Buckling enhancement of tubular metamaterial with axial zero thermal expansion by integrating two adjustment mechanisms

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Abstract
Artificially designed mechanical metamaterials with desired property of zero thermal expansion (ZTE) have already made great progress motivated by the urgent needs of high-end equipment and instruments served in large fluctuating temperature environment. Various thermal expansion adjustment mechanisms are developed to achieve controllable thermal deformation. However, only designing ZTE is not normally sufficient, but must be combined with enough mechanical performances for carrying mechanical loads. Hence in this study, a method of buckling enhancement for designing tubular metamaterials with axial ZTE is firstly proposed by integrating two existing adjustment mechanisms. Compared with the previous design under the single Poisson contraction mechanism, the present axial ZTE property is mainly achieved through thermally bending-adjustment mechanism, and therefore avoid the unfeasibility of requiring too large thermal expansion coefficient difference for constituent materials. Meanwhile, the significant buckling capacity loss caused by the introduced initial curvature used for triggering thermally bending-adjustment mechanism is prominently improved by taking the advantage of Poisson contraction mechanism. The results obtained from detailed numerical simulations verify the design targets of simultaneous axial ZTE and buckling enhancement. The proposed design strategy of mechanism combination is also proved effective to enhance the buckling capacity of present dual-mechanism metamaterial without obvious increase of structural mass.

1. Introduction
Tubular structures consisting of thin cylindrical shell are used as a primary support structure in marine engineering, automobile, aerospace and other industrial fields due to their geometrically advantageous to resist buckling. Designing tubular structures with axial zero thermal expansion (ZTE) is beneficial to eliminate thermally induced deformations and distortions so as to maintain shape accuracy and function of high-end equipment and precision instruments supported by them [1–3]. However, only designing ultralow thermal expansion is not normally sufficient, but must be combined with adequate stiffness [4], strength and robustness [5] to carry external mechanical load. Thus, the main aim of this study is to carry out the collaborative design of tubular structures between the available low thermal expansion property and high buckling capacity.

The property of ZTE for tubular structures can be achieved through resorting to the recently emerged concept of mechanical metamaterial with tunable thermal expansion [6–8]. The abnormal behavior of ultralow thermal expansion is dependent on elaborately designed microstructures rather than from the properties of constituent materials [9, 10]. Since the constituents consisting of such metamaterials are commonly used materials with positive coefficients of thermal expansion (CTEs), it is therefore necessary to introduce thermal expansion adjustment mechanism for them to tailor effective CTE to zero. Up to now, there are three commonly
used mechanisms had been reported in the open literatures, including thermally bending-adjustment mechanism\cite{11}, thermally stretching-adjustment mechanism\cite{12} and mechanism of Poisson contraction\cite{13}, all of them are utilizing the mismatched thermal expansion produced by the two constituents with distinct CTEs. These pioneering research works inspire more valuable design concepts and methods to meet various application requirements\cite{14–18}.

More importantly, extremely high designability permits such artificially designed materials to simultaneously obtain enhanced mechanical performances through utilizing their vast design space with triangular cell configuration\cite{19}, multi-hierarchy design\cite{20,21} and further shape and size optimizations\cite{22}. Different from the previous works, this study attempts to improve the buckling capacity of axial ZTE tubular design by integrating the two existing thermal expansion adjustment mechanisms. In doing so, the desired property of axial ZTE will be achieved mainly through the introduced thermally bending-adjustment mechanism\cite{23,24}. The basis element can reflect this adjustment mechanism is the bi-layer curved rib that consists of two constituents with different CTEs. As an increased temperature is applied, the differing thermal expansions for two layers generate bending moments that cause transverse bending to the rib element, which results in the chordal contraction that can compensate the thermal elongation in the same direction. In order to fully compensate the chordal thermal elongation, an initial curvature must be involved to enlarge the magnitude of the required transverse bending.

