INVESTIGATIONS ON THE THERMAL ACTUATION OF CARBON BLACK REINFORCED PDMS COMPOSITE UNI-LAYER AND BI-LAYER CANTILEVER BEAMS

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Abstract: Actuators are the essential components of robots, switches, relays, and many other automatic systems. There are various actuator types based on material, geometry, and stimulus. Nowadays, polymer composite based actuators are gaining importance due to their flexibility, ease of processing, low cost, and easy way of tailoring the properties. Among the polymers, Polydimethylsiloxane (PDMS) is one of the promising polymers for the actuator.

In the present study, unilayer and bilayer cantilever beams of PDMS based composite subjected to a thermal stimulus are investigated. The Finite Element (FE) and the analytical models are developed for unilayer and bilayer polymer composite beams and simulated for actuator response. The deflection behavior of these beams is investigated for a temperature input range of 308K to 368K. The beams are analyzed for varying Carbon Black(CB) content from 5 to 25 Vol% in PDMS polymer and beam thickness from 1mm to 5mm.

It is observed that with an increasing percentage of filler content, the increment in deflection of the bilayer beam is appreciably higher when compared to the unilayer beam. For 25 Vol% of CB, the bilayer beam shows 11.48 times improvement in deflection value. Also, it is noticed that the thickness of the beams influences deflection more compared to the percentage of the CB content. The deflection of the unilayer and bilayer beam is observed to increase linearly with temperature input. At 368K, the bilayer beam deflection is 6.87 times greater than the unilayer. Hence this analysis is the baseline for predicting the actuator performance of the unilayer and bilayer polymer composite beams considering the set of variables.

Key words: Composite beam, Analytical model, FE modeling, polymer material, deflection.

1. INTRODUCTION

Actuators are the transducers responsible for generating the movement/deformation when subject to different stimuli such as electrical, thermal, light, and so on [1-3]. Actuators are popular in many modern devices and systems that operate on electrothermal and photothermal principles. A lab on a chip, biomedical devices, chemical systems, etc. are a few examples used by the uses actuators. In recent times researchers are developing micro and nano-level actuators using various materials like metals, alloys, semiconductors, ceramics, and in particular polymers and their composites [4-6].

Nowadays, many of the actuators are made out of polymeric materials by replacing the traditional material due to their sensitivity to a broad range of stimuli, ease of processing, and excellent mechanical/thermal properties [7, 8]. Also, the potential of polymeric material could be enhanced by reinforcing with different filler material. Recent research is focused on exploring thermally stimulated polymer composite actuators in detail [9, 10].

In the present study, the polymer composite-based actuator beam is modeled, simulated, and analyzed for thermal (temperature) input. Polydimethylsiloxane (PDMS) is selected as the matrix material, with carbon black (CB) as a conductive filler. It's one of the good conductive and less expensive material compared to other fillers attempted in earlier works [11-13], suitable for thermal actuation in addition to improving mechanical properties. The design concept is proposed for beam deflection related to thermal actuators. The model is developed using commercially available software for unilayer and bilayer PDMS based beams with variation in CB content and beam thickness. Analytical and finite element models are used to study the effect of temperature on a deflection, and the behavior of the actuator is compared.

