

Impact of carbon dioxide on the stability of the small-scale structures by trapping the material properties

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Abstract. The existence of active material in the environment causes the small-scale systems to be sensitive to the actual environment. Carbon dioxide is one of the active materials that exists a lot in the air conditions of the living environment. However, in some applications, the carbon dioxide-coated is used to improve the performance of systems against the destructive factors such as the corrosion; nevertheless, in the current research, the stability analysis of a carbon dioxide capture mechanism-coated beam is investigated according to the mathematical simulation of a rectangular composite beam utilizing the modified couple stress theory. The composite mechanism of carbon dioxide trapping is made of a polyacrylonitrile substrate that supports a cross-link polydimethylsiloxane gutter layer as the carbon dioxide mechanism trapping. Three novel types of carbon dioxide trapping mechanism involving methacrylate, poly (ethylene glycol) methyl ether methacrylate, and three pedant methacrylates are considered, which were introduced by Fu *et al.* (2016). Finally, according to introducing the methodology of carbon dioxide (CO₂) trapping, the impact of various effective parameters on the stability of composite beams will be analyzed in detail.

Keywords: carbon dioxide trapping; mathematical modelling; stability analysis; trapping material mechanism

1. Introduction

The concentration of anthropogenic carbon dioxide in ambient air is rising due to significant industrial sources of emissions such as fossil fuel power plants, chemical processing, and deforestation. This is a critical difficulty in the continuous attempt to create more efficient and enhanced carbon dioxide (CO₂) capture and sequestration processes in order to lessen the impact of greenhouse gases on global climate change. The direct absorption of carbon dioxide from the atmosphere by plants is one suggested solution to these emissions. Carbon dioxide collection from the atmosphere, followed by separation and recovery on a massive scale, is an area that has recently piqued the attention of experts all over the globe. Isotopic carbon dioxide may be absorbed from ambient air at normal temperature and pressure using clay-based solids that contain several viable amines with different densities and adsorption sites for the three most frequent carbon dioxide (¹²C¹⁶O¹⁸O, ¹²C¹⁶O₂, and ¹³C¹⁶O₂) isotopes (Das *et al.* 2016). On the other hand, due to the high heat capacity of aqueous amine, which makes the endothermic regeneration step highly energy-intensive, the liquid phase amine scrubbing process is a well-established industrial technique for carbon dioxide capture due to amines' ability to chemisorb acidic carbon dioxide, has a high regeneration cost. Furthermore, the gas's limited thermal stability due to solvent vapour contamination, equipment corrosion, and oxidative amine degradation leads to high regeneration costs (Tian *et al.* 2022, Yin *et al.* 2022a, Yin *et al.* 2022b).

Many ways have been suggested to trap carbon dioxide, which has advantages and disadvantages in their performance (Gray 1985, Brown and Zeiler 1993, Benson and Surles 2006, Cooperband and Cardé 2006, Anderson *et al.* 2009, Pehnt and Henkel 2009, Wang *et al.* 2009, Wang *et al.* 2013). Mulcahey and Taylor (1992) suggested a solid surface and also a sorbent surface in order to capture the carbon dioxide that this method was the basis of many new methodologies to capture the carbon dioxide. Wu *et al.* (2019) exemplified a dynamic porous coordination polymer to facilitate carbon dioxide trapping. This process might be identified and characterized using X-ray structural analysis. The porous coordination polymer has outstanding catalytic activity and transformation kinetics, as well as considerable size selectivity for a range of organic and inorganic substrates due to its strong affinity for carbon dioxide and the confinement effect. Using a heterogeneity-induced trapping mechanism in potential synergy with a self-sealing gravitational trapping mechanism, Dai *et al.* (2018) explored the efficacy of carbon dioxide storage in marine sediments that are both secure and long-lasting. Yang *et al.* (2012) introduced the novel methodology of a non-amine-containing porous solid for trapping carbon dioxide. Lin *et al.* (2010) reviewed and suggested some techniques for trapping carbon dioxide, methane, and Hydrogen via imperfect solid surfaces due to the porosity.

