

Instability analysis of microfilaments with and without surface effects using Euler theory

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Abstract. The study of cell components has been an active area of research since the last few decades. Cytoskeleton of the cell which gives shape and provides structure to the cell has three main components, microtubules, microfilaments and intermediate filaments. Each of the cytoskeletal components is surrounded by various filamentous or the other cytoskeletal components act as a surface layer on these filaments. The stability of these components affected when cell perform various functions in the body and as a result these filaments buckle, vibrate and bend. In the present study the buckling behavior of microfilament is discussed with the effects of surface by using Euler Bernoulli beam theory and the obtained results for free and surrounded microfilament are shown in the tables and figures.

Keywords: microfilaments; Euler conventional beam model; buckling; surface effects

1. Introduction

All living organisms depend upon cell. Therefore cell is the basic structural unit of all living objects. So, the study of structure of a cell is very important especially in the subjects of biological and medical sciences (van der Lebenskraft). During the last few decades many researchers have given their intensions about the structure, and mechanics of cell and its components that provide the shape and strengthen the cell (Alberts *et al.* 2002). It is the cytoskeleton that strengthens the cell by giving strength and by providing shape to the cell.

There are three major cytoskeleton components, microtubules (MTs), intermediate filaments (IFs) and microfilaments (MFs) (Netter and Colacino 1989), (Lundin *et al.* 2010). Among all these three filaments, microfilaments (MFs) are the linear polymers of globular actin (G-Actin) subunits and occur as microfilaments in cytoskeleton of the cell (Bennett and Baines 2001). MFs are the smallest cytoskeleton components as compared with other filaments: microtubules (MTs) and intermediate

filaments (IFs) with persistent length up to 15 μm , bending stiffness $7 \times 10^{-26} \text{ Nm}^2$ and Young's modulus $1.3 - 2.5 \times 10^9 \text{ Pa}$ (Jérusalem and Dao 2012, Elzinga *et al.* 1973). These filaments are thin, relatively flexible like threads that can be cross-linked together in different ways to form their structure. The structure of MFs is helical in nature with diameter 7 nm (Mofrad and Kamm 2006) approximately. They are also responsible in maintaining the shape and strengthen the cytoskeleton of the cell.

Therefore study of these filaments is a need for the current research in biological and medical sciences. Many researchers experimentally studied the structure and mechanics of MFs in the recent decade (Vindin and Gunning 2013, Simons *et al.* 2004). AlSaid-Alwan and Avcar (2020) examined the projected structure to serve all the engineering purposes, the theory to be used during the modeling stage is also of great importance. In the present work, an analytical solution of the free vibration of the beam composed of functionally graded materials (FGMs) is presented utilizing different beam theories. The comparison of supposed beam theory for free vibration of functionally graded (FG) beam is examined. For this aim, Euler-Bernoulli, Rayleigh, Shear, and Timoshenko beam theories. MFs build their structures by growing from the polymerization of G-actins monomers which are the basic unit of MFs, called as globular actins or G-Actins (Jérusalem and Dao 2012). Civatek and Avcar (2020)

