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Effect of external force on buckling of cytoskeleton intermediate filaments within viscoelastic media

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Abstract. Cytoskeleton components in living cell bear large compressive force and are responsible in maintaining the cell shape. Actually these filaments are surrounded by viscoelastic media within the cell. This surrounding, viscoelastic media affects the buckling behavior of these filaments when external force is applied on these filaments by exerting continuous pressure in opposite directions to the incipient buckling of the filaments. In this article a mechanical model is applied to account the effects of this media on the buckling behavior of intermediate filaments network of cytoskeleton. The model immeasurably associates; filament's bending rigidity, adjacent system elasticity, and cytosol viscosity with buckling wavelength, buckling growth rate and buckling amplitude of the filaments.

Keywords: intermediate filaments; viscous cytosol; Euler beam theory

1. Introduction

There are three main structural cytoskeletal components, microtubules (MTs), actin filaments (AFs) and intermediate filaments (IFs). MTs, AFs and IFs interrelate with each others non-covalently. Eukaryotic cell contains proteins and infact these proteins are MTs, MFs and IFs, together formed the cytoskeleton. Cytoskeletal proteins are multifunctional and concerned in the cell movements and movements of substances (Herrmann *et al*. 2007). Intermediate filaments (IFs) are one of the components of cytoskeletal structure which are present in cells of vertebrates and many invertebrates (Lim *et al.* 2007, Chang and Goldman 2004, Traub 2012). Likely to IFs, there are other proteins observed in an invertebrate, the cephalochordate branchiostoma (Whittington *et al.* 1997).

IFs are infact the collection of large number of associated proteins distributing ordinary structural and sequence facial appearance. The term "intermediate" is used since diameter of IFs proteins is about 10 nm which is approximately the average of the diameters of microfilaments and microtubules (Ishikawa, Bischoff and Holtzer, 1968). Most of the types of IFs are cytoplasmic but one of the types is nuclear lamin. Different from MTs, IFs in cell show no good correlation with others, mitochondria, endoplasmic reticulum (Soltys and Gupta 1992). Structurally intermediate filaments (IFs) are formed by the proteins, was primary forecasted by mechanized analysis of amino acid, a sequence of human being keratin resulting from cloned DNAs (Hanukoglu and Fuchs 1983). It was revealed in the examination of second keratin sequence, there are two types of keratins divide up only about 30% amino acid sequence homology but distribution is in the similar patterns of lesser configuration domains.

Since it was seen in first model that all "IFs proteins" appear to have a central alpha-helical bar domain, constructed by four alpha-helical fragments which are alienated by three linker sections (Hanukoglu and Fuchs 1983, Lee *et al.* 2012). The central building block of IFs which is a pair of two tangled proteins, called a coiled-coil organization. The name imitates that the organization of each protein is a helical and tangled pair of proteins is also helical in nature. Structural studies of a pair of keratins prove that the two proteins that structure the central building block of IFs are bind by hydrophobic interactions (Hanukoglu and Ezra 2014, Qin *et al.* 2009). Aydogdu *et al.* (2017) designed metaheuristic algorithms in general use of uniform random numbers in their search. Levy Flight (LF) is a random walk consisting of a series of consecutive random steps. The use of LF instead of uniform random numbers improves the performance of metaheuristic algorithms. Fatahi-Vajari *et al.* (2019) studied the vibration of single-walled carbon nanotubes based on Galerkin's and homotopy method. This work analyses the nonlinear coupled axial-torsional vibration of single-walled carbon

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nanotubes (SWCNTs) based on numerical methods. Two-second order partial differential equations that govern the nonlinear coupled axial-torsional vibration for such nanotube are derived. Mehar *et al*. (2019) reported the buckling load parameters of the graded nanotube sandwich structure under the influence of uniform thermal loading. The corresponding properties of the graded nanotube sandwich evaluated via the extended rule of mixture including temperature dependent properties of each constituent. Avcar (2014) presented the elastic buckling of steel columns with three different cross sections, ie square, rectangle and circle cross sections, and two different boundary conditions, ie fixed-free (FF) and pinned-pinned (PP) boundary conditions, under axial compression has been investigated. At first, the basic equations of the problem have been given. IFs in the cytoplasm come together addicted to non-polar unit length filaments. The same unit length filaments relate tangentially into stagger, antiparallel, soluble tetramers which relate head to tail addicted to protofilaments that pair up tangentially into protofibers, four of which coil jointly to form an IF (Lodish *et al.* 2000). Benmansour *et al*. (2019) investigated the dynamic and bending behaviors of isolated protein microtubule. Microtubules (MTs) can be considered as bio-composite structures that are elements of the cytoskeleton in eukaryotic cells and posses considerable roles in cellular activities. They have higher mechanical characteristics such as superior flexibility and stiffness. Asghar *et al*. (2019a, b) conducted the vibration of nonlocal effect for double-walled carbon nanotubes using wave propagation approach. Many material parameters are varied for the exact frequencies of many indices of double-walled carbon nanotubes.