Investigating the stability of structures (Ghadiri and Shafiei 2016b, Ghadiri *et al.* 2016a, b, c, d, Shafiei *et al.* 2016b), especially the mechanism of carbon dioxide trapping, is essential to improve the quality of this technology (Azimi *et al.* 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al.* 2016a, e, g). These structures are affected by different loading and different conditions, and information on their stability is necessary (Ebrahimi and Shafiei 2016,

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Table 1 Young's modulus of utilized material (Fu *et al.* 2016)

| | polyacrylonitrile | T1 | T2 | T3 |
|----------------------|-------------------|--------|-------|------|
| Young's modulus (Pa) | 894e6 | 63.6e6 | 105e6 | 67e4 |

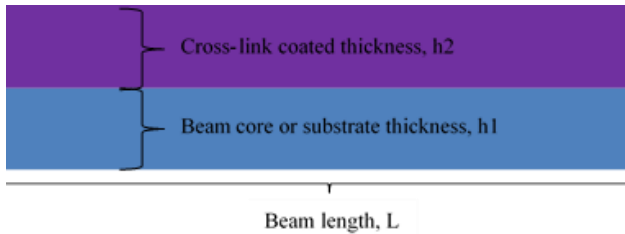


Fig. 1 A schematic of the assembled ultrathin film composite beam made by a cross-link polydimethylsiloxane initiator on a polyacrylonitrile substrate.

Shafiei *et al.* 2016c, d, f, Ebrahimi *et al.* 2017, Shivanian *et al.* 2017). The exploration of buckling analysis of different structures is attracted by many researchers, and this analysis provided helpful information in structural analysis. Sulem *et al.* (2011) investigated the stability analysis due to the dynamic behavior of the granular material under the shear heating. Rameshbabu *et al.* (2017) studied the stability of a nanocrystalline alloy in thermal conditions and under high-temperature thermal shock. Yin *et al.* (2017) proposed the novel theory to investigate the stability analysis due to the quantitative analysis of bi-directional separation microstructures. Lobato *et al.* (2020) worked on the chemical stability of functionally graded nanostructures made by magnetic and SILICA phases. Komijani *et al.* (2014) presented a micro-sized actuators beam made of functional piezoelectric material in the thermal environment to investigate the stability analysis under the nonlinear effects. SoltanRezaee *et al.* (2019) theoretically investigated the stability of micro-scale piezoelectric wires in order to study the surface effect, electronic force, and other effective parameters. Moyers-Gonzalez *et al.* (2011) analyzed the impact of Reynolds numbers on the stability of microstructures plane-Poiseuille flow. Peelaers *et al.* (2009) examined the phonon dispersion relations and sound velocities as a function of wire diameters in order to assess the structural stability of nanowires. Song *et al.* (2007) reported the thermal gravimetry behavior of microscale capsules made by nano-particles in order to investigate thermal stability. Wang *et al.* (2011) worked on both thermogravimetric and differential thermal analyses of microstructures composed of copper oxide and aluminum for the thermal stability investigation.

As reviewed (Ghadiri *et al.* 2017a, b, Mirjavadi *et al.* 2017b, c, Shafiei *et al.* 2017a, b), there are a lot of mechanisms and technologies for trapping carbon dioxide (Ehyaeei *et al.* 2017, Ghadiri *et al.* 2017c, d, Mirjavadi *et al.* 2017d, Shafiei and Kazemi 2017b, Shafiei *et al.* 2017c), they usually are the polymetric structures supported by a strong substrate to improve the mechanical properties (Ebrahimi and Shafiei 2017, Ghadiri *et al.* 2017e, Mirjavadi *et al.* 2017a, Shafiei and Kazemi 2017a, Shafiei *et al.*

2017d, Azimi *et al.* 2018). Enormous analyses have been done on these structures (Shafiei and She 2018, Shafiei *et al.* 2019, 2020), but the stability analysis due to the mechanical buckling behavior still needs study. In the present paper, an ultrathin film composite beam is assumed to be made by a cross-link polydimethylsiloxane initiator as the mechanism of carbon dioxide trapping supported by a polyacrylonitrile substrate. To investigate the buckling behavior of the ultrathin film composite beam, the conservation energy method is employed to generate the general equations based on the classical beam theory and modified couple stress theory to model the size impact of small-scale structures. A numerical approach is used to solve the governing equations, and different parameters have been analyzed in detail.

