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Buckling influence of intermediate filaments with and without surface effects

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Abstract. Intermediate filaments are the mechanical ropes for both cytoskeleton and nucleoskeleton of the cell which provide tensile force to these skeletons. In providing the mechanical support to the cell, they are likely to buckle. We used conventional Euler buckling model to find the critical buckling force under different boundary conditions which they assume during different functions. However, there are many experimental and theoretical studies about other cytoskeleton components which demonstrate that due to mechanical coupling with the surrounding surface, the critical buckling force increases considerably. Motivated with these results, we also investigated the influence of surface effects on the critical buckling force of intermediate filaments. The surface effects become profound because of increasing ratio of surface area of intermediate filaments to bulk at nano-scale. The model has been solved analytically to obtain relations for the critical forces for the buckling of intermediate filaments without and with surface effects. We found that critical buckling force with surface effects increases to a large extent due to mechanical coupling of intermediate filaments with the surrounding surface. Our study may be useful to develop a unified experimental protocol to characterize the physical properties of Intermediate filaments and may be helpful in understanding many biological phenomenon involving intermediate filaments.

Keywords: buckling; Euler beam model; intermediate filaments; surface effects

1. Introduction

The cytoskeleton of all eukaryotic cells is composed of Nano structural components such as intermediate filaments (IFs), protein microtubules (MTs) and actin filaments (MFs) (Alberts *et al.*). Among these components, the diameter of IFs are 10 nm and, therefore, intermediate in thickness between the MTs with diameter 12 nm and MFs, having diameter 7 nm, and are present in both cytoplasm and nucleus (Franke *et al.* 1978, Herrmann and Aebi 2004, Herrmann *et al.* 2007).

They along with MTs and MFs give strength and mechanical stability to the cell, forming a rope like structure (Chang and Goldman 2004). They are of different types such as in the epithelia, they are known as keratins, in connective tissue as vimentin and in the nerve cells known as neurofilaments that provide support in development when the axons dramatically increases their diameter (Yoon *et al.* 1998). Many researchers are using different types of (IFs) in tumor characterization techniques. The main type of (IFs) found in the nucleus, is called nuclear lamins and is present in all nucleated cells which strengthens the nuclear envelope and protects the genome inside (Gruenbaum *et al.* 2005). Under the inner core of nuclear envelop, nuclear lamins lie which are responsible for the mechanical support to nuclear membrane as well as providing attachment sites for the chromosomes, but do break down during mitosis cell division (Ishikawa *et al.* 1968, Soltys and Gupta 1992). Kolahchi and Cheraghbak 2017) studied with the nonlocal dynamic buckling analysis of embedded microplates reinforced by single-walled carbon nanotubes (SWCNTs). The material properties of structure are assumed viscoelastic based on Kelvin–Voigt model. Agglomeration effects are considered based on Mori–Tanaka approach. The elastic medium is buckling simulated by orthotropic visco-Pasternak medium.

Mehar *et al.* (2018a) evaluated the frequency behavior of nanolpate structure using FEM including the nonlocal theory of elasticity. Computer generated results are created by using the software first time robustly to check the vibration of nanoplate. The efficiency was checked by comparing the results of available data.

Kolahchi (2017) investigated the bending, buckling and of embedded nano-sandwich plates based on refined zigzag theory (RZT), sinusoidal shear deformation theory (SSDT), first order shear deformation theory (FSDT) and classical plate theory (CPT). In order to present a realistic model, the material properties of system are assumed viscoelastic using Kelvin–Voigt model. Bilouei *et al.* (2016) used as concrete the most usable material in construction industry it's been required to improve its quality. Nowadays, nanotechnology