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presented the free vibration and buckling analyses of functionally graded carbon nanotube-reinforced (FG-CNTR) laminated non-rectangular plates, i.e., quadrilateral and skew plates, using a four-noded straight-sided transformation method. At first, the related equations of motion and buckling of quadrilateral plate have been given, and then, these equations are transformed from the irregular physical domain into a square computational domain using the geometric transformation formulation via discrete singular convolution. In many cases these filaments, bundle together with other actins filaments or with their related motor proteins to form a network known as actins cytoskeleton. MFs in combined with MTs and IFs perform various functions within the cell (Noria *et al.* 2004, Raff *et al.* 2002). Panda and Singh (2010) studied the buckling and post-buckling behaviours of a laminated composite spherical shallow shell panel embedded with shape memory alloy (SMA) fibres. System equations for a laminated composite spherical shell panel embedded with SMA fibres are for the first time derived by modelling the geometric non-linearity in the Green–Lagrange sense and the material non-linearity in SMA fibres in the framework of the higher-order shear deformation theory. Civalek *et al.* (2020) presented the bending, stability (buckling) and vibration response of nano sized beams based on the Eringen's nonlocal elasticity theory in conjunction with the Euler-Bernoulli beam theory. For this purpose, the bending, buckling and vibration problem of Euler-Bernoulli nanobeams are developed and solved on the basis of nonlocal elasticity theory. It is thought that these filaments provide protrusive and contractile forces to MTs to form a polarized network allowing organelles and proteins movement throughout the cell (Pan *et al.* 2013). Ebrahimi *et al.* (2019) explored the transient vibration of piezoelectric sandwich nanobeams. The flexoelectric effect on the mechanical properties of vibration piezoelectric sandwich nanobeam with different boundary conditions is investigated. According to the Nonlocal elasticity theory in nanostructures, the flexoelectricity is believed to be authentic for such size-dependent properties. Kar *et al.* (2016) evaluated the post-buckling behaviour of functionally graded curved shell panels of different shell geometries (spherical, elliptical, cylindrical and hyperbolic) under the uniaxial and the biaxial edge compression. The inhomogeneity of the functionally graded material along the thickness direction is achieved using power-law distribution through Voigt's micromechanical model to obtain the effective material properties. On the other hand IFs are considered as the most rigid cytoskeleton component that provides strength and shape to the cell (Gunning *et al.* 2015). MFs are in fact the globular proteins that polymerize to form other long enough filaments (Stehn *et al.* 2013). Mehar *et al.* (2018) predicted the eigenfrequency responses of a nanoplate structure numerically via a novel higher-order mathematical model and finite-element method including nonlocal elasticity theory. A new computer program has been prepared based on the present model to compute the frequencies of the nanoplate structure. The accuracy of the numerical solutions has been checked through proper convergence and comparison with available

published data by evaluating an adequate number of examples. Akbas *et al.* (2020) investigated the buckling and post-buckling cases in aorta artery with higher pressure. Also, its stability has a vital importance to humans and animals. The loss of stability in arteries may lead to arterial tortuosity and kinking. In this paper, post-buckling analysis of aorta artery is investigated under axial compression loads on the basis of Euler-Bernoulli beam theory by using finite element method. In particular these filaments also participated in many cellular functions including muscle contraction, cell motility, cell division and cytokinesis, vesicle and organelle movement, cell signaling, establishment and maintenance of cell junction and shape of the cell (Crowley *et al.* 1980, Hanukogole *et al.* 1983, Almor *et al.* 2004, Baulies *et al.* 2004). Panda and Singh (2013a, b) investigated the postbuckling behavior of laminated shell panel in thermal environment is reported in this article. The geometric nonlinearity is introduced in Green–Lagrange sense and the model is developed for the geometrically large translations and/or rotations and the excess thermal deformation of the curved panel based on higher order shear deformation theory (HSDT) using nonlinear finite element. Like other filaments, MFs buckle and vibrate and their buckling and vibration force depends upon the medium, surrounded these nanofibrous (Taj *et al.* 2020). Kar and Panda (2017) examined the buckling and postbuckling behavior of functionally graded spherical shell panel under nonuniform thermal environment. The effective material properties of the graded structure are evaluated using the Voigt's micromechanical model through the power-law distribution. For the analysis purpose, a general nonlinear higher order mathematical model is developed in conjunction with Green–Lagrange geometrical nonlinearity. Avcar (2019) conducted the free vibration of beams made of imperfect functionally graded materials (FGMs) including porosities. Because of faults during process of manufacture, micro voids or porosities may arise in the FGMs, and this situation causes imperfection in the structure. Therefore, material properties of the beams are assumed to vary continuously through the thickness direction according to the volume fraction of constituents described with the modified rule of mixture including porosity volume fraction. Pandey *et al.* (2019) conducted the effect of an increasing percentage of nanofiller (glass cenosphere) with Glass/Epoxy hybrid composite curved panels modeled mathematically using the multiscale concept and subsequent numerical eigenvalues of different geometrical configurations (cylindrical, spherical, elliptical, hyperboloid and flat). The medium around these filaments can be either a layer of other filaments network or may be both. Theoretical work about MFs is limited as compared with MTs. Schliwa and Woehlke (2003) and Carter and Cross (2005) studied the functions of protein MTs as a moving core of cilia and flagella. In the same period mechanical vibration of protein MTs are also studied by Sirenko *et al.* (1996), Stroschio *et al.* (1996), Pokorný (1997), Jelínek *et al.* (1997) and Tuszyński (2005), Luchko *et al.* (2005). Katariya *et al.* (2017) reported the thermal buckling strength of the sandwich shell panel structure and subsequent improvement of the same by embedding shape