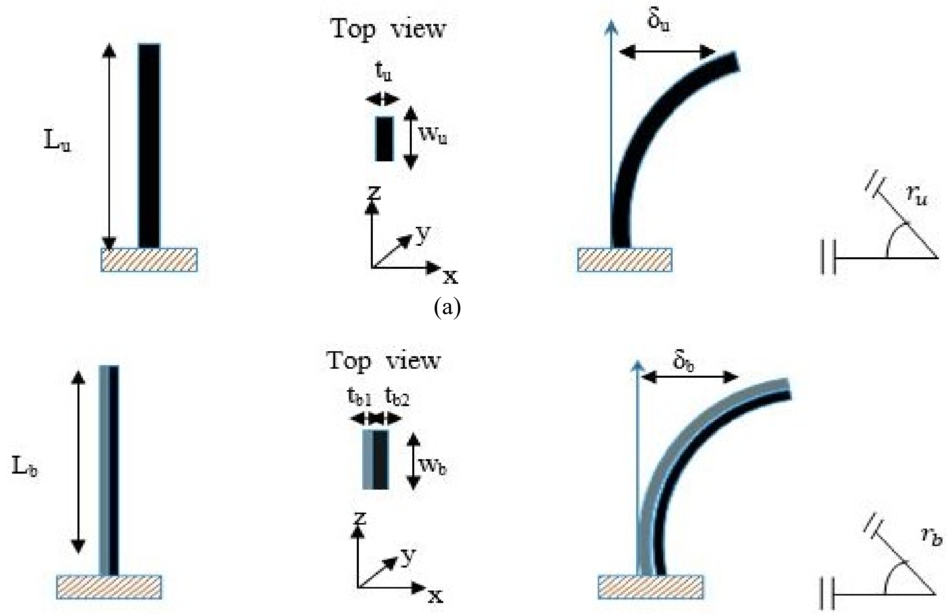
2. METHODOLOGY

An actuator consisting of a polymer composite beam bending upon thermal stimulus is proposed. The schematic representation of a unilayer and bilayer actuator is shown in Figure 1(a) and Figure 1(b). The geometry parameters of the actuator are mentioned in Table 1. The unilayer actuator consists of a polymer composite (PDMS/CB) material with varying filler percentage of CB. Figure 1(b) shows a bilayer actuator, which is a sandwich of plain PDMS and PDMS/CB composites.

Table 1. Unilayer and bilayer beam parameters

Length of the:	unilayer (L_u)	bilayer (L_b)
Width of the:	unilayer (w_u)	bilayer (w_b)
The thickness of the unilayer composite (t_u)		
The thicknesses of the:	plain polymer (PDMS) (t_{b1})	composite (PDMS/CB) bilayer (t_{b2})
CTE of the unilayer composite (α_u)		
CTE of the:	plain polymer (PDMS) (α_{b1})	composite (PDMS/CB) bilayer (α_{b2})
Young's modulus of the:	plain polymer (PDMS) (E_{b1})	composite (PDMS/CB) bilayer (E_{b2})
The radius of curvature:	unilayer (r_u)	bilayer (r_b)
Deflection of the:	unilayer (δ_u)	bilayer (δ_b)
Reference temperature (T_i) and increment of the temperature (T_f)		

Thermal conductivity and coefficient of thermal expansion of the composites estimate the effect of the beam deflection. These properties depend on the filler content, and hence, the study is carried out for different filler content. The thickness of the unilayer and bilayer beams, which also influences the deflection, is incremented from 1mm to 5mm. Particularly in a bilayer, the thicknesses of both the layers are equally incremented (for example, in the case of a 5mm beam, t_{b1}=2.5mm; t_{b2} =2.5mm). In the present study, the performances of unilayer and bilayer actuators are determined using an analytical model and with an FE model.



(b)

Fig. 1. Schematic representation of unilayer and bilayer composite beam

2.1 Material properties

Table 2 shows the properties of plain PDMS and Carbon black. The properties of composites with a different volume percentage of CB are obtained from the rule of the mixture are used in both analytical and FE methods.

Table 2. Material properties used for FE and analytical modeling

Material properties	PDMS [14, 15]	Carbon black [16, 17, 18]
Young modulus (E) MPa	1.84	10.04
Density (ρ) kg/m^3	1030	1890
Poison's ratio (ν)	0.45	0.27
Thermal conductivity (k) W/(m·K)	0.27	6-174
Specific Heat capacity (Cp) J/(kg.K)	1460	690.82
Coefficient of thermal expansion (α) (1/K)	310×10^{-6}	9×10^{-6}

2.2. Analytical model for unilayer and bilayer beam

The analytical model is derived to predict the deflection of the uni and bilayer beams [19, 20]. The deflection of the unilayer beam can be derived using the bending equation for the beam. It is related to the curvature of the beam (i.e. $1/r_u$=M/EI), where E is the elastic modulus of the beam, I is the moment of inertia, and M is the bending moment. The bending (deflection) of the beam due to variation of the temperature in terms of the curvature of the beam is given in equation (1). The beam deflection is subjected to the temperature gradient ($\Delta T=T_i-T_f$) over the thickness of unilayer given in the equation (2):

$$M=EI\,\alpha_u\,\Delta T/t_u \quad (1)$$

$$\delta_u = \alpha_u (T_i-T_f)\, L_u^2 /2t_u \quad (2)$$

The actuation performance of the unilayer beam depends on the material parameters, thickness, and temperatures. The deflection behavior of the unilayer is analyzed using the above equations. In the same way, bilayer stacked configuration is evaluated for the beam deflection. The radius of curvature of the bilayer deformation is given in equation (3). The deflection/bending of the bilayer beam obtained from the radius of the curvature is represented in equation (4).