Mehar and Panda (2019) explored the thermal buckling temperature values of the graded carbon nanotube reinforced composite shell structure using higher-order mid-plane kinematics and multiscale constituent modeling under two different thermal fields. Numanoğlu and Civalek (2019) introduced the small-scale material technology and **engineering**, discovery of carbon nanotube (CNT) and invention of different devices such as atomic force microscope (AFM). However, there is no study about small scale effect for truss and frame in the **scientific** literature before this. Mehar *et al*. (2018) evaluated the eigenfrequency responses of a nanoplate structure 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. Shahrma *et al*. (2019) studied the functionally graded material using sigmoid law distribution under hygrothermal effect. The Eigen frequencies are investigated in detail. Frequency spectra for aspect ratios have been depicted according to various edge conditions. Sofiyev and Avcar, (2010) investigated the stability of cylindrical shells that composed of ceramic, FGM, and metal layers subjected to axial load and resting on Winkler-Pasternak foundations is investigated. Material properties of FGM layer are varied continuously in thickness direction according to a simple power distribution in terms of the ceramic and metal volume fractions. 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. Jamali *et al*. (2019) studied the post-buckling analysis of functionally graded carbon nanotubes reinforced composite (FG-CNTRC) micro plate with cut out subjected to magnetic field and resting on elastic medium. The basic formulation of plate is based on first order shear deformation theory (FSDT) and the material properties of FG-CNTRCs are presumed to be changed through the thickness direction. 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. Rahmani *et al*. (2017) examined the various nonlocal higher-order shear deformation beam theories that consider the size dependent effects in Functionally Graded Material (FGM) beam. The presented theories fulfill the zero traction boundary conditions on the top and bottom surface of the beam and a shear correction factor is not required. Hussain *et al*. (2017) demonstrated an overview of Donnell theory for the frequency characteristics of two types of SWCNTs. Fundamental frequencies with different parameters have been investigated with wave propagation approach.

Katariya *et al*. (2017a) 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. There are N and C terminals of IFs proteins which are non-alpha helical in nature and confirm the large variations in their span and sequence across the family units. The N terminal "head domain" joins DNA, while C terminal "tail domain" confirm the span variation in special IFs proteins (Wang *et al.* 2001, Quinlan *et al.* 1994). Recently Hussain and Naeem (2019a, b, c, d, 2020) 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 have been calculated for zigzag and chiral indices.

Katariya *et al*. (2017b) investigated the nonlinear thermal buckling load parameter of the laminated composite panel structure numerically using the higher-order theory including the stretching effect through the thickness and presented in this research article. The large geometrical distortion of the curved panel structure due to the elevated thermal loading is modeled via Green-Lagrange strain field including all of the higher-order terms to achieve the required generality. Unlike MTs and MFs, IFs have antiparallel orientation of tetramers with lack polarity and cannot serve as basis for cell motility and intracellular transport. In addition, IFs do not undergo tread milling, as MTs and MFs undergo tread milling (Takemura *et al.* 2002). Panda and Katariya (2015) analyzed the free vibration and the buckling (mechanical and/or thermal) behaviour of laminated composite flat and curved panels. Simulation model has been developed using ANSYS Parametric design language code in the ANSYS environment. Batou *et al.* (2019) studied the wave propagations in sigmoid functionally graded (S-FG) plates using new Higher Shear Deformation Theory (HSDT) based on two-dimensional (2D) elasticity theory. The current higher order theory has only four unknowns, which mean that few numbers of unknowns, compared with first shear deformations and others higher shear deformations theories and without needing shear corrector. Panda and Katariya (2016) proposed a general mathematical model for laminated curved structure of different geometries using higher-order shear deformation theory to evaluate in-plane and out of plane shear stress and strains correctly. Subsequently, the model has to be validated by comparing the responses with developed simulation model (ANSYS) as well as available published literature. Over the past several years vibration of nanostructures of various configurations and boundary conditions have been extensively studied (Hussain *et al.* 2018a, Hussain *et al.* 2018b, Hussain *et al.* 2018c, Hussain and Naeem 2018b, Hussain *et al.* 2019a, Hussain *et al.* 2019b, Hussain *et al.* 2020a, Sehar *et al.* 2020, Hussain *et al.* 2020b, c, d).