memory alloy (SMA) fibre via a general higher-order mathematical model in conjunction with finite element method. The geometrical distortion of the panel structure due to the temperature is included using Green-Lagrange strain-displacement relations. Flexural rigidity of MTs is investigated by many researchers (Venier *et al.* 1994, Maggs *et al.* 1994, Gittes *et al.* 1993, Takasone *et al.* 2002, Kikumoto *et al.* 2006). It is experimentally found that waves propagate along protein MTs, therefore in 2007 (Qian *et al.* 2007) explore the wave propagation along free MTs. Ebrahimi and Daman (2017) introduced the free vibration analysis of nanosize rings and arches with consideration of surface effects. The Gurtin-Murdach model is employed for incorporating the surface effect parameters including surface density, while the small scale effect is taken into consideration based on nonlocal elasticity theory of Eringen. An analytical Navier solution is presented to solve the governing equations of motions. Panda and Singh (2013a, b) investigated the thermal post-buckling of laminated composite panel with SMA subjected to uniform temperature change. The panel model is derived taking the geometric nonlinearity in Green-Lagrange sense based on the HSDT and then it is extended to incorporate the material nonlinearity arises due to temperature in the SMA via marching technique. The panel is discretized using nonlinear finite element.

Later on in 2014 (Taj and Zhang 2014) studied the wave propagation of embedded MTs within an elastic media. In 2019, Safer *et al.* (2019) investigate the effects of viscoelastic media on the wave propagation of MTs. Taj and Muhammad (2019) studied the vibration of protein MTs within medium. Buckling behavior of IFs in viscoelastic medium is studied in 2020 (Taj *et al.* 2020). Several researchers used different techniques for the investigation of frequency analysis (Bilouei *et al.* 2016, Golabchi *et al.* 2018, Lal and Markad 2018, Mousavi *et al.* 2019, Loghman *et al.* 2017, Zamani *et al.* 2017, Mousavi *et al.* 2019, Sayin and Calayir 2015).

Mechanical behavior and function of MFs are very similar to MTs and IFs therefore it is necessary to investigate the mechanical behaviors of these filaments of the cytoskeleton. Like MTs and IFs, MFs can also buckle and affect the functions of the cell. In the present paper, author studied the buckling behavior of MFs with the effects of surface by using Euler Bernoulli beam theory and shows these effects graphically.

2. Materials and methods

Many theoretical and experimental methods have been used extensively to estimate the mechanical behavior of nanofibrous. Qian *et al.* (2007) explore the wave propagation along free microtubules while in 2014, Taj and Zhang studied the wave propagation along embedded microtubules by using orthotropic elastic shell model. Similarly in 2019, Taj (2019) investigate the vibration of protein microtubules within medium by using orthotropic shell model. The buckling behavior of intermediate filament is discussed within viscoelastic medium by using a

mechanical model (Taj *et al.* 2020). In the present work, Euler Conventional Beam Model is used to study the buckling of microfilament with and without external surface effects.