$$1/r_b = 6E_{b1}/E_{b2}\, t_{b1}/t_{b2}^2 \left[1 + t_{b1}/t_{b2}\left(1 + 4E_{b1}/E_{b2}\right)\right] \left(\alpha_{b1} - \alpha_{b2}\right)\Delta T \quad (3)$$

$$\delta_b = 3L_b^2/t_{b1} + t_{b2}\left[\left(1 + t_{b2}/t_{b1}\right)^2/X\right]\left(\alpha_{b1} - \alpha_{b2}\right)\Delta T \quad (4)$$

Where:

$$X = 3\left(1 + t_{b2}/t_{b1}\right)^2 + \left(1 + t_{b2}E_{b2}/t_{b1}E_{b1}\right)\left(t_{b2}^2 + t_{b1}E_{b1}/t_{b1}^2 + t_{b2}E_{b2}\right)$$

The analytical models of unilayer and bilayer deflection are based on the thermal stress distribution on the composites[21-23]. However, these equations do not have certain material parameters to obtain the bending/deflection, which are otherwise used in FE analysis. Analytical and FE modeling is performed using MATLAB and COMSOL Multiphysics software. The geometrical dimensions, material properties, and other parameters for unilayer and bilayer are given in Tables 1, 2 and 3.

2.3 Finite element modeling

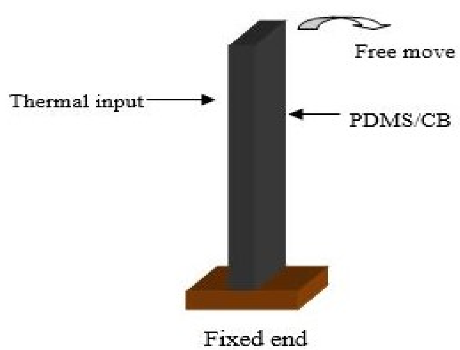
The proposed actuator is modeled as a cantilever beam of various thicknesses. The unilayer beam has been modeled using PDMS composite with varying CB reinforcement. In the same way, the bilayer beam comprises one layer of PDMS and another layer of PDMS composite with varying CB reinforcement, with each layer having equal thickness. When activated thermally (Temperature input on the surface), the beams undergo deformation. The FE modeling for both types of beams is carried out using commercially available COMSOL multiphysics software. The coupled analysis is done using solid mechanics and heat transfer physics under the steady-state condition and applying appropriate boundary conditions.

The configuration of the unilayer and bilayer actuator model and boundary conditions imposed are shown in Figure 2(a) and Figure 2(c). The temperature input is applied on the left vertical surface, and the temperature is varied from 308K to 368K, whereas the remaining surfaces are fixed at a constant temperature of 298K. The linear tetrahedral meshing is adopted and is shown in Figure 2(b) and Figure 2(d). In the case of the bilayer, the two surfaces where the transition of heat takes place from plain PDMS to composite are merged.

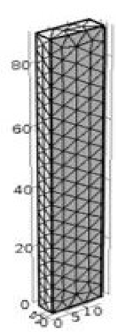
Table 3. Geometry and input parameters used for modeling

Geometry and dimensions	Values
Length of the unilayer(L_u) and bilayer (L_b)	90mm
Width of the unilayer (w_u) and bilayer (w_b)	14mm
The thickness of the unilayer (t_u)	1 to 5mm
The thickness of the bilayer (t_{b1}),(t_{b2})	2.5mm plain polymer; 2.5mm composite
Reference temperature (T_i)	298 K
Varied (applied) temperature (T_f)	308 to 368 K

For every beam of unilayer and bilayer, the thermal input is incremented from room temperature to the maximum in steps of 10°C. The deflections are determined for various thickness and filler content of CB from the modeling. The analysis is performed to investigate the effects of variation in the material properties and thickness with respect to deflection for unilayer and bilayer beams.



(a)



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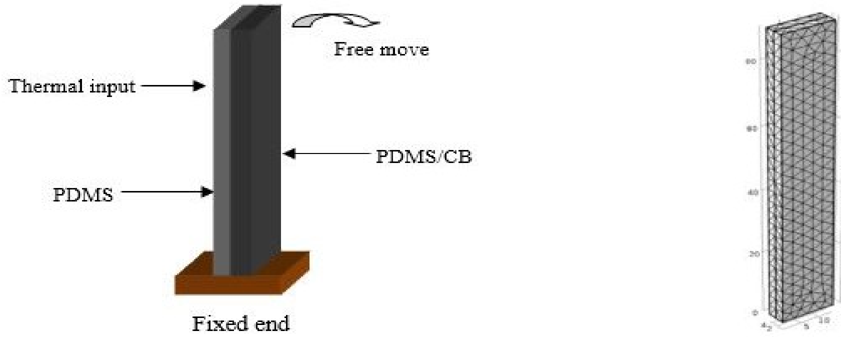


(c) (d)

Fig. 2. (a) Boundary conditions of the unilayer beam (b) FE mesh model for unilayer beam, (c) Boundary conditions of bilayer beam, and (d) FE mesh model for bilayer beam

3. RESULTS AND DISCUSSIONS

The actuation values are presented as deflections of unilayer and bilayer composite beams. The results are presented for different volume percentages of CB content, various thickness of the beams and varying input temperatures in both analytical and FE models.