Note, adopting single thermally bending-adjustment mechanism to tailor axial CTE for tubes will cause a significant loss on buckling capacity due to the bending deformation as a result of the introducing of initial curvature. Aiming at this issue, another mechanism of Poisson contraction is combined to enhance structural buckling capacity. This mechanism utilizes a nested tube element that consists of two concentric tubes with differing CTEs. As ambient temperature is increased, the outer tube of material two with high CTE will expand more rapidly than the inner tube. This action will cause a circumferential tension in material one and resulting in a longitudinal Poisson contraction that can compensate the axial thermal elongation in the axial direction. However, a detailed parameter analysis\cite{25} indicates that it is likely not possible to fully compensate the axial thermal expansion if the aforementioned two concentric tubes are bonded perfectly. The reason for that is

Figure 1. (a)–(c) The unit cells of the three kinds of tubular metamaterial designs under different thermal expansion adjustment mechanisms; (d)–(f) The sketches of the adjustment mechanisms of thermally bending-adjustment (TB) Poisson contraction (PC) and their combined mechanism (TB&PC); (g)–(i) The corresponding periodic structures consist of the three kinds of tubular metamaterials.
mainly due to the longitudinal thermal strain of outer tube with high CTE will pass to the inner tube through material interface, resulting in an additional axial thermal elongation of inner tube. Thus, an ideal condition of slip material interface for decoupling axial thermal deformations of two layers must be involved as desired axial ZTE property is considered. In practical cases, one may approximate such a condition by segmenting the larger CTE material into rings, or a wrapping of helical wire, but results in another problem of requiring large CTE difference for two constituents. This requirement of material selection will largely limit these tubes applicability since it is hard to find appropriate bulk material pairs with large enough CTE difference, and as a result, very few of follow-up works are carried out on this topic.

In this study, a dual-mechanism tubular metamaterial design with desired axial ZTE property is firstly proposed. Differing with the similar design under single Poisson contraction mechanism, the axial ZTE property is achieved mainly through thermally bending-adjustment mechanism, and therefore avoid the requirement of large CTE difference for constituents. This requirement of material selection will largely limit these tubes applicability since it is hard to find appropriate bulk material pairs with large enough CTE difference, and as a result, very few of follow-up works are carried out on this topic.

In this study, a dual-mechanism tubular metamaterial design with desired axial ZTE property is firstly proposed. Differing with the similar design under single Poisson contraction mechanism, the axial ZTE property is achieved mainly through thermally bending-adjustment mechanism, and therefore avoid the requirement of large CTE difference for constituents. In the meantime, the significant buckling capacity loss caused by the introduced initial curvature used for triggering thermally bending-adjustment mechanism is prominently improved by taking the advantage of Poisson contraction mechanism. The remainder of this paper is organized as follows: The design descriptions for the proposed tubular metamaterial are presented in section 2. The illustrations of the adopted thermal expansion adjustment mechanisms are also presented; section 3 carries out finite element analyses to reveal the essence reasons of buckling capacity enhancement benefiting from the design strategy of mechanism combination. The finite element simulations are performed at the end to verify the designed axial ZTE property of the proposed tubular metamaterials and their corresponding periodic tubular structures. Conclusions are drawn in section 4.

2. Designed metamaterials and their mechanisms

Figures 1(a)–(c) show the unit cells of three kinds of dual-constituent tubular metamaterials with unique property of axial zero thermal expansion (ZTE). The corresponding mechanisms used for adjusting their axial thermal expansion behaviors are illustrated in figures 1(d)–(f), respectively, which are named as the mechanism of thermally bending-adjustment (TB) [24], mechanism of Poisson contraction (PC) [25] and their combined mechanism (TB&PC). The main principle of these three mechanisms is utilizing the mismatched thermal expansion caused by the differing CTEs of two constituent materials. In these dual-constituent unit cells, constituent 2 with high CTE \( \alpha_2 \) generally forming the key component triggers the potential mechanism to cause circumferential expansion, which resulting in a longitudinal contraction in inner tube consisted of constituent 1 with low CTE \( \alpha_1 \). By carefully choosing constituent properties and geometric parameters, it is possible to fully compensate for the axial thermal elongation. The designed tubular metamaterials and their periodic structures illustrated in figure 1(g)–(i), can provide high axial thermal dimensional stability for eliminating the undesirable deformations and distortions in the potential applications, such as the drawtubes of the space telescopes and platforms in satellites.