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offers the possibility of great advances in construction. For the first time, the nonlinear buckling of straight concrete columns armed with single- walled carbon nanotubes (SWCNTs) resting on foundation. The column is modeled with Euler-Bernoulli beam theory. IFs are of multiple types even within same cell but some IFs are specific to specialized cells. For example, neurofilaments are specific to neurons, particularly in long axons of these cells, muscle cells contain desmin filaments, and in epithelial cells the IFs are named as keratins (Hanukoglu and Fuchs, 1982, Karabinos *et al.* 1998). Kolahchi *et al.* (2016a) concerned with the dynamic stability response of an embedded piezoelectric nanoplate made of polyvinylidene fluoride (PVDF). In order to present a realistic model, the material properties of nanoplate are assumed viscoelastic using Kelvin–Voigt model. The visco-nanoplate is surrounded by viscoelastic medium which is simulated by orthotropic visco-Pasternak foundation. The PVDF visco-nanoplate is subjected to an applied voltage in the thickness direction. Mehar and Panda (2016a, b, 2018a) computed the vibration behavior, bending and dynamic response of FG reinforced CNT using shear deformation theory and finite element method. For the sake of generality, the mathematical model was presented with the mixture of Green Lagrange method. The convergence of these methodologies has been checked for the variety of results. The composite plates with different graded was investigated with isotropic and core phase. Arani and Kolahchi (2016) used a concrete material in construction industry it's been required to improve its quality. Nowadays, nanotechnology offers the possibility of great advances in construction. For the first time, the nonlinear buckling of straight concrete columns armed with single-walled carbon nanotubes (SWCNTs) resting on foundation is investigated in the present study. The column is modelled with EulerBernoulli and Timoshenko beam theories. The characteristics of the equivalent composite being determined using mixture rule. The foundation around the column is simulated with spring and shear layer. Other (IFs) are found in many cells.

Akbaş (2017a, b) investigated the free vibration analysis of edge cracked cantilever microscale beams composed of functionally graded material (FGM) based on the modified couple stress theory (MCST). The material properties of the beam are assumed to change in the height direction according to the exponential distribution. The FG nanobeam is excited by a transverse triangular force impulse modulated by a harmonic motion. Mechanical properties of FG beam depend on the position. The Kelvin–Voigt model is considered in the damping effect. In solution of the dynamic problem, finite element method is used within Timoshenko beam theory. For example, a considerable cell types contain vimentin filaments and very often associate with (MTs) (Gyoeva and Gelfand 1992). All eukaryotic cells contain lamins which give strength to the nuclear membrane (Gruenbaum and Foisner 2015). Motezaker and Kolahchi, (2017a) Investigated the Seismic response of the concrete column covered by nanofiber reinforced polymer (NFRP) layer. The concrete column was studied. The column is modeled using sinusoidal shear deformation beam theory (SSDT). Mori-Tanaka model was used for obtaining the effective material properties of the NFRP layer considering agglomeration effects. Using the nonlinear strain-displacement relations, stress-strain relations and Hamilton's principle, the motion equations are derived. Mehar *et al.* (2017a, b, c, d) studied the frequency response of FG CNT and reinforced CNT using the simple deformation theory, finite element modeling, Mori-Tanaka scheme. They investigated a new frequency phenomena with the combination of Lagrange strain, Green-Lagrange, for double curved and curved panel of FG and reinforced FG CNT. The characteristics of sandwich and grades CNT was found with labeling the temperature environ. The thermoelastic frequency of single shallow panel was determined using Mori-Tanake formulations.