2. Methodology

2.1 Geometric and material structures of carbon dioxide trapping mechanism

The theoretical investigation is done in the present paper, in which a small-scale ultrathin film composite (UFC) beam is assumed. UFC beam length is indicated with 'L', the UFC beam width is 'wb', and the UFC beam thickness is 'h=h1+h2', which means the UFC beam thickness is the sum of substrate thickness (h1) and cross-link polydimethylsiloxane gutter layer (h2) (Habibi *et al.* 2016, 2018b, Ebrahimi *et al.* 2019a, Esmailpoor Hajilak *et al.* 2019). The considered structures are made with a substrate covered by a coating cross-link polydimethylsiloxane gutter, as shown in Fig. 1 (Habibi *et al.* 2018a, 2019b, d, e, Pourjabari *et al.* 2019, Safarpour *et al.* 2019a). The covered layer is used to trap the carbon dioxide according to a cross-linked coating introduced by Fu *et al.* (2016) i.e., a constant pressure variable volume device was used to validate the UFC membranes' capacity to separate carbon dioxide from N₂. In this trapping CO₂ method, polyacrylonitrile (PAN) substrate is used to improve the mechanical characteristics for the stability of the case study, and a cross-link polydimethylsiloxane initiator was coated on it. The detail of geometry is shown in Fig. 1, and the mechanical properties of the used materials are listed in Table 1. In this study, three types of cross-link coated involving T1 (over 40 trinket methacrylate groups per chain, Mn=20kDa), T2 (a couple of poly(ethylene glycol) methyl ether methacrylate, Mn~500 Da, and methacrylate parties, Mn~570 Da), and T3 (three pedant methacrylates, Mn=1.5kDa) is assumed (Fig. 2), which have different performances in separating carbon dioxide/N₂ according to a one-step continuous assembly of polymers (CAP) procedure (Fu *et al.* 2016).

2.2 Motion equations of UFC beam

The classical beam theory correlated with the modified couple stress theory (Habibi *et al.* 2019a, Safarpour *et al.* 2019b, Alipour *et al.* 2020, Ebrahimi *et al.* 2020a, Chen *et al.* 2022) is considered to derive the motion equations of the small-scale ultrathin film composite beam (Habibi *et al.*

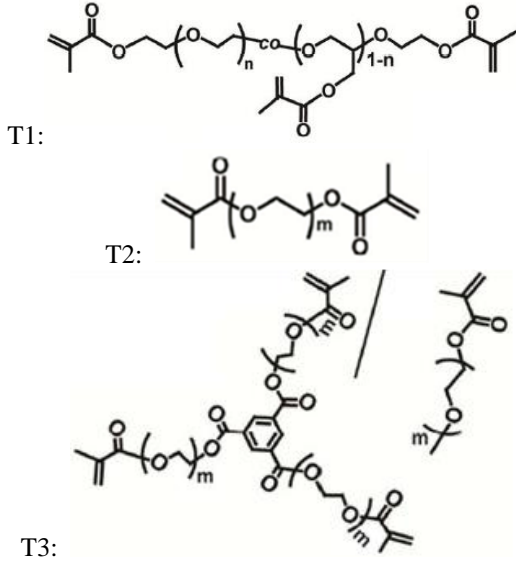


Fig. 2 Chemical structures of the cross-link polydimethylsiloxane gutter layer (Fu *et al.* 2016).

2017, Safarpour *et al.* 2018, 2022, Habibi *et al.* 2019c, Ghazanfari *et al.* 2020). The governing equations and associated boundary conditions will be derived using the following equation based on the conservation energy principle (Mohammadgholiha *et al.* 2019, Ebrahimi *et al.* 2019b, c, 2020b, Mohammadi *et al.* 2019, Habibi *et al.* 2020, Shariati *et al.* 2020a, Shokrgozar *et al.* 2020).

$$\delta \Pi = \delta S + \delta V = 0 \quad (1)$$

‘S’ is the strain energy due to the internal energy of the system (Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, b, Oyarhossein *et al.* 2020, Shariati *et al.* 2020b), and ‘V’ is the energy of external work applied on the UFC beam (Hashemi *et al.* 2019, Al-Furjan *et al.* 2020e, Cheshmeh *et al.* 2020, Lori *et al.* 2020, Najaafi *et al.* 2020, Shariati *et al.* 2020c). The strain energy of the UFC beam on the basis of the couple stress theory can be calculated as follows:

$$S = \frac{1}{2} \iiint (m : \chi + \sigma : \varepsilon) dv \quad (2)$$

In the presented equation, ‘m’ is the deviatoric part of the stress tensor, and ‘ χ ’ is the symmetric curvature tensor applied to modelling the small-scale impact based on the modified couple stress theory (Al-Furjan *et al.* 2020c, Al-Furjan *et al.* 2020d, Al-Furjan *et al.* 2020f, Bai *et al.* 2020, Li *et al.* 2020a, Zhang *et al.* 2020, Guo *et al.* 2021b, Liu *et al.* 2021a). Also, ‘ ε ’ and ‘ σ ’ are the strains and stresses tensors. The explained parameters are defined as follows:

$$\sigma_{ij} = E \varepsilon_{ij} \quad (3a)$$

$$m = 2l^2 \kappa \chi \quad (3b)$$

$$\varepsilon_{ij} = \frac{1}{2} u_{i,j} \quad (3c)$$

$$\chi_{ij} = \frac{1}{2} \left(\nabla \left(\frac{1}{2} \text{curl}(u_i) \right) + \left(\nabla \left(\frac{1}{2} \text{curl}(u_i) \right) \right)^T \right) \quad (3d)$$

where ‘l’ is the small-scale parameter, and ‘ κ ’ is the Lamé constant. Also, ‘ u_i ’ is the displacement fields defined as follows along the x-axis (u_1), y-axis (u_2), and z-axis (u_3) based on the classical beam theory (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, Al-Furjan *et al.* 2020b, Li *et al.* 2020b, Zare *et al.* 2020, Dai *et al.* 2021b).

$$u_1(x, y, z) = u - z \frac{\partial w(x)}{\partial x} \quad (4a)$$

$$u_2(x, y, z) = 0 \quad (4b)$$

$$u_3(x, y, z) = w(x) \quad (4c)$$

‘w’ is the lateral displacement, and ‘ $\partial w / \partial x$ ’ is the rotation component. Utilizing the definition of the parameters (Liu *et al.* 2020b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Liu *et al.* 2021b, Zhang *et al.* 2021), the strain energy will be presented as follows:

$$\delta S = \iint \left\{ \begin{array}{l} E_s \int_0^{D_1} \left[\begin{array}{l} \left(\frac{\partial u}{\partial x} \right) \delta \left(\frac{\partial u}{\partial x} \right) \\ + \frac{1}{2} \left(\frac{\partial w}{\partial x} \right)^3 \delta \left(\frac{\partial w}{\partial x} \right) \\ + \frac{\partial u}{\partial x} \left(\frac{\partial w}{\partial x} \right) \delta \left(\frac{\partial w}{\partial x} \right) \\ + \frac{1}{2} \left(\frac{\partial w}{\partial x} \right)^2 \delta \left(\frac{\partial u}{\partial x} \right) \\ + z^2 \left(\frac{\partial^2 w}{\partial x^2} \right) \delta \left(\frac{\partial^2 w}{\partial x^2} \right) \\ + \frac{l^2}{2(1+\nu)} \left(\frac{\partial^2 w}{\partial x^2} \right) \delta \left(\frac{\partial^2 w}{\partial x^2} \right) \end{array} \right] dz \\ + E_L \int_{D_1}^{D_2} \left[\begin{array}{l} \left(\frac{\partial u}{\partial x} \right) \delta \left(\frac{\partial u}{\partial x} \right) \\ + \frac{1}{2} \left(\frac{\partial w}{\partial x} \right)^3 \delta \left(\frac{\partial w}{\partial x} \right) \\ + \frac{\partial u}{\partial x} \left(\frac{\partial w}{\partial x} \right) \delta \left(\frac{\partial w}{\partial x} \right) \\ + \frac{1}{2} \left(\frac{\partial w}{\partial x} \right)^2 \delta \left(\frac{\partial u}{\partial x} \right) \\ + z^2 \left(\frac{\partial^2 w}{\partial x^2} \right) \delta \left(\frac{\partial^2 w}{\partial x^2} \right) \\ + \frac{l^2}{2(1+\nu)} \left(\frac{\partial^2 w}{\partial x^2} \right) \delta \left(\frac{\partial^2 w}{\partial x^2} \right) \end{array} \right] dz \end{array} \right\} dy dx \quad (5)$$

‘ E_s ’ is the Young’s modulus of the substrate (polyacrylonitrile), and ‘ E_L ’ is the Young’s modulus of the cross-link polydimethylsiloxane gutter layer. The mechanical load (F) is applied in the axial axis in order to analyze the stability of the UFC beam due to the buckling behavior that the energy of the external energy is given as follows:

$$y \delta V = \iiint_0^{D_2} F \left(\frac{\partial w}{\partial x} \right) \delta \left(\frac{\partial w}{\partial x} \right) dz dy dx \quad (6)$$