IFs are the proteins, go under deformation, can be prolonged a large from its initial span[1]. This deformation is due to hierarchical organization of IFs, make it easy a flow foundation of deformation mechanism at special phase of strain. In many experimental findings, it was observed that due to this large deformation IFs vibrate, buckle and bend by the application of external agents (Koester *et al.* 2015, Block *et al.* 2015). Inspired by the study of MTs bending and buckling, (Gao and An 2010, Qian *et al.* 2007, Wang *et al.* 2006, Shi *et al.* 2008, de Pablo *et al.* 2003, Nogales 2001, Gittes *et al.* 1993, Ishida *et al.* 2007, Taj and Zhang 2012, Taj and Zhang 2011) and with living cells (Kwon *et al.* 2016, Jo*et al.* 2019, Basini *et al.* 2019, Li 2008, Thai 2012). Salah *et al.* (2019) employed a simple four-variable integral plate theory for examining the thermal buckling properties of functionally graded material (FGM) sandwich plates. The proposed kinematics considers integral terms which include the effect of transverse shear deformations. In the present study we tried to explore the buckling behavior of IFs by considering a mechanical model and axial compressive forces and then compare the results graphically with dimensionless wave number. For the geometrical instability, the present modeling is due to Euler beam model which is one dimensional and the buckling load is due to the surrounding viscoelastic medium.

2. Materials and methods

Euler beam theory is used to model the physical problem by considering the viscous cytosol as a medium. The model physical problem is a boundary value problem that is solved analytically and obtained the critical buckling load as a function of wave vector.

3. Mathematical formulations

Consider a straight elastic intermediate filament (IF), which is under the compressive force f_0 in the viscoelastic medium of elastic modulus E_C and viscosity μ. Viscoelastic medium is actually the combined effect of surrounding filaments including microtubules, microfilaments etc. and the cytosol. We consider single intermediate filament (IF) as a cylinder with radius R_0 and bending rigidity EI. Buckling of IF is considered as of the sinusoidal shape with wave length, $\frac{2\pi}{k}$ and amplitude $w(z,t) = w(t)\sin(kz)$. Our next target is to investigate the growth rates of incipient buckling of IF by the combine solutions of elastic deformation and adjacent filament system with adjacent viscous flow of the cytosol. Elastic deformation of IF with adjacent viscous flow can be coupled by the interface between IF and adjacent cytoplasm, where displacement and traction are considered to be permanent.

3.1 Elastic deformation of intermediate filaments and surrounding filament network

When compressive force f_0 is applied on IF, it buckles and then the adjacent filament system is deformed. In response this filaments system exert pressure on IF as a surface traction in converse way of incipient buckling of IF. The whole cross stresses on IF can be observed with the help of "Euler beam theory" (Li 2008)

$$F_e = -EI\frac{\partial^4 w(z,t)}{\partial z^4} - f_0\frac{\partial^2 w(z,t)}{\partial z^2} - \zeta w(z,t) \tag{1}$$

$\zeta \approx 2.7E_C$ (Landau and Lifshitz, 1986). First term in (1) represents the bending of IF, second term represents the axial compression and the last term indicates the elastic limit from the adjacent filament system. It is given earlier that, $w(z,t) = w(t) * \sin(kz)$, so we have from (1):

$$F_e = -(EIk^4 - f_0k^2 + \zeta)w(t)\sin(kz) \tag{2}$$

Eq. (2) indicates that the total traction force F_e in IF is linearly relative to the incipient buckling amplitude $w(t)$.