Zamanian *et al.* (2017) considered the use of nanotechnology materials and applications in the construction industry. However, the nonlinear buckling of an embedded straight concrete columns reinforced with silicon dioxide (SiO2) nanoparticles was investigated. The column is simulated mathematically with Euler-Bernoulli and Timoshenko beam models. Agglomeration effects and the characteristics of the equivalent composite are determined using Mori-Tanaka approach. The foundation around the column is simulated with spring and shear layer. Structurally, IFs differ from (MTs) and (MFs) because both laterally mentioned filaments subunits are globular monomeric proteins, but the (IFs) subunit is elongated (45 nm) and thin (2-3 nm) rod-like dimers (Strelkov *et al.* 2003). The (IFs) units align to form filament parallel to the axis, and these filaments associate laterally to form IFs (Crewther *et al.* 1983). Akbaş (2016a, b) studied the forced vibration analysis of a simple supported viscoelastic nanobeam based on modified couple stress theory (MCST). The nanobeam is excited by a transverse triangular force impulse modulated by a harmonic motion. The elastic medium is considered as Winkler-Pasternak elastic foundation. The damping effect is considered by using the Kelvin–Voigt viscoelastic model. The cracked beam is modeled using a proper modification of the classical cracked-beam theory consisting of two sub-beams connected through a massless elastic rotational spring. Akbaş (2017a, b) investigated the forced vibration analysis of a cracked functionally graded microbeam using modified couple stress theory with damping effect. Mechanical properties of the functionally graded beam change vary along the thickness direction. The crack is modelled with a rotational spring. The Kelvin-Voigt model is considered in the damping effect. static bending of an edge cracked cantilever nanobeam composed of functionally graded material (FGM) subjected to transversal point load at the free end of the beam is investigated based on modified couple stress theory. Material properties of the beam change in the height direction according to exponential distributions. Kolahchi *et al* (2017) studied the dynamic buckling of sandwich nanoplate (SNP) subjected to harmonic compressive load based on nonlocal elasticity theory. The material properties of each layer of SNP are supposed to be viscoelastic based on Kelvin-Voigt model. In order to mathematical modeling of SNP, a novel formulation, refined Zigzag theory (RZT) is developed. Furthermore, the surrounding elastic medium is simulated by visco-orthotropic Pasternak foundation model in which damping, normal and transverse shear loads are taken into account. Akbaş (2018) presented the forced vibration responses of a cantilever nanobeam with crack using modified couple stress theory with damping effect. The crack is modeled with a rotational spring. The Kelvin–Voigt model is considered in the damping effect. In solution of the dynamic problem, finite element method is used within Timoshenko beam theory in the time domain. Influences of the geometry, crack and material parameters on forced vibration responses of cracked nanobeams are examined and discussed. Mehar *et al.* (2018b) studied the bending responses of nanotube-reinforced curved sandwich shell panel structure under the influence of the thermo-mechanical loading. Further, the temperature dependent material properties of the sandwich structure are assumed to evaluate the exact responses. Civalek (2020) presented the free vibration characteristics of thick skew plates reinforced by functionally graded carbon nanotubes (CNTs) reinforced composite. Discrete singular convolution (DSC) method is used for the numerical solution of vibration problems via geometric mapping technique. Using the geometric transformation via a four-node element, the straight- sided quadrilateral physical domain is mapped into a square domain in the computational space.

Akbaş (2020) investigated the axially damped forced vibration responses of viscoelastic nanorods within the frame of the modal analysis. The nonlocal elasticity theory is used in the constitutive relation of the nanorod with the Kelvin-Voigt viscoelastic model. In the forced vibration problem, a cantilever nanorod subjected to a harmonic load at the free end of the nanorod is considered in the numerical examples.

Motezaker and Eyvazian (2020) deals with the buckling and optimization of a nanocomposite beam. The agglomeration of nanoparticles was assumed by Mori-Tanaka model. The harmony search optimization algorithm is adaptively improved using two adjusted processes based on dynamic parameters. The governing equations were derived by Timoshenko beam model by energy method. The optimum conditions of the nanocomposite beam- based proposed AIHS are compared with several existing harmony search algorithms. The polarity of both (MTs) and (MFs) allows active movement of motor proteins with their associated cargo along the filament, but assembled IFs have no polarity because IFs subunits are oriented in both directions along the axis of the filament (Green *et al*. 1992, Safeer *et al*. 2019). They also differ in reversible association and dissociation. The (IFs) dimers association and dissociation can occur any way all along the length of the filament, whereas said phenomena occurs only at the ends of (MTs) and (MFs) (Bornheim *et al*. 2008, Hanukoglu and Fuchs 1983).

Kolahchi and Bidgoli (2016) presented a model for dynamic instability of embedded single-walled carbon nanotubes (SWCNTs). SWCNTs are modeled by the sinusoidal shear deformation beam theory (SSDBT). The modified couple stress theory (MCST) is considered in order to capture the size effects. The surrounding elastic medium is described by a visco-Pasternak foundation model, which accounts for normal, transverse shear, and damping loads. The motion equations are derived based on Hamilton's principle. Mehar and Panda (2018d) developed a general mathematical model for the evaluation of the theoretical flexural responses of the functionally graded carbon nanotube- reinforced composite doubly curved shell panel using higher-order shear deformation theory with thermal load. Akbaş (2019) presented axially forced vibration of a cracked nanorod under harmonic external dynamically load. In constitutive equation of problem, the nonlocal elasticity theory is used. The Crack is modelled as an axial spring in the crack section. In the axial spring model, the nonrod separates two sub-nanorods and the flexibility of the axial spring represents the effect of the crack. Boundary condition of the nanorod is selected as fixed-free and a harmonic load is subjected at the free end of the nanorod.