2.1. TB mechanism

Figure 2 shows a dual-constituent curved rib element with tailorable thermal expansion along chord direction. The present TB mechanism utilizes the mismatched expansion of two constituents with distinct CTEs to cause...
transverse bending to the rib during temperature variation, which results in the chord contraction that can compensate the thermal expansion in the same direction. The effective chordal CTE of the curved rib element can be expressed as

\[
\alpha_{\text{chord}}^* = \frac{6(\alpha_2 - \alpha_1)(1 + d)^2 \theta_{\text{arc}}}{12t \left(3(1 + d)^2 + (1 + d\frac{d}{dn}) \left(d^2 + \frac{1}{dn}\right)\right)} + \frac{\alpha_1 + \alpha_2}{2} + \left(\alpha_2 - \alpha_1\right) \left(\frac{4d^2 + 3d + \frac{1}{dn}}{nd^2 + 4d^2 + 6d + \frac{1}{dn} + 4}\right)\right) \frac{1}{2}
\]  
\(1\)

where \(t\) and \(L_{\text{arc}}\) are the total thickness and length of the rib, respectively. \(\theta\) is the initial curvature for enlarging the magnitude of thermally induced transverse bending in order to fully compensate simultaneously produced thermal expansion.

Resorting to the design principle of the above curved rib element, a dual-constituent tubular metamaterial with axial ZTE property as shown in figure 1(a) is proposed. The TB mechanism is triggered through adding the outer reinforcement rib of high CTE constituent to the inner low CTE tube with an initial curvature. Note, adopting excessive small curvature may lead to insufficient axial contraction, and as a consequence, it inevitably fails in tailoring axial CTE. However, it is apparent that the buckling capacity of designed tube reduce significantly due to the bending deformation as a result of the introducing of slight curvature. As shown in figure 3, compared with normal straight tube with positive axial CTE, a non-negligible sacrifice on structural mechanical performance is observed if the single TB mechanism is adopted.

2.2. PC mechanism

Focusing on PC mechanism as shown in figure 1(e), Poisson effect is utilized to cause the axial contraction to compensate the axial elongation of tube. As the ambient temperature is increased, the greater expansion of outer ring with high CTE will cause circumferential tension in inner tube. Due to the effect of Poisson ratio, the required axial contraction is obtained. The effective axial CTE of the tube can be expressed as [25]

\[
\alpha_{\text{axial}}^* = \alpha_1 + \frac{\nu_1(\alpha_1 - \alpha_2)}{1 + ndl}
\]  
\(2\)

where the geometry parameters \(d = t_1/t_2\) and \(l = L_1/L_2\) are the ratio of thickness and length of layers consisted of constituents 1 and 2, respectively. The material parameter \(\nu = E_1/E_2\) is the ratio of Young’s Modulus of two constituents. Note, the derivation of equation (2) closely relies on the aforementioned sliding interface assumption that the axial stress and strain of the two layers are independent and are allowed to slide relative to one another. In term of equation (2), the required cross-sectional area ratio of two layers \(A_1/A_2\) for axial zero
CTE is obtained

\[
\frac{A_1}{A_2} = \frac{1}{n} \left( \frac{\nu_2 (\alpha_2 - \alpha_1)}{\alpha_2} - 1 \right)
\]  

Equation (3) is illustrated in figure 4 with the commonly used constituents of Invar and aluminum for tailorable CTE metamaterials [26]. Figure 4 demonstrates that the CTE difference required for the two constituents for ZTE is linearly increased with increasing ratio of \(A_1/A_2\). As a very large cross-sectional area ratio for satisfying the necessary sliding interface assumption is adopted, this CTE difference is so large that is hard to be satisfied by matched natural material pair. As a result, it is practically difficult to design axial ZTE tubular structure using single PC mechanism.

2.3. TB and PC combined mechanism

In order to improve the buckling capacity of axial ZTE tubular designs, an idea of mechanism combination for designing a dual-mechanism tubular metamaterial as shown in figure 5 is proposed. The newly designed tubular cell will take the advantages of both adjustment mechanism, and thus possesses benign comprehensive performance. The axial ZTE property is mainly provided by TB mechanism, which is triggered through adding outer reinforcement rib of high CTE along the axial direction. The efficiency of thermally bending-adjustment can be promoted through introducing an initial curvature design, and subsequently lower the CTE difference requirement of constituent materials for obtaining axial ZTE. On the other hand, the loss in buckling capacity caused by the curvature is improved by purposely adding inner circumferential reinforcement rib (same effect as adding outer circumferential reinforcement rib). Note, theses circumferential ribs can trigger the other PC
Figure 6. The effect of the introduction of PC mechanism on effective axial CTE $\alpha_{\text{eff}}^a$ of the tubular metamaterial.