3.2 Viscous flow of cytosol

Upon incipient buckling of IF, there is viscous flow of cytosol within the cytoplasm of cell. Viscous flow is modeled as

$$\sigma_{ij,j} = 0, \tag{3}$$

σ_{ij} the stress tensor of in the cytosole. Body forces are assumed to be negligible because the cytosole flow is slow enough. Cytosol flow is considered as the Newtonian flow and the stress components relate to the velocities by

$$\sigma_{ij} = \mu(u_{i,j} + u_{j,i}) - p\delta_{ij} \tag{4}$$

Symbols, u_i and δ_{ij} stand respectively for velocity components and kronecker delta and $p = -\frac{1}{3}\sigma_{kk}$

Continuity equation for this kind (incompressible) of flow is

$$u_{i,j} = 0 \tag{5}$$

There are no slip conditions between IF and cytoplasm at the interface and the velocities of cytosol at the interface is given by

$$u_r(R_0,\theta) = u_0 \sin(kz)\, cos\theta$$
$$u_\theta(R_0,\theta) = u_0 \sin(kz)\, sin\theta \quad (6)$$

u_0 is the velocity of IF in buckling directions while θ is the azimuthal angle in the plane, in which the buckling occurs. Viscous flow of cytosole decays spatially away from MF and disappear at a certain distance R_1 from the centerline of IF, i.e.

$$u_r(R_1,\theta) = 0 = u_\theta(R_1,\theta) \quad (7)$$

Eqs. (3)-(7) represent a boundary value problem, whose solution is an analytical solution which is stress field of viscous flow in cytosol and can be obtained as follows:

The viscous flow of the cytosol is considered as in plane strain deformation state in $r-\theta$ plane. Two dimensional equations of motions in $r-\theta$ take the form

$$\frac{\partial p}{\partial r} = \mu(\nabla^2 v_r - \frac{v_r}{r^2} - \frac{2}{r^2}\frac{\partial v_r}{\partial \theta})$$
$$\frac{1}{r}\frac{\partial p}{\partial \theta} = \mu\left(\nabla^2 v_\theta - \frac{v_\theta}{r^2} + \frac{2}{r^2}\frac{\partial v_r}{\partial \theta}\right) \quad (8)$$

Whereas the continuity equation takes the form

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{1}{r}\frac{\partial v_\theta}{\partial \theta} = 0 \quad (9)$$

Introducing a stream function, ψ i.e.

$$v_r = \frac{1}{r}\frac{\partial \psi}{\partial \theta},\ \ v_\theta = -\frac{1}{r}\frac{\partial \psi}{\partial r} \quad (10)$$

Since,

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}$$

This implies,

$$\nabla^2 v_r = \frac{2}{r^3}\frac{\partial \psi}{\partial \theta} - \frac{1}{r^3}\frac{\partial \psi}{\partial \theta} + \frac{1}{r^3}\frac{\partial^3 \psi}{\partial \theta^3}$$

Similarly,

$$\nabla^2 v_\theta = -\frac{1}{r}\frac{\partial^3 \psi}{\partial r^3} - \frac{1}{r^3}\frac{\partial \psi}{\partial r} - \frac{1}{r^2}\frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r^3}\frac{\partial^3 \psi}{\partial \theta^2 \partial r}$$

Putting the values of, v_r, v_θ, $\nabla^2 v_r$ and $\nabla^2 v_\theta$ in (8) then comparing the result we obtained:

$$\nabla^4 \psi = 0$$

or

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}\right)\left(\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \psi}{\partial \theta^2}\right) = 0 \quad (11)$$

Assuming the stream function is in the form, $\psi(r,\theta) = g(r)\sin(kz)sin\theta$ then Eq. (11) reduces to

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} - \frac{1}{r^2}\right)\left(\frac{\partial^2 g}{\partial r^2} + \frac{1}{r}\frac{\partial g}{\partial r} - \frac{1}{r^2}g\right) = 0 \quad (12)$$

This is an ordinary differential equation of order four with solution

$$g(r) = Ar^3 + Br + C\frac{1}{r} + Drlnr \quad (13)$$

Constant A, B, C and D are to be investigated by using the boundary conditions (6 and 7).