2.1 Euler conventional beam model

Euler Bernoulli Beam theory is the most simplified form of linear elasticity theory that is a mean of finding the load and deflection of the beam. It covers the case of very small deflection of the beam when the external lateral load is subjected to the beam. This theory describes the mathematical relationship between beam deflection and the external applied load without the effects of external surface as

$$EI \frac{\partial^4 w}{\partial x^4} + E \frac{\partial^2 w}{\partial x^2} = 0 \quad (1)$$

where $w(x)$ is the buckling deflection of the beam at position x and EI is used for flexural rigidity of the beam. For circular beam,

$$EI = E\pi D^4/64 \quad (2)$$

2.2 Buckling of microfilament without the external surface effects

The structure of MFs is very similar to that of a beam therefore their structure suggests to model these nanofibrous by Euler conventional beam theory to check their buckling behavior. In the present work we use (1) as

$$(EI)_o \frac{\partial^4 w}{\partial x^4} + E \frac{\partial^2 w}{\partial x^2} = 0 \quad (3)$$

where $w(x)$ is the buckling deflection of the filament at position x and $(EI)_o$ is used for flexural rigidity of MFs. For circular structural MFs the flexural rigidity is

$$(EI)_o = E\pi D_0^4/64, \quad (4)$$

where E and D_0 are Young's modulus and diameter of MFs respectively. Fourth order ordinary differential Eq. (3) can be solved by using the boundary conditions at the ends of the filaments for the critical axial force of buckling

$$E_{cr} = \mu \frac{\pi^2 (EI)_o}{l^2} \quad (5)$$

where μ is a dimensionless constant, with values depending upon the four boundary conditions at the ends, l is the length of the filament. We calculate that $\mu = 4$ when one end is fixed and other is free and $\mu = 3$ when both ends are hinged. Similarly, $\mu = 5$ when one ends is fixed and other is hinged and finally $\mu = 46$ when both ends are fixed of the filament.

We first calculate the critical buckling force of MFs without the effects of external surface layer. For this purpose, we use $E = 1.8 \text{ Gpa}$, $D = 7 \text{ nm}$, and $E^s = 170 \text{ N/m}$ (Kreplak *et al.* 2005, Kamali *et al.* 2018). By using the parameters, $E = 1.8 \text{ Gpa}$, $D_0 = 7 \text{ nm}$, and $E^s = 170 \text{ N/m}$, the critical compressive force of buckling of MFs with different boundary conditions is calculated and is shown in Fig. 1.

It can be seen in the figure that as value of μ increases, the buckling force also increases. We have demonstrated these results in the form of Tables 1-4.

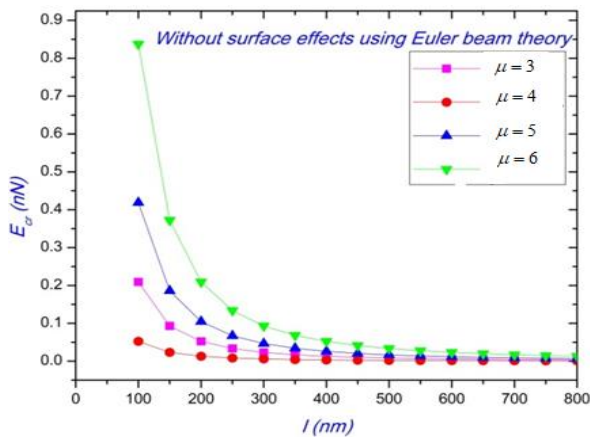


Fig. 1 The critical buckling force for MFs with different boundary conditions without surface effects

Table 1 The comparison of buckling force for MFs with surface effects and without surface effects for $\mu = 1$

| For $\mu = 1$ | | |
|---------------|--------------|----------------------|
| Length(nm) | $E_{cr}(nN)$ | $E^{\circ}_{cr}(nN)$ |
| 100 | 0.20938 | 22.99108 |
| 150 | 0.093058 | 10.31937 |
| 200 | 0.052345 | 5.88427 |
| 250 | 0.033501 | 3.831453 |
| 300 | 0.023264 | 2.716342 |
| 350 | 0.017092 | 2.043966 |
| 400 | 0.013086 | 1.607567 |
| 450 | 0.01034 | 1.308374 |
| 500 | 0.008375 | 1.094363 |
| 550 | 0.006922 | 0.936019 |
| 600 | 0.005816 | 0.815586 |
| 650 | 0.004956 | 0.72186 |
| 700 | 0.004273 | 0.647491 |
| 750 | 0.003722 | 0.587495 |
| 800 | 0.003272 | 0.538392 |

