be positive [5]. If the matrix material has a large magnitude of negative Poisson's ratio, the Poisson's ratio of the IPCs could have a large magnitude negative Poisson's ratio.

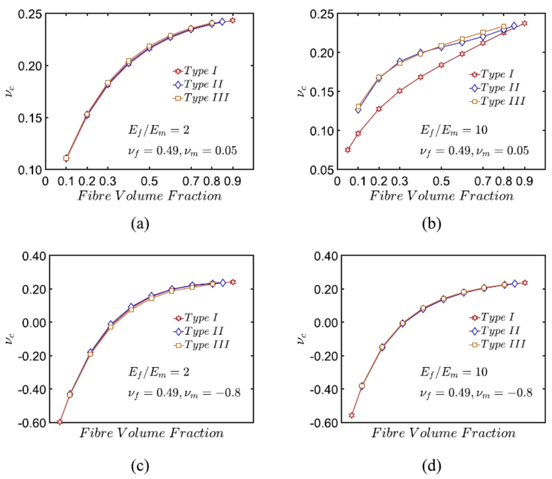

Fig. 4. Effects of the different combinations of the constituent material properties on the Poisson's ratio of different types of normal IPCs [5] reinforced by a normal fibre network.

For different types of IPCs with different fibre volume fractions and reinforced by an auxetic fibre network shown in Fig. 2, the effects of the different combinations of the constituent material properties on the Poisson's ratio of the IPCs [4] are demonstrated in Fig. 5. In contrast to the results of the IPCs reinforced by a normal fibre network, even if the Poisson's ratios of both the matrix and the fibre materials are positive, the IPCs reinforced by an auxetic fibre network can have a large magnitude negative Poisson's ratio.

Based on the results demonstrated in Figs. 4 and 5, it is concluded that the Poisson's ratio of PCs could be designed to achieve a desired value (i.e. positive, or negative or zero) by carefully choosing the combination of the properties of the constituent materials.

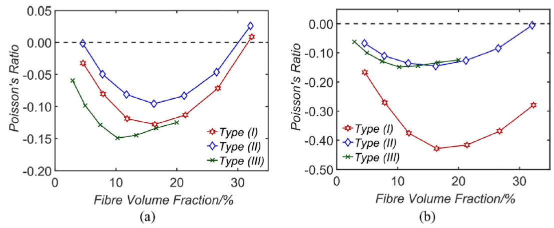

Fig. 5. Effects of fibre volume fraction on the Poisson's ratio of the composites [4] when α = 20°. (a) $v_m = 0.1$, $v_f = 0.25$, $E_f / E_m = 1000$; (b) $v_m = 0$, $v_f = 0.25$, $E_f / E_m = 1000$.

Superior conductivity

In two phase composites, the constituent fibre and matrix are assumed to be homogenous and isotropic materials A and B, with conductivities μ_A and μ_B and volume fractions V_A and V_B, respectively.

For composites with anisotropic conductivity, the largest and the smallest possible effective conductivities can be easily achieved if the two constituent materials A and B are uniformly arranged in parallel, for example, sandwich/laminate composites with layers of uniform thickness. For such anisotropic composites, their upper limit of conductivity is given by $\mu_U = \mu_A V_A + \mu_B V_B$ and their lower limit is given as $\mu_L = \frac{\mu_A \mu_B}{\mu_A V_B + \mu_B V_A}$ where $V_A + V_B = 1$.

For composites with isotropic conductivity, the magnitude of the conductivity is limited by the Hashin and Shtrikman's upper and lower bounds [6].

$$\mu_{HS\_U} = \mu_A + \frac{V_B}{\frac{1}{\mu_B - \mu_A} + \frac{V_A}{3\mu_A}} \tag{2}$$

$$\mu_{HS\_L} = \mu_B + \frac{V_A}{\frac{1}{\mu_A - \mu_B} + \frac{V_B}{3\mu_B}} \tag{3}$$

where it is assumed that $\mu_A \geq \mu_B$.

For IPCs reinforced by the normal type-I fibre network with $V_A = 0.104$, the relationship between the effective conductivity and the ratio μ_A / μ_B has been obtained by theoretical analysis and finite element simulation using ABAQUS [3]. Fig. 6 shows the effects of the ratio μ_A / μ_B on the effective conductivity of such IPCs, where different bounds/limits are plotted for comparison [3] and the results are normalized by μ_B.

As can been seen, the theoretical results are very close to those of the finite element simulation results, and the conductivities of the IPCs are closer to the Hashin-Shtrikman's upper bound than to their lower bound (see Fig. 6), and much larger than the experimentally measured results of the conventional particle or short- fibre composites, as shown in Fig. 7.

