International Journal of Mechanical Sciences 135 (2018) 23–30

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Thermal effects on the structural response of planar serpentine interconnects

Z.G. Yan[a], B.L. Wang[a,b], K.F. Wang[a,*]

[a] Graduate School at Shenzhen, Harbin Institute of Technology, Harbin 150001, PR China
[b] Centre for Infrastructure Engineering, School of Computing, Engineering and Mathematics, Western Sydney University, Penrith, NSW 2751, Australia

ARTICLE INFO

Keywords:
Serpentine interconnects
Stretchable electronics
Stiffness
Maximum tensile strain
Thermal effect

ABSTRACT

Serpentine-shaped interconnects are widely employed to achieve high level of stretchability in stretchable electronic devices. In the current work, an analytical model for the mechanical response of planar serpentine interconnects with thermal effect is developed and verified by finite element method (FEM). Specifically, the closed-formed expressions to compliance and stretchability are derived based on curved beam theory and energy method. The numerical results indicate that a considerable error (e.g., >10% relatively) could be induced for many representative configurations using the model with thermal loads absent. The present work provides more accurate predictions for the structural response of serpentine interconnects in practical working conditions, which help in optimal design in future applications.

1. Introduction

The last decade has seen rapid advancements and exciting applications in the field of stretchable electronics [1–6]. Compared with traditional electronics, they have some special advantages such as flexibility and stretchability that meet the pursuit of modern technologies, which include flexible electronic display, thin film solar cell, electronic skin and epidermal health monitors [4,5,7]. These devices are designed with advanced materials and mechanics to stand up to extreme deformability without failure in mechanical strength and electrical functionalities [8,9].

Generally in stretchable electronics, the active components are still made by traditional microelectronics, which are stiff and brittle, so they are fixed at stiff cell islands well bonded to flexible substrate and interconnected with surrounding ones by electrical interconnects [9,10]. This effective method of achieving ultra-stretchability is called as “island-bridge” architecture, where stiff islands remain almost undeformed and the interconnects are largely responsible to accommodate the applied strain [11–13]. Unfortunately, to achieve high performance of the stretchable devices, it requires high areal coverage of cell islands(i.e. active components) that leaves less space for interconnects to exert stretchability [14,15]. Therefore, it presents a challenge for the design of the electrical interconnects. So far many kinds of strategies have been put forward for the design of interconnects, including planar configurations in curvy, serpentine, fractal patterns or Kirigami patterns [16–19]. Of all those profiles the planar serpentine geometry stands out as a popular one for its convenience in fabrication and efficiency in the stretchability [11,20].

There are two kinds of serpentine interconnects categorized according to width/thickness ratio, which is also corresponding to their different working behaviors upon stretching [11,21]. In some cases like radio-frequency coils low electrical resistances are desired, so smaller width/thickness ratios (often <1.0) are adopted, serpentine interconnects will just deform in the two-dimensional plane [17,22]. While the other kind of ultra-thin ribbons with bigger width/thickness ratios (often >1.0) are also common in applications, they buckle out of plane upon stretching to accommodate the applied strain [9,23,24]. The object of study in this paper is the former planar serpentine interconnects dominated by in-plane bending deformations, and theoretical models have been developed for that to study the structural response, specifically stretchability and compliance, to axial stretching [23,25,26]. Also, many analysis have been done around the buckling and post-buckling behaviors of suspended serpentine interconnects through analytical, experimental and FEM approaches [16,23,24,27]. Recently, elasticity solutions to nonbuckling serpentine interconnects around the effects of geometric parameters on the strain field and the stiffness are presented [23,25]. However, these investigations are on the premise that the effect of temperature difference is ignored and not included in the models. In practical applications, stretchable electronics do generate heat in the electrical interconnects due to the flow of electric current, thus the serpentine interconnects suffer constant temperature change and the consequent thermal loads [28–30]. In some projects like robots in electronic

* Corresponding author.
E-mail address: wangkf@hit.edu.cn (K.F. Wang).

https://doi.org/10.1016/j.ijmecsci.2017.11.006
Received 29 July 2017; Received in revised form 11 October 2017; Accepted 6 November 2017
Available online 7 November 2017
0020-7403/

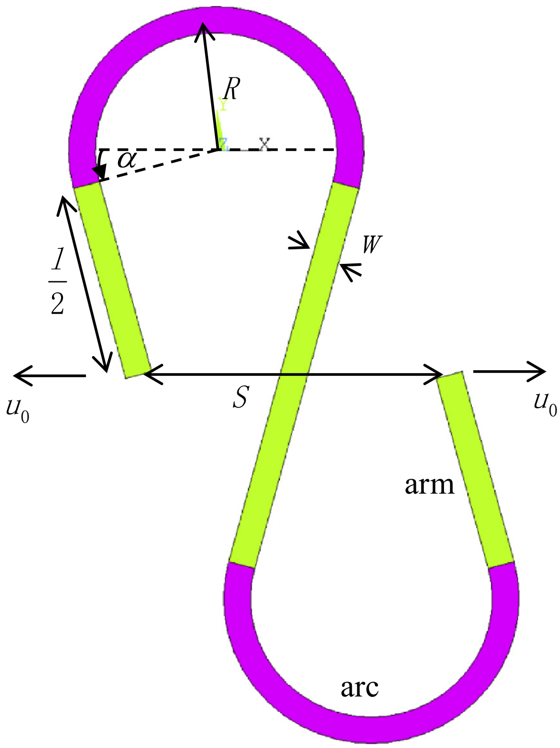

Fig. 1a. A clamped serpentine interconnect subjected to an axial stretching (u_0) at the two ends.