2.3 Buckling of microfilament with external surface effects

It was demonstrated previously that due to mechanical coupling with the surrounding surface, the critical buckling force of protein MTs increases considerably (Kamali et al. 2018, Zhao and Rajapakse 2009). Therefore in the presentwork we include the surface effects on the critical buckling force of MFs as the surface area increases to bulk at MFs size level. It is established that the effects of surfaces can be described either by surface energy or surface stress. The surface stress tensor $\sigma_{\alpha\beta}^s$ is related to the surface energy density γ (Zhao and Rajapakse 2009,

Table 2 The comparison of buckling force for MFs with surface effects and without surface effects for $\mu = 2$

| For $\mu = 2$ | | |
|---------------|--------------|----------------------|
| Length(nm) | $E_{cr}(nN)$ | $E^{\circ}_{cr}(nN)$ |
| 100 | 0.418759146 | 45.80015899 |
| 150 | 0.186115176 | 20.45673733 |
| 200 | 0.104689786 | 11.58653975 |
| 250 | 0.067001463 | 7.480905439 |
| 300 | 0.046528794 | 5.250684333 |
| 350 | 0.03418442 | 3.905931346 |
| 400 | 0.026172447 | 3.033134937 |
| 450 | 0.020679464 | 2.434748592 |
| 500 | 0.016750366 | 2.00672636 |
| 550 | 0.013843278 | 1.690038314 |
| 600 | 0.011632198 | 1.449171083 |
| 650 | 0.009911459 | 1.26171974 |
| 700 | 0.008546105 | 1.112982837 |
| 750 | 0.007444607 | 0.992989493 |
| 800 | 0.006543112 | 0.894783734 |

Table 3 The comparison of buckling force for MFs with surface effects and without surface effects for $\mu = 1/4$

| For $\mu = 1/4$ | | |
|-----------------|--------------|----------------------|
| Length(nm) | $E_{cr}(nN)$ | $E^{\circ}_{cr}(nN)$ |
| 100 | 0.418759146 | 5.884269874 |
| 150 | 0.186115176 | 2.716342166 |
| 200 | 0.104689786 | 1.607567469 |
| 250 | 0.067001463 | 1.09436318 |
| 300 | 0.046528794 | 0.815585542 |
| 350 | 0.03418442 | 0.647491418 |
| 400 | 0.026172447 | 0.538391867 |
| 450 | 0.020679464 | 0.463593574 |
| 500 | 0.016750366 | 0.410090795 |
| 550 | 0.013843278 | 0.370504789 |
| 600 | 0.011632198 | 0.340396385 |
| 650 | 0.009911459 | 0.316964967 |
| 700 | 0.008546105 | 0.298372855 |
| 750 | 0.007444607 | 0.283373687 |
| 800 | 0.006543112 | 0.271097967 |

Cammarata 1994) as

$$\sigma_{\alpha\beta}^s = \gamma\delta_{\alpha\beta} + \frac{\partial\gamma}{\partial\varepsilon_{\alpha\beta}^s} \tag{6}$$

where $\varepsilon_{\alpha\beta}^s$ is strain tensor for surface. The one-dimensional and linear form of Eq. (4) is

$$\sigma^s = \tau_0 + E^s\varepsilon \tag{7}$$

where τ_0 is the residual surface tension, and E^s is the surface Young's modulus. In Eqs. (6) and (7), the surface