Madani *et al*. (2016) presented vibration analysis of embedded functionally graded (FG)-carbon nanotubes (CNT)- reinforced piezoelectric cylindrical shell subjected to uniform and non-uniform temperature distributions. The structure is subjected to an applied voltage in thickness direction which operates in control of vibration behavior of system. The tight association between proto-filaments provides (IFs) with a high tensile strength which balance compressive, twisting, stretching and bending forces (Wagner *et al.* 2007). Mehar and Panda (2018b) investigated the curved shell and CNT vibration with thermal environment using higher order deformation theory. This CNT was mixed with different configurations of the layers. The results have been verified with the earlier investigations.

Kolahchi *et al*. (2016b) investigated the nonlinear dynamic stability analysis of embedded temperature-dependent viscoelastic plates reinforced by single-walled carbon nanotubes (SWCNTs). The equivalent material properties of nanocomposite are estimated based on the rule of mixture. For the carbon-nanotube reinforced composite (CNTRC) visco-plate, both cases of uniform distribution (UD) and functionally graded (FG) distribution patterns of SWCNT reinforcements are considered. The surrounding elastic medium is modeled by orthotropic temperature-dependent elastomeric medium. The viscoelastic properties of plate are assumed based on Kelvin–Voigt theory. The (IFs) play vital role in cell cohesion and by extensive interactions between the constituent proto-filaments of an (IFs), they balance the tensile force, thus preventing the acute fracture of epithelial cell sheets. This association of IFs, proto-filaments helps to stabilize the extended axons of nerve cells (Goldman *et al*. 2012, Lee *et al*. 2012). Hussain and Naeem (2017) examined the frequencies of armchair tubes using Flügge's shell model. The effect of length and thickness-to-radius ratios against fundamental natural frequency with different indices of armchair tube was investigated. Mehar and Panda (2018c) investigated numerically the deflection behavior of carbon nanotube-reinforced composite plate is using the finite-element method and the result accuracy is established via three-point experimental bending test data. Civalek and Jalaei (2020) studied a geometric transformation method based on discrete singular convolution (DSC) to solve the buckling problem of a functionally graded carbon nanotube (FG-CNT)-reinforced composite skew plate. The straight-sided quadrilateral plate geometry is mapped into a square domain in the computational space using a four-node DSC transformation method. Hussain and Naeem (2019a, b) and performed the vibration of SWCNTs based on wave propagation approach and Galerkin's method. They investigated many physical parameters for the rotating and non-rotating vibrations of armchair, zigzag and chiral indices. Moreover, the mass density effect of single walled carbon nanotubes with in-plane rigidity has been calculated for zigzag and chiral indices. Mehar and Panda, (2018e) reported the nonlinear finite solutions of the nonlinear flexural strength and stress behavior of nano sandwich graded structural shell panel under the combined thermo-mechanical loading.