The following Euler-Lagrange equations (Liu *et al.* 2020a, Wang *et al.* 2020, Zhou *et al.* 2020, Dai *et al.* 2021a, Guo *et al.* 2021a, Shao *et al.* 2021, Wu and Habibi 2021) will be obtained by substituting the Eqs. (5) and (6) into Eq. (1).

$$\delta u: A_s \frac{\partial^2 u_s}{\partial x^2} + A_L \frac{\partial^2 u_L}{\partial x^2} = \frac{\partial F}{\partial x} \quad (7a)$$

$$\delta w: (C_S + D_S l^2) \frac{\partial^4 w_S}{\partial x^4} + (C_L + D_L l^2) \frac{\partial^4 w_L}{\partial x^4} + F \frac{\partial^2 w}{\partial x^2} = 0 \quad (7b)$$

And the boundary conditions are:

$$u = 0 \quad \text{Or} \quad A_S \frac{\partial u_S}{\partial x} + A_L \frac{\partial u_L}{\partial x} - F = 0 \quad (7c)$$

$$w = 0 \quad \text{Or} \quad \begin{aligned} & A_S \frac{\partial u_S}{\partial x} \frac{\partial w_S}{\partial x} + A_L \frac{\partial u_L}{\partial x} \frac{\partial w_S}{\partial x} - F \frac{\partial w}{\partial x} \\ & - (C_S + D_S l^2) \frac{\partial^3 w_S}{\partial x^3} + (C_L + D_L l^2) \frac{\partial^3 w_L}{\partial x^3} = 0 \end{aligned} \quad (7d)$$

$$\partial w / \partial x \quad \text{Or} \quad \begin{aligned} & (C_S + D_S l^2) \frac{\partial^2 w_S}{\partial x^2} + (C_L + D_L l^2) \frac{\partial^2 w_L}{\partial x^2} \\ & = 0 \end{aligned} \quad (7e)$$

3. Result and discussion

This section uses the numerical procedure to investigate the stability analysis of a small-scale ultrathin film composite beam due to the buckling analysis of the mentioned structures. The generalized differential quadrature method (GDQM) is the numerical approach employed to solve the derived eigenvalue problem. In this methodology, the derivative functions reform the weighting

$$F = \text{eigenvalue} \left(\begin{array}{ccc|cc} A_S \sum_{s=1}^n C_{rs}^{(2)} & A_L \sum_{s=1}^n C_{rs}^{(2)} & 0 & 0 & 0 \\ 0 & 0 & (C_S + D_S l^2) \sum_{s=1}^n C_{rs}^{(4)} w_S & (C_L + D_L l^2) \sum_{s=1}^n C_{rs}^{(4)} w_L & \\ \hline \sum_{s=1}^n C_{rs}^{(1)} & \sum_{s=1}^n C_{rs}^{(1)} & \sum_{s=1}^n C_{rs}^{(1)} & \sum_{s=1}^n C_{rs}^{(1)} & \\ 0 & 0 & \sum_{s=1}^n C_{rs}^{(2)} & \sum_{s=1}^n C_{rs}^{(2)} & \end{array} \right) \begin{pmatrix} u_S \\ u_L \\ w_S \\ w_L \end{pmatrix} \quad (13)$$

coefficient matrices according to the following equation (Zhao *et al.*, Huang *et al.* 2021b, Jiao *et al.* 2021, Moradi *et al.* 2021, Xu *et al.* 2021).

$$\left. \frac{\partial^r f(x)}{\partial x^r} \right|_{x=x_p} = \sum_{j=1}^n C_{ij}^{(r)} f(x_j) \quad (8)$$

' r ' is the order of derivative function of 'f', and 'C' is the weighting coefficient represented as follows.

$$C_{ij}^{(r)} = r \left[C_{ij}^{(r-1)} C_{ij}^{(1)} - \frac{C_{ij}^{(r-1)}}{(x_i - x_j)} \right], i, j \quad (9a)$$

$$= 1, 2, \dots, n, i \neq j \quad \text{and} \quad 2 \leq r \leq n - 1$$

$$C_{ii}^{(r)} = - \sum_{j=1, j \neq i}^n C_{ij}^{(r)}, i, j = 1, 2, \dots, n \text{ and } 1 \leq r \leq n - 1 \quad (9b)$$

where

$$C_{ij}^{(1)} = \frac{\tilde{M}(x_i)}{(x_i - x_j) \tilde{M}(x_j)}, \text{ if } i \neq j \quad (9c)$$

$$C_{ij}^{(1)} = - \sum_{j=1, j \neq i}^n C_{ij}^{(1)}, \text{ if } i = j \quad (9d)$$