Figure 7. The initial curvature $\theta$ for axial ZTE tubular metamaterials under single TB mechanism ($t_1 = 0$) and dual TB &PC mechanism with different constituents.
element analysis to derive the corresponding analytical solutions of axial CTEs and critical buckling loads. Therefore, the thermal expansion analysis, the effective axial CTE and enhanced buckling capacity. In all numerical models, the tubular cells are meshed by adequate four-node elements.

Due to the geometric complexities of the proposed dual-mechanism tubular metamaterials, it is difficult to define the effective axial CTE $\alpha_{\text{axial}}^*$ observed clearly in figure 6. As can be seen, the enhanced effect of PC mechanism due to increasing thickness of circumferential rib $t_3$ significantly reduce the required initial curvature $\theta$ for obtaining axial zero CTE. As a result, the desired buckling enhancement will be achieved due to the large initial curvature leading to bending deformations that will greatly weaken buckling resistance of designed tubular metamaterial.

3. Numerical verification

Due to the geometric complexities of the proposed dual-mechanism tubular metamaterials, it is difficult to derive the corresponding analytical solutions of axial CTEs and critical buckling loads. Therefore, the finite element analysis (FEA) is conducted here through ANSYS to verify the design objectives of axial ZTE property and enhanced buckling capacity. In all numerical models, the tubular cells are meshed by adequate four-node shell element (shell 181 in ANSYS definition) to ensure that the numerical results are mesh independent. In the thermal expansion analysis, the effective axial CTE $\alpha_{\text{axial}}^*$ is calculated from the cell axial macroscopic thermal strain $\varepsilon_{\text{axial}}^*$ during temperature variation $\Delta T$ as

$$\alpha_{\text{axial}}^* = \frac{\varepsilon_{\text{axial}}^*}{\Delta T} = \frac{\Delta L/L}{\Delta T}$$

where $\varepsilon_{\text{axial}}^*$ is calculated numerically by measuring the relative thermal displacements of a pair of node located at the top and bottom of the cell. To this end, the axial freedoms of the nodes located at the top of the cell are coupled together so as to obtain uniform axial thermal deformation. Note, the absolute zero value of CTE is unattainable, and an alternative definition [27] of axial ZTE is give as follows

$$\left(\frac{\alpha_{\text{axial}}^*}{\alpha_1}\right)^2 \leq 1 \times 10^{-4}$$

The equation (5) defines that the axial ZTE is obtained as the effective axial CTE $\alpha_{\text{axial}}^*$ decreases at least two orders magnitude compared with that of constituents. The proposed tubular metamaterial design includes no size effect and therefore the cell geometry parameters used in the process of numerical simulations can be chosen arbitrarily. Throughout the finite element analysis, an overall cell size of $L \times R \times t_1 = 15 \times 10 \times 0.3 \text{mm}^3$ is adopted. As for materials selection, three isotropic materials used includes steel, aluminum and Invar. Among them, Invar is known for its low CTE, whereas steel and aluminum are commonly used for structural materials and have differing CTEs. The material properties for each material are listed in Table 1.

| Material | $E_1$ | $E_2$ | $E_3$ | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\rho_1$ | $\rho_2$ | $\rho_3$ |
|----------|-------|-------|-------|------------|------------|------------|---------|---------|---------|
| Invar    | 140 GPa | 70 GPa | 200 GPa | 1.0 ppm     | 22.2 ppm   | 12 ppm     | 8.1 mg mm$^{-3}$ | 2.8 mg mm$^{-3}$ | 7.8 mg mm$^{-3}$ |
| Aluminum |       |       |       |            |            |            |         |         |         |
| Steel    |       |       |       |            |            |            |         |         |         |

3.1. Buckling enhancement analysis

In this sub-section, the initial curvatures $\theta$ required to trigger TB mechanism for achieving axial ZTE property is investigated. The curvatures $\theta$ for axial ZTE tubular metamaterials under single TB mechanism ($t_3 = 0$) and dual TB&PC mechanism with different constituents are shown in figures 7(a) and (b), respectively. It can be seen that compared with the tubular cell designs under single TB mechanism, the smaller curvature $\theta$ will be adopted by the dual-mechanism designs. The main reason is that the introduction of PC mechanism causes an additional axial contraction that also could effectively decrease the axial CTE of cell. The increasing thickness of inner reinforcement rib $t_1$ gradually enhances the effect of Poisson contraction produced by PC mechanism and as a result, the required $\theta$ used to tailor the value of axial CTE to zero is therefore decreased significantly.