IFs organize themselves in such a way that can provide mechanical stability to plasma membrane where it comes into contact with other cells or with the extracellular matrix (Fletcher and Mullins 2010). They also provide support to mechanically stressed cells such as muscle cells, neurons and some epithelial cells and also provide integrity to the entire cytoskeleton by organizing in rope like structure (Potschka *et al*. 1990, Wang *et al*. 2001). They are often most developed in areas of the cell which are subjected to regular mechanical stress by the extracellular environment. They can also provide support for the (MFs) and (MTs) which are more fragile and are connected to both of the other types of cytoskeletal fibers by plakin proteins. IFs are necessary for stretching in epithelial cells (Gittes *et al*. 1993). Under such circumstances, the IFs are just like to be buckle. But to date, there are no studies on buckling of these filaments. Motezaker and Kolahchi (2017b) presented the dynamic analysis of a concrete pipes armed with Silica ($ SiO_2 $) nanoparticles subjected to earthquake load. The structure is modeled with first order shear deformation theory (FSDT) of cylindrical shells. Mori-Tanaka approach is applied for obtaining the equivalent material properties of the structure considering agglomeration effects. Kolahchi *et al*. (2017a) focused with general wave propagation in a piezoelectric sandwich plate. Ackbarow *et al*. (2007) used continuum model to discuss viscoelastic properties and variation of strain rate of IFs. Ackbarow *et al*. (2007) found these properties at molecular level. Later, in (Qin *et al*. 2009, 2012) an atomistic model is used for vimentin intermediate filament to measure mechanical stress, under tensile loading at nanolevel and found that stretching causes the transition from alpha-helices to beta-sheets, a phenomenon known as alpha–beta transition. IFs are semi-flexible biopolymers as their persistence length is rather short as compared to MTs and MFs which varies from 7 μm to several mm (Block *et al*. 2015) while for IFs, it ranges from few hundred nm to few μm. Thus, they are one order of magnitude more flexible than MFs. The core is consisted of several viscoelastic nanocomposite layers subjected to magnetic field and is integrated with viscoelastic piezoelectric layers subjected to electric field. The piezoelectric layers play the role of actuator and sensor at the top and bottom of the core, respectively. Furthermore, (Ramm *et al*. 2014) both experimentally and theoretically analyzed vimentin IFs for the folding and stability properties and observed that their physical and mechanical properties have a distinct dependence on the diameter/width which shows that due to large ratio of surface area to volume at nanoscale, the surface effects may affect their physical and mechanical properties (Guzman *et al*. 2006). Experimentally, the surface effects on nanomaterials have been discussed by using atomic force microscopy AFM and found that these effects have profound effects on elastic properties of nanowires due to large diameter (Cuenot *et al*. 2004). Motezaker *et al*. (2020) presented the present research post-buckling of a cut out plate reinforced through carbon nanotubes (CNTs) resting on an elastic foundation. Material characteristics of CNTs are hypothesized to be altered within thickness orientation which is calculated according to Mori-Tanaka model. For modeling the system mathematically, first order shear deformation theory (FSDT) is applied and using energy procedure, the governing equations can be derived.

Theoretically, the size dependence of the stretching, bending and buckling behavior of such nanosized structural elements has been investigated (Miller and Shenoy 2000, Wang and Feng 2009). Recently some researcher used different methods for microsystem (Siddiqui *et al*. 2016, Qadir *et al*. 2017, Geronimo *et al*. 2019, Min *et al*. 2019, Ampiaw *et al*. 2019) such as deformation theory (Mehar *et al*. 2016), finite element method (Mehar *et al*. 2018c), Green–Lagrange strain field (Mehar *et al*. 2018c), Multiscale modeling approach (Mehar and Panda 2019, Mehar *et al*. 2019), Grey Wolf algorithm (Kolahchi *et al*. 2017a, b, 2020), and viscoelastic cylindrical shell (Hosseini and Kolahchi 2018, Hajmohammad *et al*. 2018c, Hussain and Naeem 2019a, b, 2020, Panda and Singh 2011, 2013a, b, Kar and Panda 2016, Katariya *et al*. 2017).

Motivated with these experimental and theoretical studies, we intended to study buckling behavior of IFs and the surface effects on buckling of these filaments because IFs are stiff and give support to both nuclear and cell membrane so there is a natural question, that whether IFs may buckle during these processes. But up to now, there is no theoretical work to study buckling of IFs. Here in this paper, we are going to explore the buckling with surface effects and giving the comparison with the critical buckling force without surface effects.