' x ' is the mesh point in the UFC beam length and is estimated as follows.

$$x_i = \frac{L}{2} \left(1 - \cos \left(\frac{(i-1)\pi}{(N-1)} \right) \right) \quad i = 1, 2, 3, \dots, n \quad (10)$$

Also, the function of 'M' is also characterized as follows.

$$\tilde{M}(x_i) = \prod_{j=1, j \neq i}^n (x_i - x_j) \quad (11)$$

To calculate the buckling load of the UFC beam based on the eigenvalue problem, the following equations will be used by substituting derivative matrices (Eq. (9)) into governing equations (Eqs. (7)).

$$\delta u: A_S \sum_{s=1}^n C_{rs}^{(2)} u_S + A_L \sum_{s=1}^n C_{rs}^{(2)} u_L = \sum_{s=1}^n C_{rs}^{(1)} F \quad (12a)$$

$$\delta w: (C_S + D_S l^2) \sum_{s=1}^n C_{rs}^{(4)} w_S + (C_L + D_L l^2) \sum_{s=1}^n C_{rs}^{(4)} w_L + F \sum_{s=1}^n C_{rs}^{(2)} w = 0 \quad (12b)$$

Finally, by assembling the boundary conditions equations with the following equation, the buckling load of the UFC beam will be obtained (Ma *et al.*, Hou *et al.* 2021, Huang *et al.* 2021c, Liu *et al.* 2021c, Yu *et al.* 2022).

4. Results and discussion

The framework of the present study is the stability analysis of the UFC beam made of a cross-link polydimethylsiloxane gutter layer on a polyacrylonitrile substrate, that the upper layer is used to trap the carbon dioxide. Since the current topic is not investigated yet, the derived governing equations compared to the published study of He and Cai (2021) in Table 2, regarding the buckling behavior of the small-scale homogeneous beam. The comparison of the results proves that the governing equations and numerical solution methodology are valid, and an excellent validation of the results will be made.

It is necessary to introduce several dimensionless parameters before proceeding to the discussion of the computed findings. These include the dimensionless buckling load (Λ) and the dimensionless length scale parameter (Γ), which will be discussed further in the following presentation.

$$\Lambda = F \times \frac{\pi L^2}{E_S I} \quad (14a)$$

$$\Gamma^2 = \frac{l}{h} \quad (14b)$$

Table 3 presents the static analysis results due to the buckling behavior of the small-scale beam used for trapping

Table 2 Validation of presented results of buckling load ($F \times L^2/E_s I$) regarding the results of Cay for the homogeneous small-scale pinned beam

| | l/h=0 | l/h=0.2 | l/h=0.4 | l/h=0.6 | l/h=0.8 | l/h=1.0 |
|-------------------|----------|----------|-----------|-----------|-----------|-----------|
| Present study | 9.868657 | 115.8474 | 167.3334 | 253.1558 | 373.296 | 9.868657 |
| He and Cai (2021) | 9.86964 | 115.859 | 167.35012 | 253.18113 | 373.33333 | 527.80966 |

Table 3 Mechanical stability analysis of UFC beam for three different types of cross-linked mechanisms of trapping CO₂ versus the different boundary conditions and thickness layers

| | Thickness of layers | T1 | T2 | T3 |
|----------------|-----------------------------|----------|----------|----------|
| Fully pinned | Without substrate, h=h2 | 2.205816 | 3.641677 | 0.023237 |
| | Non-equal thickness, 4h1=h2 | 8.380391 | 9.508415 | 6.665739 |
| | Equal thickness, h1=h2 | 12.18998 | 13.12807 | 10.76402 |
| | Non-equal thickness, h1=4h2 | 26.06714 | 26.31338 | 25.69284 |
| | Without cross-linked, h=h1 | 31.00628 | 31.00628 | 31.00628 |
| Clamped-Pinned | Without substrate, h=h2 | 4.512544 | 7.449955 | 0.047538 |
| | Non-equal thickness, 4h1=h2 | 17.14417 | 19.45183 | 13.63643 |
| | Equal thickness, h1=h2 | 24.93762 | 26.85673 | 22.02049 |
| | Non-equal thickness, h1=4h2 | 53.32681 | 53.83056 | 52.56108 |
| | Without cross-linked, h=h1 | 63.43104 | 63.43104 | 63.43104 |
| Fully clamped | Without substrate, h=h2 | 8.823263 | 14.56671 | 0.092949 |
| | Non-equal thickness, 4h1=h2 | 33.52156 | 38.03366 | 26.66295 |
| | Equal thickness, h1=h2 | 48.7599 | 52.51229 | 43.0561 |
| | Non-equal thickness, h1=4h2 | 104.2685 | 105.2535 | 102.7713 |
| | Without cross-linked, h=h1 | 124.0251 | 124.0251 | 124.0251 |