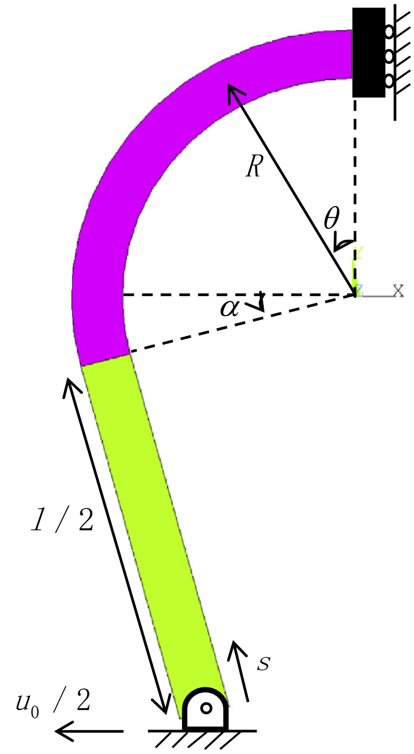

Fig. 1b. Schematic illustration of the simplified model for the serpentine interconnect.

skin operating on the moon, where exists several hundreds of temperature difference between day and night, taking thermal loads into consideration is essential [31–33]. The existing theoretical models could cause evident errors (e.g., >10% relatively) in the predictions of structure response in the practical working conditions.

The paper is outlined as follows. Section 2 describes the procedure of developing the mechanical model based on energy method and curved beam theories. Section 3.1 compares the results obtained in this paper with those derived without thermal loads, and validates the results with FEM results. Section 3.2 presents the effect of thermal loads on structure response for a wide range of geometric parameters. The results indicate that the neglect of temperature difference can lead to a considerable error (e.g., >10% relatively) of maximum tensile strain, which calls for attention in practical applications. The conclusions are drawn in Section 4.

2. Mechanical model formulation

We consider suspended serpentine interconnects with small width/thickness ratios as the object of study, and the frictional resistance of substrate is ignored. It can be described with a plane strain model, a typical one consist of two antisymmetrical parts, each part is composed of one arc and two arms. The arc radius is R, arc angle is α, the length of an arm is $l/2$, they are tangentially connected at each end of the arc, and the ribbon width is w, as shown in Fig. 1a. As it is regarded as a basic cell of a long periodical serpentine interconnect (e.g., with more than 5 unit cells) whose ends are clamped, the model in Fig. 1a can be simplified further into a quarter of the basic cell due to symmetry and anti-symmetry, as shown in Fig. 1b. The thickness of the model in Fig. 1b is treated to be unit based on the plane strain model, θ is the angular variable for the arc section and s is the linear variable for the arm section. As shown in Fig. 1b, the left end of the model is pinned and undergoes a displacement of $u_0/2$ which corresponds to the equivalent tensile displacement u_0 at each end of the serpentine interconnect in Fig. 1a, and the right side end is constrained in that way only be able to move in y-direction, which can also bear the reaction bending moment. The left end of the basic cell is hinged so that it can rotate freely. It subsequently suffers a homogeneous thermal loading. The effective applied strain ε_{app} is defined as $\varepsilon_{app} = 2u_0/S$. The corresponding reaction force at the end is symbolized by P in the absence of thermal loads and by P' in the presence of thermal loads.

As illustrated in Fig. 1a, the end-to-end length of the serpentine interconnect S is obtained according to geometrical parameters, and given by [23]

$$S = 4\left(R\cos\alpha - \frac{l}{2}\sin\alpha\right) \tag{1}$$

The serpentine ribbon becomes a straight ribbon when $\alpha = -\pi/2$, in that case the stiffness is given by $\bar{E}w/S$, where $\bar{E}$ symbolizes the plane strain modulus, $\bar{E} = E/(1-\nu^2)$ with Young's modulus E and Poisson's ratio ν. The thermal strain induced by a temperature difference of ΔT is expressed by $\varepsilon^{th} = \lambda\Delta T$, where λ stands for the linear thermal expansion coefficient, ΔT for the temperature change.

Effective stiffness can be expressed by the ratio between the reaction force and the effective displacement, e.g. $P/2u_0$ for the case excluding thermal loads. Consequently, the effective stiffness of a serpentine interconnect can be further normalized by that of the reduced straight ribbon when $\alpha = -\pi/2$, which can be denoted as k given by $PS/(2\bar{E}wu_0)$. From Ref. [23] the expression of k can be obtained directly as

$$k = \frac{\frac{w^2}{R^2}\left(\cos\alpha - \frac{l}{2R}\sin\alpha\right)}{2\left(A\cos^2\alpha + B\sin 2\alpha + C\frac{w^2}{R^2} + 18\eta\right)} \tag{2}$$

where $\eta = \pi/2 + \alpha$,

$$A = \frac{l^3}{2R^3} + 3\eta\frac{l^2}{R^2} + 12\frac{l}{R} - 12\eta, \tag{3a}$$

$$B = 6\eta\frac{l}{R} + 9, \tag{3b}$$

$$C = \eta\left(\frac{l}{2R}\cos\alpha + \sin\alpha\right)^2 + \frac{l}{2R}\left(\sin^2\alpha + \frac{3\bar{E}}{2G}\cos^2\alpha\right) \tag{3c}$$