Figures 7(a) and (b) provides the comparison of required curvature $\theta$ for axial ZTE schemes with different constituent materials. Instead of adopting Steel as high CTE constituent for the inner and outer reinforcement ribs, the axial ZTE schemes constituted by Aluminum and Invar will requires smaller initial curvature. As mentioned by the mechanism analysis in section 2.1, the tunability of axial CTE is originated from the mismatched thermal expansion produced by the constituents with different CTEs. The larger CTE difference
provided by Aluminum and Invar will enlarge the magnitude of bending deformation, and as a consequence, the curvature used for producing enough axial contraction is decreased. In addition, the CTE differences for present constituents are 21.2 ppm (Aluminum and Invar) and 11.0 ppm (Steel and Invar), both of them are so small that disable to single PC scheme to achieve desired axial ZTE as explained in section 2.2.

As different inner reinforcement rib layouts used for triggering PC mechanism are adopted, the critical buckling loads for axial ZTE tubular metamaterials under single TB mechanism ($t_1 = 0$) and dual TB&PC mechanism with different constituents are shown in figure 8. It can be seen that the critical buckling loads are increased monotonically with increasing $t_3$. In other words, as desired property of axial ZTE is achieved, the introduced PC mechanism will prominently improve cell buckling capacity. This buckling enhancement is getting more prominent as the number and thickness of inner reinforcement rib is increased. The reason causing this enhancement on the one hand, is mainly due to the introduction of PC mechanism lower the required curvatures. On the other hand, the layout design of circumferential reinforcement rib itself will also enhance the bucking resistance of cylindrical shell structures.

Furthermore, the higher buckling capacity of Steel and Invar scheme is observed from figure 8 compared with those of adopting the Aluminum as the high CTE constituent. Although the smaller CTE difference between the Steel and Invar requires larger initial curvature to achieve axial ZTE, the higher Young's modulus of Steel as constituent could compensate this buckling capacity loss. Thus, it is concluded that the final buckling capacity of the present dual-mechanism tubular cell is determined by both of CTE difference and mechanical property of constituents.
3.2. Structural efficiency analysis

Although the introduced PC mechanism enhances the buckling capacity of axial ZTE tubular cell, but also results in increase of structural mass. Thus, in this sub-section, the structural efficient defined as the ratio of critical buckling load to cell mass is used to evaluate the critical lightweight characteristic for the present dual-mechanism tubular design. As shown in figure 9, the cell structural efficiencies are increased significantly with the increasing thickness of inner reinforcement rib \( t_3 \). This means that the present design strategy of mechanism combination is effective to enhance the buckling capacity of axial ZTE tubular metamaterials without obvious increase of structural mass. Moreover, the unequal cell structural efficiencies are observed from figure 6 for the axial ZTE tubular designs with different constituents. Adopting the Steel as the high CTE constituent tends to higher structural efficiency as the thin thickness of inner reinforcement rib is used. However, with the increasing of this thickness, the scheme of Aluminum and Invar will lead to more lightweight characteristic due to the lower material density of Aluminum.