Table 4 The comparison of buckling force for MFs with surface effects and without surface effects for $\mu = 4$

| For $\mu = 1/4$ | | |
|-----------------|--------------|----------------|
| Length(nm) | $E_{cr}(nN)$ | $E_{cr}^o(nN)$ |
| 100 | 0.837518291 | 91.41831799 |
| 150 | 0.372230352 | 40.73147466 |
| 200 | 0.209379573 | 22.9910795 |
| 250 | 0.134002927 | 14.77981088 |
| 300 | 0.093057588 | 10.31936867 |
| 350 | 0.06836884 | 7.629862693 |
| 400 | 0.052344893 | 5.884269874 |
| 450 | 0.041358928 | 4.687497185 |
| 500 | 0.033500732 | 3.83145272 |
| 550 | 0.027686555 | 3.198076628 |
| 600 | 0.023264397 | 2.716342166 |
| 650 | 0.019822918 | 2.341439479 |
| 700 | 0.01709221 | 2.043965673 |
| 750 | 0.014889214 | 1.803978986 |
| 800 | 0.013086223 | 1.607567469 |

energy density is the function of the strain at the surface and known as surface elasticity and can be modeled by a very thin isotropic elastic layer beneath the surface. We first consider its effects on the critical buckling force of MFs. Let t and E_1 be the thickness and Young's modulus of surface layer respectively. We assumed that t approaches to zero to idealize the surface with zero thickness, while keeping $E_1 t$ as constant, E^S (Gurtin *et al.* 1998) i.e., $E_1 t = E^S$ for explanation of size-dependent deformation of nanomaterial (He and Lilley 2008). Therefore, the effects of surface elasticity on buckling of MFs can be calculated by replacing the flexural rigidity $(EI)_o$ with the effective flexural rigidity $(EI)^*$ (Zhao and Rajapakse 2009), which is given by

$$(EI)^* = \frac{1}{64}\pi E D_0^4 + \frac{1}{8}\pi E^S D_0^3 \quad (8)$$

It is found that the residual surface tension τ^0 creates a transverse distributed load along the span of buckling of MFs which can be determined by Laplace-Young equation (He and Lilley 2008, Chen *et al.* 2006)

$$\langle \sigma_{ij}^+ - \sigma_{ij}^- \rangle n_i n_j = \tau_0 k \quad (9)$$

where n_i and k are the unit vector normal to the surface and k is its principle curvature respectively. The curvature of buckled MFs can be approximated by $\frac{\partial^2 w}{\partial x^2}$. The Laplace-Young' Eq. (9) indicates that the residual surface tension induces distributed transverse load given by

$$q(x) = P \frac{\partial^2 w}{\partial x^2}, \quad (10)$$

where the constant P , can be evaluated by the residual surface tension and the shape of cross section of the nanofibrous. As the cross-section of microfilament is

circular, P is given by

$$P = 2\tau^0 D_0 \quad (11)$$

By considering both, the surface elasticity and residual surface tension, governing equation of MFs becomes

$$(EI)^* \frac{\partial^4 w}{\partial x^4} + (E - P) \frac{\partial^2 w}{\partial x^2} = 0 \quad (12)$$

From Eq. (12), the critical load of axial buckling of MFs can be found as

$$E_{cr}^o = \mu \frac{\pi^2 (EI)^*}{l^2} + P \quad (13)$$

The derivations of the above equations based on the boundary condition, mentioned earlier. The different values of μ under different boundary conditions, suggest that there is a great impact of BC's on the critical load of buckling. Therefore, the value of μ must be determined according to the actual supported conditions of MFs, when the buckling method is used to measure the mechanical properties. By using the parameters, $E = 1.8 \text{ Gpa}$, $D_0 = 7 \text{ nm}$, $E^S = 170 \text{ N/m}$ and $\tau_0 = 0.013 \text{ N/m}$, the critical buckling force is calculated against the various length of microfilament, shown in Fig. 2.

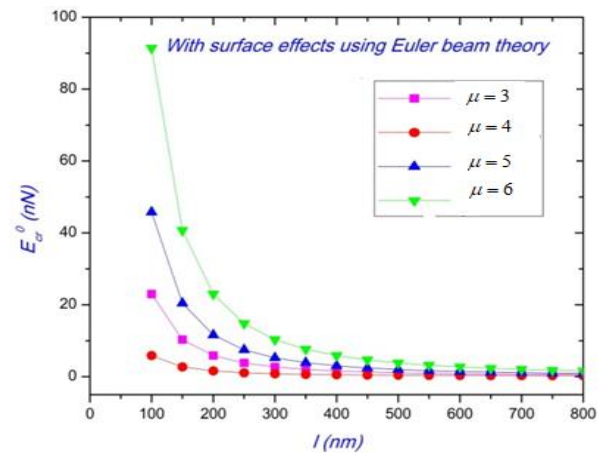


Fig. 2 The critical buckling force for MFs with different boundary conditions with surface effects