2. Mathematical formulation

As IFs structure suggests that, these filaments are like beams and Euler conventional beam model is most suitable to check the buckling of IFs. So we shall use the Euler conventional beam model. This beam model without surface effects can be described mathematically as

$$(EI)_{\circ}\frac{\partial^4 w}{\partial x^4} + F\frac{\partial^2 w}{\partial^2 x} = 0 \tag{1}$$

where $w(x)$ is for deflection at position x, and $(EI)_{\circ}$ denotes the flexural rigidity of the intermediate filaments. For an (IFs) the flexural rigidity is given by

$$(EI)_o = E\pi D^4/64, \tag{2}$$

Here, E is for Young's modulus while D represents the diameter of intermediate filament. Eq. (1) can be solved by using the boundary conditions at the ends of the intermediate filaments for critical axial force of buckling as

$$F^\circ{}_{cr} = \mu \frac{\pi^2 (EI)_o}{l^2} \tag{3}$$

where μ is a dimensionless constant, whose values depend on the following four boundary conditions at the ends. We calculated this constant, for instance, $\mu = 1/4$ when one end is fixed and other is free, for $\mu = 1$ when both ends are hinged, $\mu = 2$ when one ends is fixed and other is hinged, and $\mu = 4$. when both ends are fixed of the IFs. First we check the buckling of IFs without considering the surface effects. For this, We consider the intermediate filaments with E = 1 Gpa, D = 10 nm, and $E^s = 140\mathrm{N/m}$ (Kreplak *et al*. 2005, Taj and Zhang 2011), using these parameters, the Fig. 1 shows the critical compressive force of the buckling of IFs with different boundary conditions, We found that as value of μ increases, the buckling force also increases. We demonstrated these results in the form of Tables 1-4.

However, experimentally and theoretically, it has been established about MTs that due to mechanical coupling with the surrounding surface, the critical buckling force increases considerably (Brangwynne *et al*. 2006). Therefore, we intended to include the surface effects on the critical buckling force of intermediate filaments because the surface area increases to bulk at IFs size level. It is established that influence of surfaces can be described either by surface energy or surface stress. The surface stress tensor $\sigma^s_{\alpha\beta}$ is related to the surface energy density γ as

$$\sigma^s_{\alpha\beta} = \gamma\delta_{\alpha\beta} + \frac{\partial\gamma}{\partial\varepsilon^s_{\alpha\beta}} \tag{4}$$

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

$$\sigma^s = \tau_0 + E^s\varepsilon \tag{5}$$

where τ_0 is the residual surface tension, and E^s is the surface Young's modulus. In Eqs. (4) and (5), the surface 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 IFs. Let t be the thickness of surface layer and E_1 the Young's modulus. We assumed that t approaches zero to idealize surface with zero thickness (Gurtin *et al*. 1998) while keeping $E_1 t$ as the constant E^S i.e., $E_1 t = E^S$ for explanation of size-dependent deformation of nanomaterial (He and Lilley 2008). Therefore, the influence of surface elasticity on buckling of IFs can be calculated by replacing the flexural rigidity $(EI)_o$ with the effective flexural rigidity$(EI)^*$, which is given by

$$(EI)^* = \frac{1}{64}\pi E D^4 + \frac{1}{8}\pi E^s D^3 \tag{6}$$

Next, residual surface tension τ^0 is considered and found that it creates a transverse distributed load along the span of the buckling of IFs which can be determined by Laplace-Young equation (Chen *et al*. 2006; Gurtin *et al*. 1998).

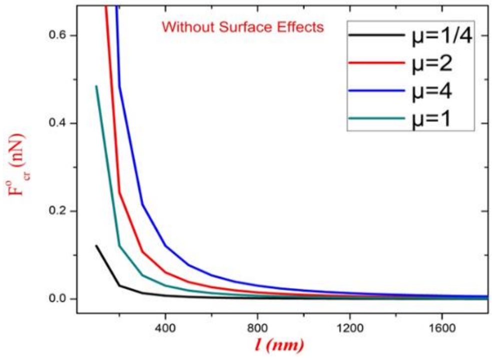

Fig. 1 The critical buckling force for IFs with different boundary conditions without surface effects