Figure 10 compares the structural efficiencies for the axial ZTE tubular cells with four layouts of outer axial reinforcement rib. The effective comparison is performed under the premise condition of adopting same layout of inner circumferential reinforcement rib. As depicted in figures 10(a) and (b) for different constituents, the layout with larger volume of outer rib tends to higher cell structural efficiency if the thinner thickness of inner reinforcement rib \( t_3 \) is used. This desired superiority in structural efficiency is gradually lost with the increasing of \( t_3 \). Consequently, the optimal outer rib layout is determined by the certain volume that is closely related to the selected thickness of inner circumferential rib.
3.3. Numerical verifications

In this sub-section, the finite element simulations are carried out for verifying the designed axial ZTE property of the proposed tubular metamaterials and their corresponding periodic tubular structures. An overall cell sizes of \( L \times R \times t_1 = 15 \times 10 \times 0.3 \text{ mm}^3 \) with outer axial rib thickness \( t_2 = 0.3 \text{ mm} \) and inner circumferential rib thickness \( t_3 = 1.0 \text{ mm} \) are taken to separately model the cells under single TB mechanism \( (t_3 = 0) \) and dual PC&TB mechanism. The applied temperature variation is \( \Delta T = 100 ^\circ \text{C} \), and the used initial geometry configurations are shown in figures 8(a)–(b), respectively. The Aluminum is selected as the high CTE constituent and the Steel is used for low CTE constituent.

Figures 11(a)–(b) illustrate that as the desired axial ZTE is achieved, the dual-mechanism tubular cell will possess the advantage of smaller curvature \( (\theta = 22.9^\circ) \) than that of single TB mechanism scheme \( (\theta = 32.6^\circ) \). The smaller curvature brings geometric advantages for dual-mechanism cell to resist buckling. Due to the introduction of thermal expansion adjustment mechanisms, the axial thermal deformation displayed in figures 11(c), (d) show circumferentially outward thermal expansion that causes axial contraction to compensate the simultaneously produced axial thermal elongation. The axial thermal displacements for the two kinds of tubular metamaterials are \( 4.96 \times 10^{-6} \text{ mm} \) and respectively, as the results of practical measure (measured at shell mid surface). The corresponding axial CTEs calculated using the equation (4) are \( 3.3 \times 10^{-3} \text{ ppm} / ^\circ \text{C} \) and \( 7.6 \times 10^{-3} \text{ ppm} / ^\circ \text{C} \), respectively, both of them decrease two orders magnitude compared with that of constituent material \( (1.0 \text{ ppm}) \). Thus, the designed axial ZTE property is verified according to the definition of ZTE in equation (5).

Moreover, the proposed tubular cells can be assembled together as the periodic structures to satisfy practical engineering applications. Thus, the finite element simulations for a special tubular periodic structure consisted of the present dual-mechanism tubular metamaterial is performed. As can be seen in figure 12(a), the periodic tubular structure consists of five axial ZTE dual-mechanism cells with the geometry sizes given in the beginning of this section. The required theoretical value of initial curvature to tailor the axial CTE to zero for a separate dual-mechanism cell is \( \theta = 22.9^\circ \). However, as for the corresponding periodic structure, this value will require to increase to \( 26.4^\circ \). The reason causing this curvature increase is due to that the connectivity between cells alters the original boundary condition of free cross-sectional rotation. The boundary restriction passed from the surrounding cells lower the tunability of TB mechanism, and the larger curvature is therefore required to enlarge the magnitude of bending deformation.
As shown in Figure 12(b), the axial thermal displacement of the present periodic structure is \(6.88 \times 10^{-5}\) mm and the corresponding axial CTE is \(8.6 \times 10^{-3}\) ppm °C\(^{-1}\), which is decreased at least two orders magnitude compared with that of the constituent material (1.0 ppm). Therefore, it is considered that near-zero axial CTE is achieved according to the definition of ZTE in equation (5).

4. Conclusion

In this paper, we conceptually propose a dual-mechanism tubular metamaterial whose axial CTE is zero and therefore can provide the superior function of axial thermal dimensional stability. Compared with the similar designs under the single PC or TB mechanism, the present tubular design takes the advantages of both mechanisms and therefore lower the requirement of CTE difference for constituents. Numerical simulations are carried out and the results indicates that as the axial ZTE is achieved, the present dual-mechanism design possesses the advantage of smaller curvature than that of the design under the single TB mechanism, and thus the buckling capacity is prominently improved. In the meantime, the present design strategy of mechanism combination is proved effective to enhance the buckling capacity of axial ZTE tubular cells without obvious increase of structural mass. Finite element simulations of the proposed tubular metamaterial and their periodic structures are performed, and then the designed property of axial ZTE is verified. The further explorations on detailed designs and fabricate process for these tubular metamaterials and their periodic structures are worthy of attentions in the future work.

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