Since,

$$v_r = \frac{1}{r}\frac{\partial \psi}{\partial \theta},\ \ v_\theta = -\frac{1}{r}\frac{\partial \psi}{\partial r}$$

This implies

$$v_r = \frac{1}{r}(Ar^3 + Br + C\frac{1}{r} + Drlnr)\sin(kz)cos\theta \quad (14)$$
$$v_\theta = -\frac{1}{r}(3Ar^2 + B - \frac{C}{r^2} + D + Dlnr)\sin(kz)sin\theta \quad (15)$$

Now substituting the boundary conditions, i.e. $v_r(R_0,\theta) = v_0\sin(kz)cos\theta$, $v_\theta(R_0,\theta) = v_0\sin(kz)sin\theta$ and $v_r(R_1,\theta) = 0 = v_\theta(R_1,\theta)$ into Eqs, (14-15) and obtained the constants ; A, B, C and D as

$$A = -\frac{v_0 q^2 lnq}{(1-q^2)(1-q^2+(1+q^2)lnq)} \quad (16)$$

$$B = \frac{v_0 {R_0}^2(2lnq+(1-q^2)(2lnR_1+1))lnq}{(1-q^2)(1-q^2+(1+q^2)lnq)} \quad (17)$$

$$C = \frac{v_0 {R_0}^2 {R_1}^2(q^2-1-lnq)}{q^2(1-q^2)(1-q^2+(1+q^2)lnq)} \quad (18)$$

$$D = -\frac{v_0 q^2}{(1-q^2)(1-q^2+(1+q^2)lnq)} \quad (19)$$

Where; $q = \frac{R_0}{R_1}$. The stress components in $r-\theta$ plan are:

$$\sigma_{rr} = -p + 2\mu\frac{\partial v_r}{\partial r}$$
$$\sigma_{r\theta} = \mu\left[r\frac{\partial}{\partial r}\left(\frac{v_\theta}{r}\right) + \frac{1}{r}\frac{\partial v_r}{\partial \theta}\right]$$

Putting the values of v_r, v_θ and ignoring the pressure term we get

$$\sigma_{rr} = -4\mu v_0 cos\theta\sin(kz)\frac{(4q^4-2)lnq+3q^2-q-2}{R_0((q^4-1)lnq-q^4+2q^2-1)} \quad (20)$$

$$\sigma_{r\theta} = 2\mu v_0 sin\theta\sin(kz)\frac{-(3q^4+1)lnq+q^4-1}{R_0((q^4-1)lnq-q^4+2q^2-1)} \quad (21)$$

Along the interface, the surface traction is calculated by the integration of stress field as:

$$F_v = \int_0^{2\pi}(\sigma_{rr}cos\theta - \sigma_{r\theta}sin\theta)R_0 d\theta$$

$$F_v = \mu v_0 \pi\sin(kz)\frac{(1-q^4)lnq - 12q^2 + 2q^4 + 10}{(q^4-1)lnq + 2q^2 - q^4 - 1}$$

Or

$$F_v = \mu v_0 \pi \chi \sin(kz) \quad (22)$$

Where,

$$\chi = \frac{(1-q^4)lnq - 12q^2 + 2q^4 + 10}{(q^4-1)lnq + 2q^2 - q^4 - 1}$$

Eq. (22) indicates that the surface traction, F_v has linear relation to the velocity v_0 of IF towards buckling.

3.3 Coupling of elastic deformation and viscous flow

In order to join elastic deformation of IF with adjacent filament system along with viscous flow of cytosol, it is assumed that the traction and the displacement across the interface are continuous, that is (Li 2008)

$$F_v = F_e,\ u_0 = \frac{dw(t)}{dt} \quad (23)$$

On substituting, Eq. (21) and (22) into Eq. (23), we obtained

$$\frac{dw(t)}{dt} = \alpha w(t) \quad (24)$$

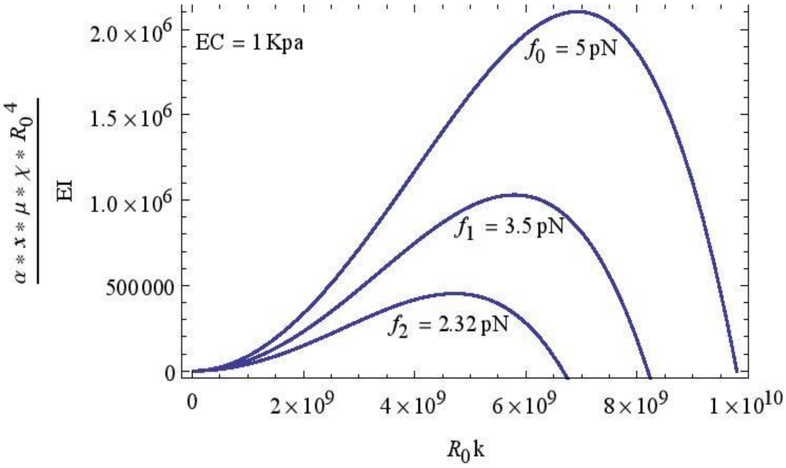

Fig. 1 Comparison of normalized buckling force $\frac{\alpha\pi\mu\chi R_0{}^4}{EI}$ with wave vector k