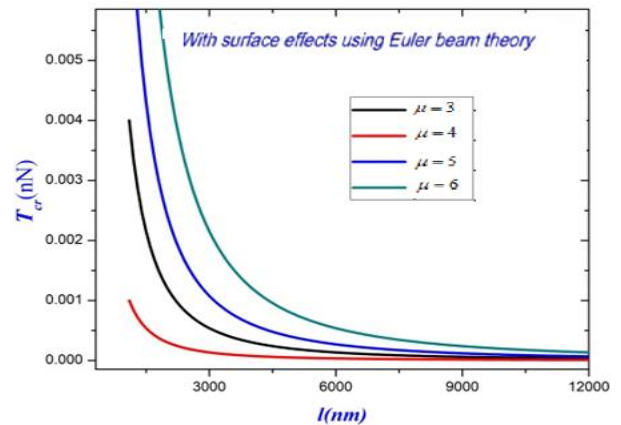


Fig. 3 Comparison of critical buckling force (by sing Euler beam theory) to length of filament by using various boundary conditions

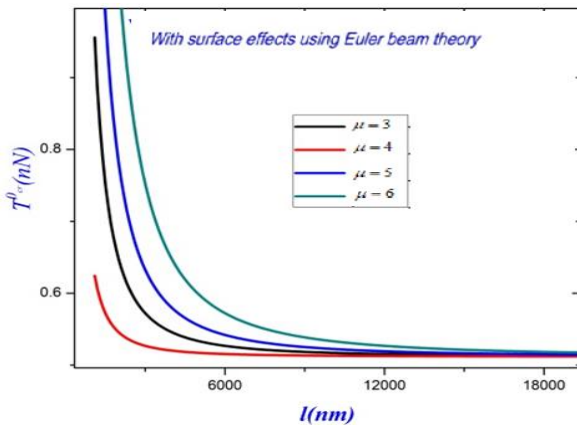


Fig. 4 Comparison of critical buckling force (by sing Euler beam theory) to length of filament by using various boundary conditions

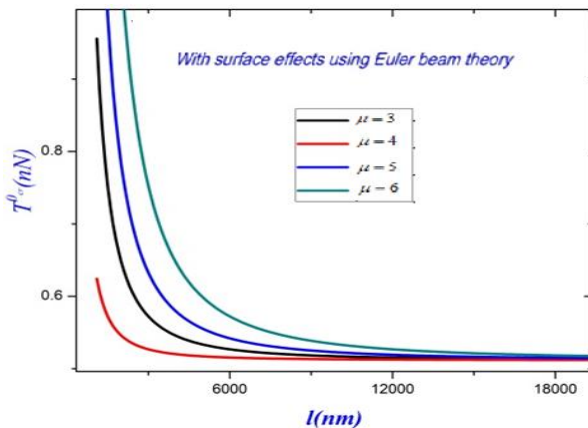


Fig. 5 Comparison of critical buckling force (by sing Euler beam theory with surface effects) to length of filament by using various boundary conditions

3. Conclusions

Euler Bernoulli Beam theory is the most simplified form of linear elasticity theory that is a mean of finding the load and deflection of the beam. It covers the case of very small deflection of the beam when the external lateral load is subjected to the beam. This theory describes the mathematical relationship between beam deflection and the external applied load without the effects of external surface. Clearly, the effects of surface on the critical buckling load are obvious due to mechanical coupling of MFs with the surrounding surface. The numerical results are displayed in the form of tables in comparison with the critical buckling force for free MFs. These findings well explain the experimental studies that critical buckling forces increases considerably when surrounding surfaces are taken into account. In the future study, the mechanical response of microfilaments can be computed during bending and stretching with Euler beam theory.

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