Table 4 The mechanical buckling load (Λ) of fully pinned UFC beam versus the small-scale parameters (Γ) and different mechanisms of carbon dioxide trapping, h1=h2

| | T1 | T2 | T3 |
|--------------------------------|----------|----------|----------|
| Macro structures, $\Gamma=0$ | 12.18998 | 13.12807 | 10.76402 |
| Micro structures, $\Gamma=0.1$ | 12.56546 | 13.52351 | 11.10916 |
| Micro structures, $\Gamma=0.2$ | 13.69189 | 14.70983 | 12.14458 |
| Micro structures, $\Gamma=0.3$ | 15.56929 | 16.68703 | 13.87028 |
| Micro structures, $\Gamma=0.4$ | 18.19765 | 19.45511 | 16.28626 |
| Micro structures, $\Gamma=0.5$ | 21.57697 | 23.01406 | 19.39251 |
| Micro structures, $\Gamma=0.6$ | 25.70724 | 27.3639 | 23.18905 |
| Micro structures, $\Gamma=0.7$ | 30.58848 | 32.50462 | 27.67586 |
| Micro structures, $\Gamma=0.8$ | 36.22068 | 38.43621 | 32.85295 |
| Micro structures, $\Gamma=0.9$ | 42.60383 | 45.15869 | 38.72032 |
| Micro structures, $\Gamma=1.0$ | 49.73794 | 52.67204 | 45.27798 |

carbon dioxide. The polymeric mechanism of carbon dioxide capture is considered for three different chemical structures involving methacrylate (T1), a couple of poly(ethylene glycol) methyl ether methacrylate (T2), and three pedant methacrylates (T3) that Fu *et al.* (2016) suggested. Fu *et al.* (2016) showed that the mentioned chemical structures have a good response in chemical stability resistance and an excellent ability to trap carbon

dioxide. Also, Fu *et al.* (2016) found the performance of T3 to respond to carbon dioxide trapping is better than other structures (T1 and T2). So, in Table 3, the mechanical stability results of the mentioned chemical structures will be calculated and analyzed. Since the stability of mechanical buckling behavior of structures depends on the boundary conditions, in this section, to investigate the stability analysis, the pinned and clamped types of boundary

Table 5 The mechanical buckling load (Λ) of clamped-pinned UFC beam versus the small-scale parameters (Γ) and different mechanisms of carbon dioxide trapping, $h_1=h_2$

| | T1 | T2 | T3 |
|--------------------------------|----------|----------|----------|
| Macro structures, $\Gamma=0$ | 24.93762 | 26.85673 | 22.02049 |
| Micro structures, $\Gamma=0.1$ | 25.70576 | 27.6657 | 22.72656 |
| Micro structures, $\Gamma=0.2$ | 28.01017 | 30.09261 | 24.84476 |
| Micro structures, $\Gamma=0.3$ | 31.85086 | 34.13746 | 28.3751 |
| Micro structures, $\Gamma=0.4$ | 37.22782 | 39.80026 | 33.31758 |
| Micro structures, $\Gamma=0.5$ | 44.14105 | 47.08099 | 39.6722 |
| Micro structures, $\Gamma=0.6$ | 52.59056 | 55.97966 | 47.43896 |
| Micro structures, $\Gamma=0.7$ | 62.57634 | 66.49627 | 56.61785 |
| Micro structures, $\Gamma=0.8$ | 74.09839 | 78.63083 | 67.20888 |
| Micro structures, $\Gamma=0.9$ | 87.15672 | 92.38332 | 79.21205 |
| Micro structures, $\Gamma=1.0$ | 101.7513 | 107.7538 | 92.62735 |