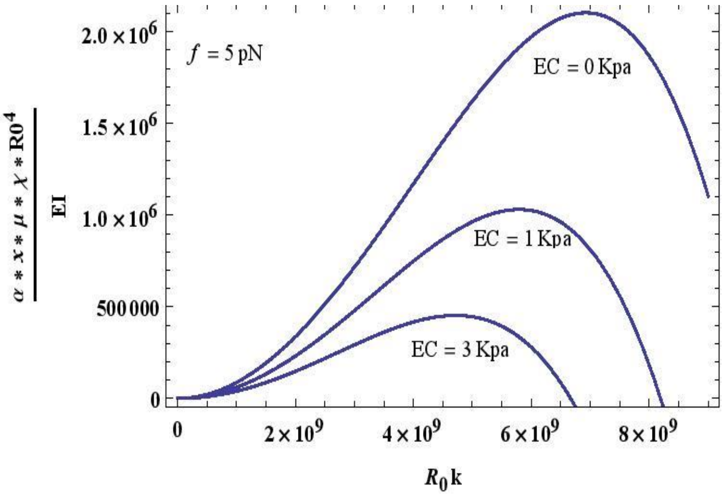

Fig. 2 Comparison of normalized buckling force $\frac{\alpha\pi\mu\chi R_0{}^4}{EI}$ with wave vector k

Where

$$\alpha = -\frac{EIk^4 - f_0k^2 + \zeta}{\pi\mu\chi} \tag{25}$$

Eq. (24) is first order ordinary differential equation whose solution is

$$w(t) = w_0 e^{\alpha t} \tag{26}$$

Eq. (26) states the amplitude of incipient buckling of IF grow or decay exponentially at a rate of α, with initial amplitude w_0.

When $\alpha = 0$ in Eq. (25) gives two critical wave numbers as

$$k_{cr}^{\pm} = \sqrt{\frac{f_0 \pm \sqrt{f_0{}^2 - 4EI\zeta}}{2EI}} \tag{27}$$

If the buckling wave length of incipient buckling of IF is too long, i.e., $k < k_{cr}^-$ or too short, i.e., $k > k_{cr}^+$, $\alpha < 0$, that is, incipient buckling of microfilament decays, thus ultimately the IF straightens up. For an incipient buckling of IF at an intermediate wavelength, i.e., $k_{cr}^- < k < k_{cr}^+$, $\alpha > 0$, that is the incipient buckling grows, leading to the buckling of IF with large amplitude.

The above observations can be discussed by an energetic thought. Buckling of IF results in an increase in the contour length of the filament, so moderates the compressive stress on IF and leading to decrease in elastic energy "ΔU_e" of the filament, as a result buckling rose up. On contrary, it is also found an increase in the bending energy "ΔU_b" of IF due to buckling and increase in elastic energy "ΔU_f" of adjacent filament system. For buckling of IF at a short wave length, i.e., $k > k_{cr}^+$, ΔU_b becomes heavier then ΔU_e, results in decay of buckling behavior of IF. Likewise for buckling of IF at long wave length, i.e., $k < k_{cr}^-$, ΔU_f is not balanced by ΔU_e, result in decay of buckling of IF behavior. For an intermediary wavelength, i.e., $k_{cr}^- < k < k_{cr}^+$, ΔU_e be greater than $\Delta U_b + \Delta U_f$, so the incipient buckling grow exponentially. The values of $k_{cr}^{\pm}$ are real when the compressive force go beyond the value $f_c = 2\sqrt{EI\zeta}$, which is the critical Euler Buckling force of IF. At such a force the two critical wave numbers are the same, $k_{cr} = \left(\frac{\zeta}{EI}\right)^{\frac{1}{4}}$. Wave number that results the fastest buckling growth rate $\alpha_{\max}$ can be calculated by using the relation, $\frac{d\alpha}{dk} = 0$. From Eq. (25), and is written as