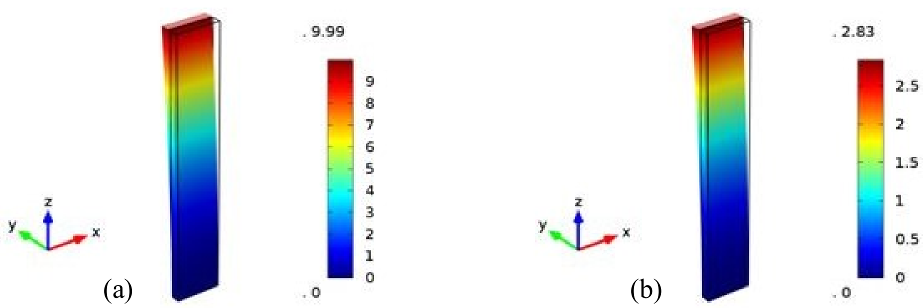
3.1 Deflections of the unilayer actuator

The deflection values of unilayer beams at 338K for varying Vol % of CB and thickness are given in Table 4. It is observed that, as the percentage of the CB increases, the deflection is decreased (owing to decreasing CTE of the composite with increasing Vol% of CB). CTE is observed to be the most dominant parameter for beam deflection under the thermal stimulus. Also, as thickness increases, deflection is reduced for the reason that the heat transfer rate is higher in the thin beams than the thick beams.

Table 4. Deflection (mm) of unilayer beams

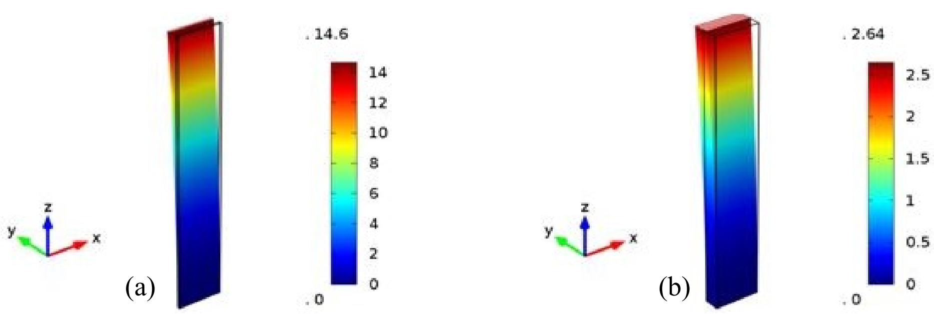
Thickness (mm) / Vol% of CB	**1**	**2**	**3**	**4**	**5**
5	18.9	9.00	5.71	4.21	3.41
10	11.6	5.53	3.51	2.59	2.10
15	8.36	3.98	2.53	1.86	1.51
20	6.53	3.11	1.97	1.46	1.18
25	5.35	2.55	1.62	1.19	0.97

The model of the unilayer is developed, as detailed in the previous section. Deflections are determined for 5 to 25 Vol % CB and thickness ranging from 1mm to 5mm. Figure 3(a) and Figure 3(b) shows the deflection obtained at 368K using the FE model for 5 Vol % and 25 Vol % CB content for the thickness of 3mm. The deflection of the unilayer at two thicknesses of 1mm and 5mm at 368K for CB content of 15 Vol% is shown in Figure 4(a) and Figure 4(b).