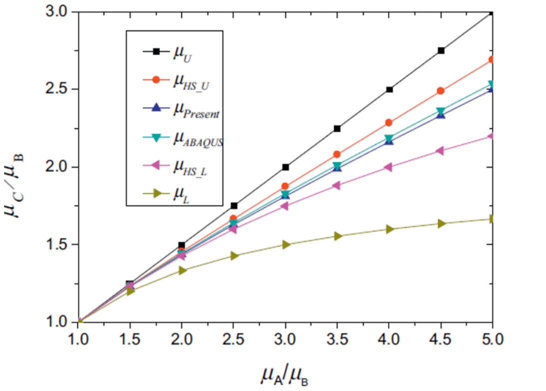

Fig. 6. Effects of $\mu A/\mu B$ on the conductivity of IPCs reinforced by a normal type-I fibre network [3], where the fibre volume fraction V_A = 0.104.

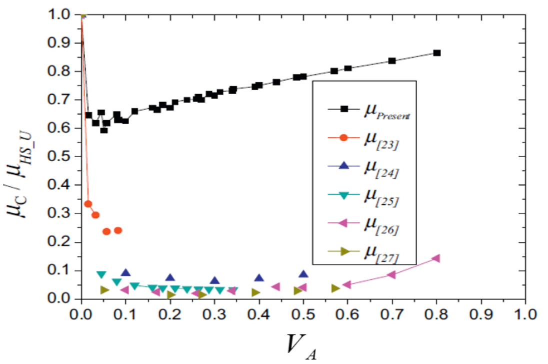

Fig. 7. Comparison between the conductivities of IPCs and the experimentally measured results of the conventional particle and short-fibre composites, where the results are normalized by the Hashin-Shtrikman's upper limit.

It is noted that for the same given amounts of the matrix and reinforcement materials, if the geometric structure of the reinforcement material is a perfect regular cubic closed cell foam with a uniform wall thickness and the matrix material fills the identical cubic cells, the resultant composite will have the largest isotropic conductivity [7], which is exactly the same as the Hashin-Shtrikman's upper limit. However, such composite is not an IPC.

DISCUSSION AND CONCLUSIONS

It is relatively easy to manufacture IPCs. The regular reinforcement fibre network structure can be produced first, the matrix material (e.g. concrete, resin, or polymer) can then be casted into the self-connected porous network of the reinforcement structure. The theoretical and finite element simulation results have demonstrated that for the same amounts of the constituent matrix and reinforcement materials used, IPCs can have a much larger nearly isotropic Young's modulus than those of the conventional particle or short fibre composites. Further, the nearly isotropic Young's modulus of IPCs could be designed to be much larger than the Voigt limit that was generally regarded as the unexceedable upper limit for all composites. In addition, IPCs can be designed as functional material with a Poisson's ratio at a desired value, e.g. positive, or negative, or zero. Moreover, IPCs have a conductivity significantly larger than those of the conventional particle and short-fibre composites. Therefore, IPCs have very important engineering applications in many different areas.

Conflicts of Interest
The authors declare no conflict of interest.

REFERENCES

[1] D. Hull and T. W. Clyne, *An Introduction to Composite Materials*, 2nd ed. Cambridge University Press, 1996. doi.org/10.1017/CBO9781139170130

[2] H. Zhu, T. Fan, C. Xu, and D. Zhang, 'Nano-structured interpenetrating composites with enhanced Young's modulus and desired Poisson's ratio', *Composites Part A: Applied Science and Manufacturing*, vol. 91, pp. 195–202, Dec. 2016. doi.org/10.1016/j.compositesa.2016.10.006

[3] H. Zhu, T. Fan, and D. Zhang, 'Composite Materials with Enhanced Conductivities', *Adv. Eng. Mater.*, vol. 18, no. 7, pp. 1174–1180, Jul. 2016. doi.org/10.1002/adem.201500482

[4] Z. Zhang *et al.*, 'Auxetic interpenetrating composites: A new approach to non-porous materials with a negative or zero Poisson's ratio', *Composite Structures*, vol. 243, p. 112195, Jul. 2020. doi.org/10.1016/j.compstruct.2020.112195

[5] Z. Zhang *et al.*, 'The near-isotropic elastic properties of interpenetrating composites reinforced by regular fibre-networks', *Materials & Design*, vol. 221, p. 110923, Sep. 2022. doi.org/10.1016/j.matdes.2022.110923

[6] Z. Hashin and S. Shtrikman, 'A variational approach to the theory of the elastic behaviour of multiphase materials', *Journal of the Mechanics and Physics of Solids*, vol. 11, no. 2, pp. 127–140, Mar. 1963. doi.org/10.1016/0022-5096(63)90060-7

[7] H. X. Zhu, T. X. Fan, and D. Zhang, 'Composite materials with enhanced dimensionless Young's modulus and desired Poisson's ratio', *Sci. Rep.*, vol. 5, no. 1, p. 14103, Sep. 2015. doi.org/10.1038/srep14103

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