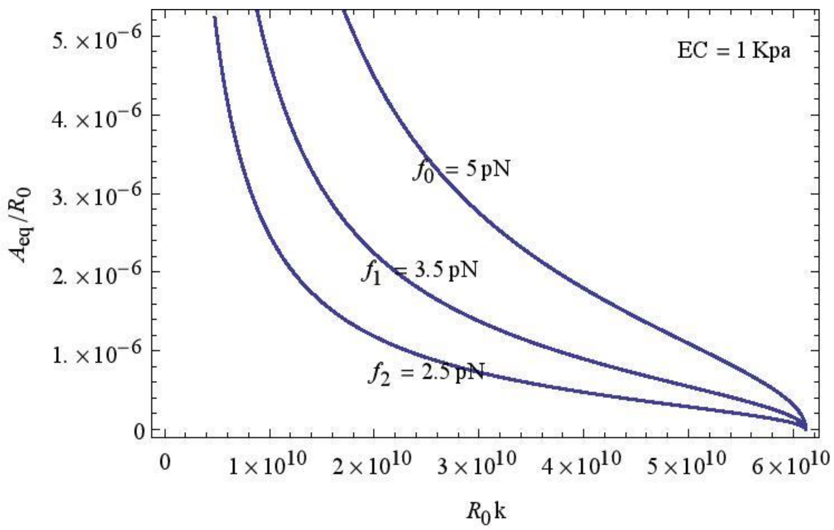

Fig. 3 Comparison of normalized buckling amplitude and wave vector

$$k_{fastest} = \sqrt{\frac{f_0}{2EI}} \tag{28}$$

4. Graphical interpretation and discussions

4.1 Wave length and growth rate of intermediate filament buckling

Figs. 1 and 2 show the plot of standardized buckling growth rate $\frac{\alpha\pi\mu\chi R_0{}^4}{EI}$ in comparison with standardized buckling wave number , R_0k, i.e., $f(R_0k) = \frac{\alpha\pi\mu\chi R_0{}^4}{EI}$ for various axial compressions f and the adjacent filament system elasticity is E_C . For a given fixed value of surrounding filament network elasticity, the rate at which buckling occurs and wave number's buckling range increased as the compressive force f increases with considerable amount as shown in Fig. 1. Similarly, Fig. 2 indicates the plot of standardized buckling growth rate as a function of buckling wave number for a fixed value of compressive force f and various intensity of adjacent filament system elasticity E_C. It is clear from the Fig. 1(b) that the rate at which buckling occurs and wave number's buckling range increased with increase in the intensity of surrounding filament network elasticity E_C . It can be concluded that the adjacent filament system has a great impact on the buckling behaviors of *IF*. Therefore it is necessary to take into account the surrounding effects while studying the buckling of such nanofibrous. In the present calculation, we used the bending rigidity $EI = 7 \times 10^{26}$ Nm^2, elastic modulus $E = 1.3 - 2.5 \times 10^9$ Pa, $R_0 = 5.5$ nm (Vaziri *et al*. 2006).

4.2 Amplitude of intermediate filament buckling at kinetically constrained equilibrium

IF buckles with short wave length and have an elastic energy greater than the elastic energy of thermodynamic equilibrium. But such type of filaments may stay with buckled shape with certain amplitude for a long time due to the kinetic constrained of viscoelatistic cytoplasm. Present target is to find that amplitude caused by kinetic constrained of the viscoelastic cytoplasm, denoted by A_{eq}.

At an equilibrium conditions, the viscous flow of cytosol stops and as a result the interface traction vanish. Euler Bernoulli beam theory gives

$$EI\frac{d^4w(z)}{dz^4} + f\frac{d^2w(z)}{dz^2} + \zeta w(z) = 0 \tag{29}$$

f is the compressive force in axial direction of IF at kinetically constrained equilibrium. Considering the solution of Eq. (29) is as the form, $w(z) = A_{eq}\sin(kz)$ Eq. (29) gives us

$$f = EIk^2 + \frac{\zeta}{k^2} \tag{30}$$

The total compressive force in axial direction can be decomposed into two components as

$$f = f_0 + f_{extra} \tag{31}$$

f_{extra} is additional compressive force due to nonlinearity in strain of IF under the buckling with large amplitude. Nonlinear strain component is given by (Timoshenko and Woinowsky-Krieger 1959)

$$\varepsilon_z = \frac{\partial u_z}{\partial z} + \frac{1}{2}\left(\frac{\partial w(z)}{\partial z}\right)^2 \tag{32}$$

u_z represents, axial deformation of IF. By elasticity thoughts, we have a mathematical relation for cytoskeleton components as

$$f_{extra} = \frac{ES(1-\nu)}{(1-2\nu)(1+\nu)}\left(\frac{\partial u_z}{\partial z} + \frac{1}{2}\left(\frac{\partial w(z)}{\partial z}\right)^2\right) \tag{33}$$