(a) (b)

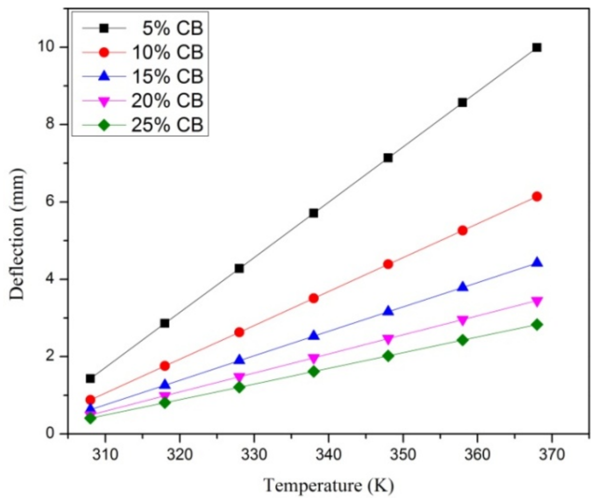
Fig. 3. Deflection of unilayer model: (a) 5 Vol% of CB; (b) 25 Vol%of CB



(a) (b)

Fig. 4. Deflection of a unilayer model for: (a) 1mm thickness; (b) 5mm thickness

Figure 5(a) shows the deflection of the unilayer for different CB Vol% content for a constant layer thickness of 3mm. Figure 5(b) shows the deflection at various thickness for a fixed CB Vol% of 15. In both cases, as the temperature increases, the deflection of the unilayer also increases. At the highest input temperature of 368K, there is a 3.53 times reduction in deflection of the unilayer as the CB content change from 5 Vol% to 25 Vol%. Also, for the beam with 15% Vol of CB at 368K, as the thickness of the unilayer change from 5mm to 1mm, the deflection increases by 5.53 times.



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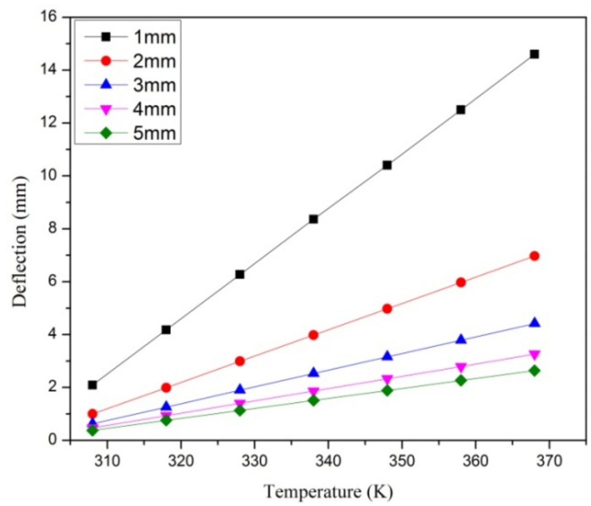


(b)

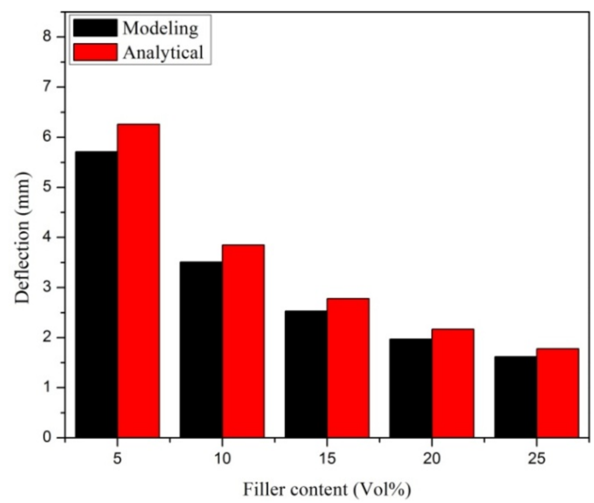
Fig. 5. Deflection of the unilayer beam with temperature change (a) for different Vol% of CB at a constant thickness of 3mm (b) for different thickness of the beam for 15 Vol% of CB.

The results of the FE model are compared with analytical results for different filler content of CB and varying thickness are shown in Figure 6(a) and Figure 6(b). Both the analysis is nearly in agreement with each other. As the filler content and thickness are increased, the deflection of the unilayer is reduced. It is noticed that the results obtained from the analytical study are slightly higher than that of FE modeling. This may be due to the non-consideration of a few of the properties like density and Young's modulus in the analysis.