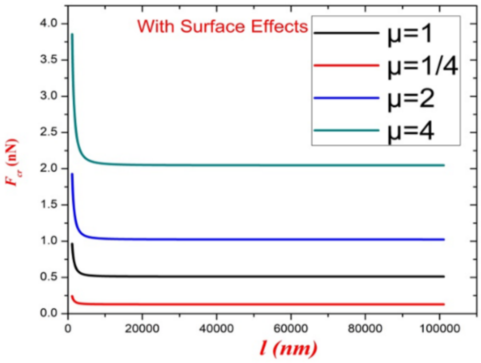

Fig. 2 The critical buckling force for IFs with different boundary conditions with surface effects

$$\langle \sigma^+_{ij} - \sigma^-_{ij} \rangle n_i n_j = \tau_0 k \tag{7}$$

where n_i is the unit vector normal to the surface and k is its principle curvature. The curvature of a buckled IFs can be approximated by $\frac{\partial^2 w}{\partial^2 x}$. The Laplace-Young equation in Eq. (7) indicates the buckling of intermediate filaments ($\frac{\partial^2 w}{\partial^2 x}$≠0), the residual surface tension induces distributed transverse load, given as

$$q(x) = P\frac{\partial^2 w}{\partial^2 x}, \tag{8}$$

where constant P can be evaluated by the residual surface tension and the shape of cross section.

For the circular cross section of intermediate filament, P is given by

$$P = 2\tau^0 D \tag{9}$$

Thus, considering surface elasticity and residual surface tension both, the governing equations of intermediate filaments becomes

$$(EI)^*\frac{\partial^4 w}{\partial x^4} + (F - P)\frac{\partial^2 w}{\partial^2 x} = 0 \tag{10}$$

From above equation the critical load of axial buckling of intermediate filaments can be found as

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

For $\mu = 1$		
Length (nm)	$F^{\circ}_{cr}(nN)$	$F_{cr}(nN)$
1100	0.00400391	0.964042
1200	0.003364396	0.891777
1300	0.002866705	0.835538
1400	0.002471801	0.790914
1500	0.002153214	0.754913

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

For $\mu = 2$		
Length (nm)	$F^{\circ}_{cr}(nN)$	$F_{cr}(nN)$
1100	0.008007819	1.928084
1200	0.006728793	1.783554
1300	0.005733409	1.671075
1400	0.004943603	1.581827
1500	0.004306427	1.509826

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

For $\mu = 1/4$		
Length (nm)	$F^{\circ}_{cr}(nN)$	$F_{cr}(nN)$
1100	0.001000977	0.24101
1200	0.000841099	0.222944
1300	0.000716676	0.208884
1400	0.00061795	0.197728
1500	0.000538303	0.188728

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

For $\mu = 4$		
Length (nm)	$F^{\circ}_{cr}(nN)$	$F_{cr}(nN)$
1100	0.016015639	3.856167
1200	0.013457585	3.567107
1300	0.011466818	3.34215
1400	0.009887206	3.163654
1500	0.008612855	3.019653

$$F_{cr} = \mu \frac{\pi^2 (EI)^*}{l^2} + P \tag{11}$$

The derivations are based on the boundary condition mentioned earlier. The different values of μ under different boundary conditions suggest that the boundary conditions of intermediate filaments have a great impact on the critical load of buckling. Therefore, the value of μ must be determined according to the actual supported conditions of the intermediate filaments when the buckling method is used to measure the mechanical properties.

Taking the values of elastic constants as E = 1 Gpa. τ^0 = 0.02558 N/m, D = 10 nm, and $E^s = \frac{140N}{m}$ the Fig. 2 displays the critical compressive force of the buckling with surface effects. Evidently, the influence of the surface effects on the critical load is obvious due to mechanical coupling with the surrounding surface. These results are displayed in the form of Tables 1-4 with comparison to the critical buckling force for free intermediate filaments. These findings well explain the experimental studies that critical buckling forces increases considerably when surrounding surfaces are taken into account.

3. Conclusions

The critical buckling forces for IFs in case of Euler Bernoulli theory for different boundary conditions are summarized in Tables 1-4. But in case of surface effects and without surface effects, it can be observed that there is a considerable difference in the buckling behaviors of IFs. It can also be observed that all types of buckling forces decreased with the increase in length of filament, so critical buckling force is inversely proportional to the length. It is concluded from the above calculations that the cross-sectional area of the filament play key role when effects of other surfaces are taken into account and when cross-sectional area is small as compared with the length, less effects the buckling behaviors and vice versa. Such types of observations are helpful for the further analysis of nanofibrous in their actual environments within the cell.

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