Table 6 The mechanical buckling load (Λ) of fully clamped UFC beam versus the small-scale parameters (Γ) and different mechanisms of carbon dioxide trapping, $h_1=h_2$

| | T1 | T2 | T3 |
|--------------------------------|----------|----------|----------|
| Macro structures, $\Gamma=0$ | 48.7599 | 52.51229 | 43.0561 |
| Micro structures, $\Gamma=0.1$ | 50.26182 | 54.09404 | 44.43666 |
| Micro structures, $\Gamma=0.2$ | 54.76758 | 58.83932 | 48.57833 |
| Micro structures, $\Gamma=0.3$ | 62.27717 | 66.74812 | 55.48112 |
| Micro structures, $\Gamma=0.4$ | 72.7906 | 77.82043 | 65.14503 |
| Micro structures, $\Gamma=0.5$ | 86.30787 | 92.05626 | 77.57005 |
| Micro structures, $\Gamma=0.6$ | 102.829 | 109.4556 | 92.75619 |
| Micro structures, $\Gamma=0.7$ | 122.3539 | 130.0185 | 110.7034 |
| Micro structures, $\Gamma=0.8$ | 144.8827 | 153.7449 | 131.4118 |
| Micro structures, $\Gamma=0.9$ | 170.4153 | 180.6348 | 154.8813 |
| Micro structures, $\Gamma=1.0$ | 198.9518 | 210.6882 | 181.1119 |

conditions are considered the boundary supported for the UFC beam. Table 3 lists the stability of the mechanical buckling load of the UFC beam in order to investigate the stability analysis of the UFC beam for the different mechanisms of CO₂ trapping. In this analysis, three different types of boundary conditions, fully clamped, fully pinned, and clamped pinned, are utilized, and the impact of the thickness of layers is investigated. T2 is more stable than T1 for all boundary conditions, and T3 is more unstable than T1. In the fully clamped boundary conditions, the rigidity of the UFC beam is higher than others, and fully clamped structures are more stable, while the fully pinned beam is more unstable than others. The impact of the thickness of layers is the other parameter investigated in Table 3, as Fu *et al.* (2016) confirmed, the mechanism of carbon dioxide trapping is unstable, and this layer should be supported with a substrate. The results demonstrate that the polyacrylonitrile substrate ($h_2=0$) is more rigid than cross-links, and also the composite beam of polyacrylonitrile and all cross-links (h_1 and $h_2 \neq 0$) are more stable than pure cross-links ($h_1=0$).

Tables 4-6 present the mechanical buckling load (Λ) of small-scale UFC beam for three different Co₂ capture

mechanisms versus the various small-scale parameters (Γ) for fully pinned, pinned-clamped, and fully clamped boundary conditions. It shows the stability of the UFC beam increases with Γ because the small-scale parameter increases both cross-link and substrate strength, and then the stiffness of the UFC beam increases. In all mentioned cross-links and both pinned and clamped types of boundary conditions, the impact of small-scale parameters is the same. Moreover, the pinned structures are softer than others, and the clamped types are stiffer than others, it is because clamped types are more fixed and more rigid.

5. Conclusions

This study presented the stability analysis due to the mechanical buckling characteristics of an ultrathin film composite beam, which was made of a polyacrylonitrile substrate that supported a cross-link polydimethylsiloxane gutter layer according to classical beam theory and modified couple stress theory to investigate the small-scale impact. The methacrylate, three pedant methacrylates, and a couple of poly(ethylene glycol) methyl ether methacrylate

were the three mechanisms of carbon dioxide trapping introduced by Fu used as the cross-links. The mathematical modeling of the UFC beam has been done. The buckling characteristics of the micro-structures composite beam have been investigated in order to study the impact of boundary conditions, the thickness of layers, small-scale parameters, and different carbon dioxide trapping mechanisms. The following main conclusions are listed:

- However, the previous studies showed the third mechanism (T3) had a better performance in the trapping CO₂, but a couple of poly(ethylene glycol) methyl ether methacrylate (T2) as the CO₂ trapping mechanism is the most stable mechanism, and T3 (three pendant methacrylates) is the most unstable mechanism.

- Increment of cross-links in the composite beam decreases the buckling load, which means the UFC beam is unstable with thickness increment of cross-links.

- The small-scale parameters have a significant impact on the stability of the UFC beam, and an increment of small-scale parameters increases the beam stability.

- The mechanical stability of the UFC beam is dependent on the boundary conditions, and the clamped types are the most rigid and the most stable structures.

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