Where ν and S are poison's ratio and cross-sectional area of IF respectively. As at kinetically constrained equilibrium, tractions along IF/cytoplasm vanish, the axial force f_0 in IF should be independent of z. Therefore from Eqs. (31) and (33), we have

$$u_z = -\frac{1}{8}kA_{eq}{}^2\sin(2kz) \tag{34}$$

Eq. (33) then becomes

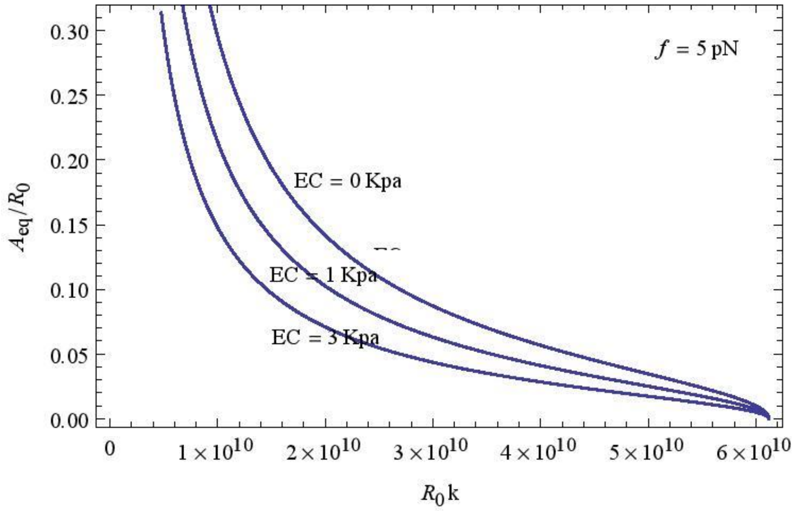

Fig. 4 Comparison of normalized buckling amplitude and wave vector

$$f_{extra} = \frac{ESk^2 {A_{eq}}^2(1-\nu)}{4(1-2\nu)(1+\nu)} \tag{35}$$

By using Eqs. (30) and (35) into Eq. (31), we have the buckling amplitude

$$A_{eq} = \sqrt{-\frac{4(1-2\nu)(1+\nu)(EIk^2+\frac{\zeta}{k^2}-f_0)}{(1-\nu)ESk^2}} \tag{36}$$

Figs. 3 and 4 show the plot of standardized IF buckling amplitude at kinetically constrained equilibrium $\frac{A_{eq}}{R_0}$ as a function of standardized buckling wave number R_0k for a variety of values of axial compressions f and adjacent filament system elasticity E_C, respectively. For the given fixed value of adjacent filament system elasticity E_C, the buckling amplitude A_{eq} increases as f is increased. The intersection of every arc through parallel axis is in contact in the direction of $k_{cr}^{\pm}$. These figure shows that the buckling amplitude, decreases with the increase in the intensity of surrounding filament network elasticity E_C and also the range of possible buckling wave umber. So it is easy to say that the adjacent filament system has great impact on the buckling amplitude of IF. Therefore it is necessary to estimate the buckling amplitude of such type of nanofibrous in their actual environment within the cell. In the present study, we used the Poisson's ratio ν =0.49999 (Sirenko *et al*. 1996, Tseng *et al.* 2002).

5. Conclusions

In the present study, Euler beam theory is applied to investigate the buckling behavior of intermediate filaments by considering the effects of viscous cytosol. The study reveals that critical buckling force is affected in the presence of viscous cytosol and its magnitude will increased. The graphical results obtained are compared with results obtained in free medium also the results for different forces and elastic effects are compared to each other's. At the end, it is easy to conclude that viscous medium has great impact on the buckling behavior of intermediate filaments; therefore it is the need to take into account the actual medium while studying the nanofibrous in the cell.

Declaration of Conflicting Interests

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