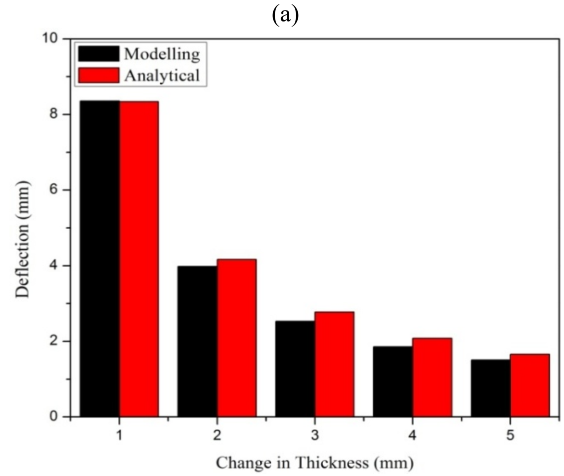
3.2 Deflections of bilayer actuator

The deflection values of bilayer beams at 338K for varying Vol % of CB and thickness are given in Table 5. The deflection of the bilayer increases with an increase in the percentage of CB content. This enhancement is due to, stacking of materials with dissimilar coefficients of thermal expansion. As the thickness of the bilayer increases, a reduction in deflection is observed, this is a similar phenomenon as in unilayer. Still, a more significant deflection is observed compared to unilayer.

The FE modeling of the bilayer is also carried out for varied Vol% of CB and different thicknesses. Figure 7(a) and Figure 7(b) shows the deflection of 3mm thick bilayer (PDMS=1.5mm and PDMS/CB=1.5mm) with different CB content (5Vol% and 25 Vol %). Similarly, the response at different thicknesses of the bilayer (1mm and 5mm) with the arrest of 15 Vol % CB is shown in Figure 8(a) and Figure 8(b).



(a)



(b)

Fig. 6. Comparison of unilayer models with a change in (a) Vol% CB content (b) Thickness of the beam

Table 5. Deflection (mm) values of bilayer beams

Vol% of CB \ Thickness (mm)	1	2	3	4	5
5	56.3	27.7	18.0	13.5	10.5
10	57.5	28.3	18.4	13.7	10.8
15	57.9	28.5	18.5	13.9	10.9
20	58.0	28.6	18.6	13.9	10.9
25	58.0	28.6	18.6	13.9	10.9

Figure 9(a) and Figure 9(b) shows the deflection of a bilayer beam for different percentage of CB and thickness, respectively. Similar to the behavior of the unilayer beams, the deflection of the bilayer beams increases with temperature input. However, for every volume fraction of CB, at each temperature input, the deflection values are significantly higher as compared to unilayer.

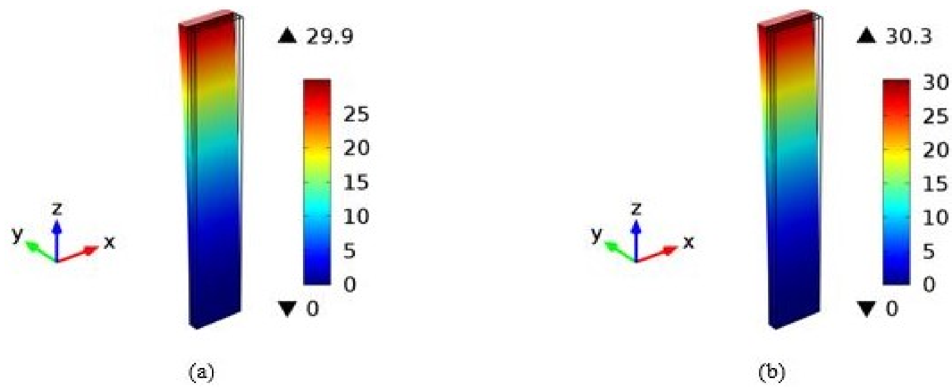


Fig. 7. Deflection of bilayer model for under different volume percentage of CB for 3mm thickness (a) 5 Vol% (b) 25 Vol%

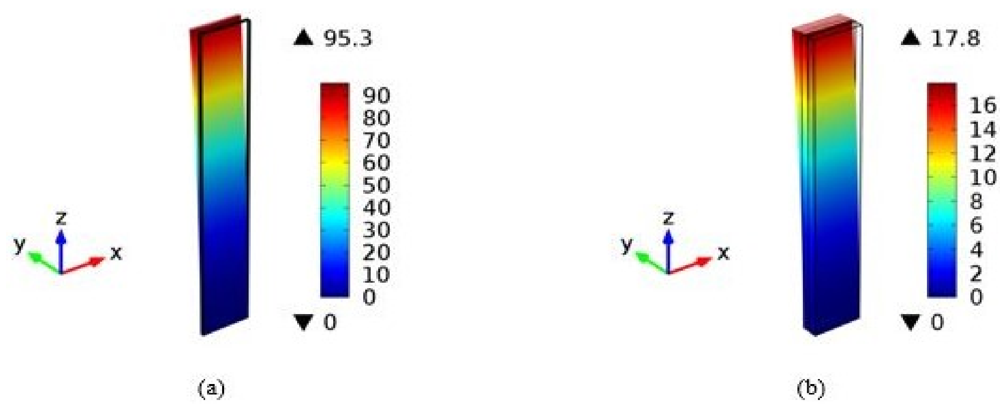


Fig. 8. Deflection of bilayer model for the at different thickness of the layers for 15 Vol % CB (a) 1mm (b) 5mm

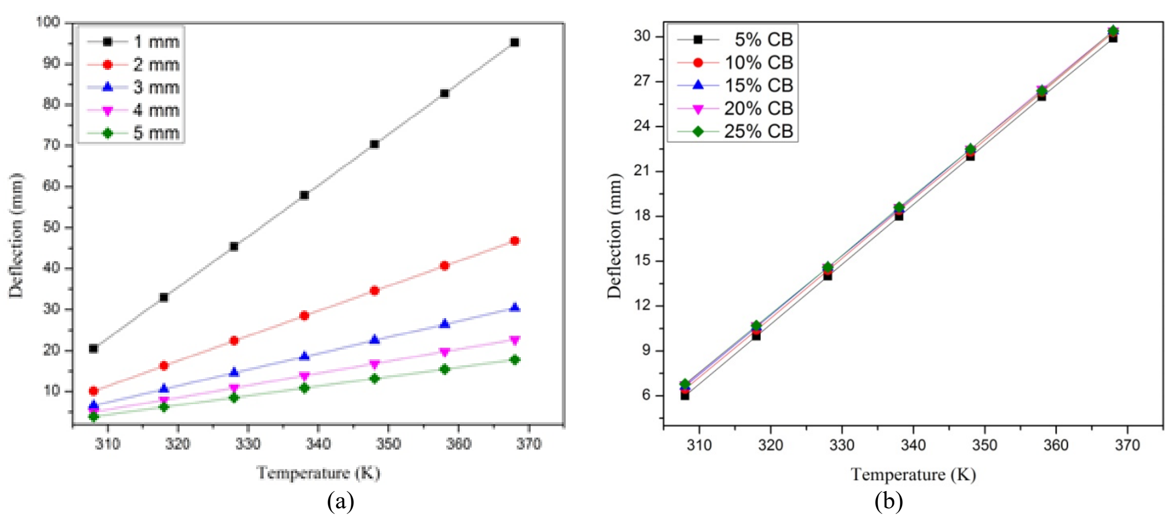


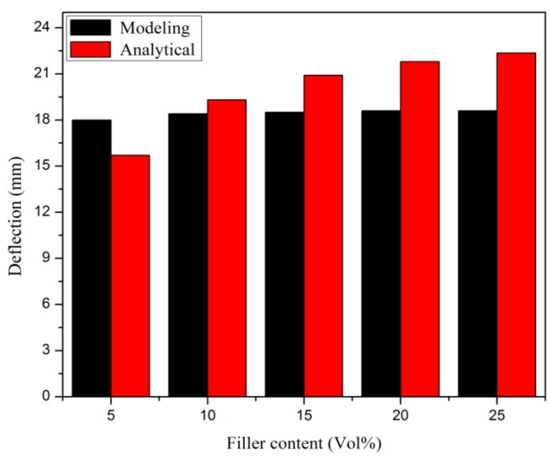
Fig. 9. Deflection of the bilayer beam with a change in (a) Vol% of CB content, (b) Thickness of the beam concerning temperature change

3.3 Comparison of unilayer and bilayer

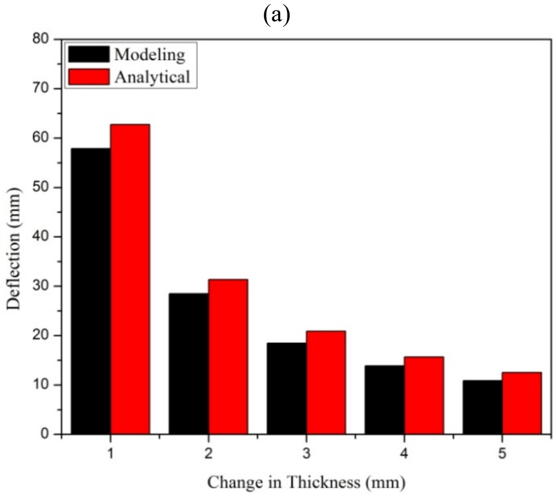
The results of the FE model are compared with analytical results for different filler content of CB and varying thickness are shown in Figure 10(a) and Figure 10(b). Figure 11 (a), Figure 11(b) and Figure 11(c) shows the deflection for varying filler content, thickness, and temperature of the unilayer and bilayer beams. As the percentage of filler content (CB) increases 11.48 times (for 3mm thickness at 368K), increment in bilayer deflection is observed when compared to unilayer. For particular thickness, the bilayer beam deflects higher than the unilayer. Also, observed that thickness of the unilayer and bilayer influence more compared to the percentage of the CB content.

The deflection of the unilayer and bilayer beam increases linearly with a temperature input range of 308K to 368K. In the same context, the bilayer beam deflection is 6.87 times more than the unilayer (for 15 Vol% at 3mm).

The present analysis is the baseline for predicting the actuator performance of the unilayer and bilayer polymer composite beam under different influencing parameters. Hence, this analysis is solid proof for developing the realistic thermal actuator.

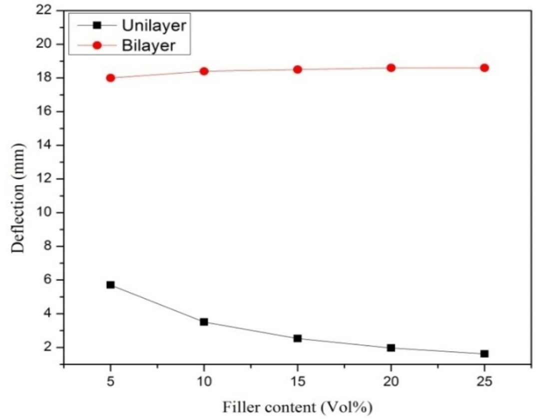


(a)

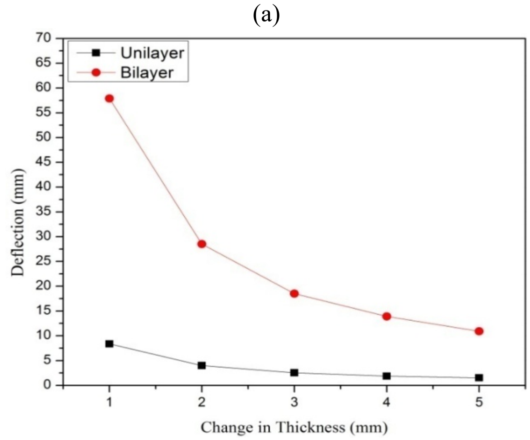


(b)

Fig. 10. Comparison of bilayer models with a change in (a) Vol% CB content, (b) Thickness of the beam



(a)



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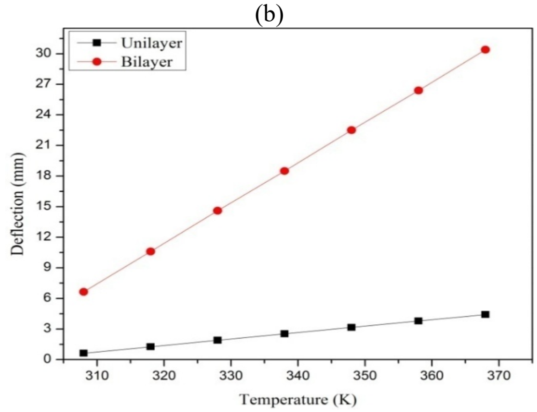

(c)

Fig.11. Comparison of unilayer and bilayer with a change in (a) Vol% CB content (b) Thickness of the beam (c) Temperature of the beam

4. CONCLUSIONS

In the present study, investigation of unilayer and bilayer actuator for thermal input using PDMS and PDMS/CB composite are explored. The beam deflection computed using FE and analytical models under different volume percentages of CB and beam thickness, along with the changing temperature inputs, are discussed.

The unilayer beam shows 3.53 times increment in deflection for 5 Vol% of CB in PDMS when compared to 25 Vol% of CB as well as 5.53 times increment for thickness change from 5mm to 1mm. The change in thickness is more influential than the percentage of filler for deflection of beams. In the case of the bilayer, the stacking of the PDMS and PDMS/CB composite maximizes the deflection of the beam. As a thermal actuator, a higher deflection of the beam can be obtained at lower temperature inputs.

The bilayer beam showed 11.48 times more deflection than the unilayer at 25 Vol% CB content. At 368K, the bilayer beam deflection is 6.87 times greater than the unilayer. Analytical and FE model results for the unilayer and bilayer under all conditions are very close to each other.

Thus, the present study reveals that the geometry and material composition significantly influence the actuation performance of the thermal actuator. These predictions are a base platform for the development of realistic actuators for the microrobots, micro switches, energy harvesting, and sensing and actuator applications.

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