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An insight into research perspectives of Tensegrity Structures

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ABSTRACT

Ever since they were first proposed in the 1950s, tensegrity structures have been put to intensive studies by many researchers in various parts of the world. Though during the earlier days they were applied in the fields of art and architecture, later on, due to their advantageous features, they have found application in other areas including aerospace structures, cell mechanics, civil engineering and robotics. In this paper, the author has endeavoured to present a broader look into historical perspectives, applications, design and advanced concepts related to tensegrity structures, based on a review of several research papers, spanning across more than half-a-century. The author also has, from her own understanding of the literature, has suggested guidelines and recommendations for carrying out further research in this exciting and still-emerging field.

KEY WORDS: Tensegrity, form-finding, configuration, pre-stress, stiffness, deploy ability, applications.

1. INTRODUCTION

The acronym 'tensegrity', coined and popularized by Buckminster Fuller from the words 'Tension' and 'Integrity', refers to those structures which are special types of trusses whose members have special functions. It demotes the integrity of structures based on shifting of loads between members in a balanced state of tension and compression. These structures are simultaneously reasonably economical and resilient in nature. They are built of struts and cables; struts bear the compressive forces while cables bear tension. Such cable-strut configurations, with continuous cables and discontinuous struts prevalent in a stable equilibrium, can alone be called tensegrity structures. The tensioned cables of the structure are self-stressed such that the entire system could be in stable equilibrium prior to the addition of any external loads, including the gravitational force. Struts cannot be attached to each other through joints, since that would impart torques.

Tensegrity is a pattern that results when a continuous ‘push’ and a discontinuous ‘pull’ have a win-win relationship to one another. The pull is balanced by push, producing the integrity of tension and compression. This basic phenomenon does not counter, but complement each other to keep up the structure in equilibrium. The design patterns followed in these structures are: 1. Load the members either in pure compression or in pure tension, so that the structure fails only when either the cables yield or the rods buckle. 2. Preload or tensional pre-stress, which allows cables to be rigid in tension. 3. Mechanical stability, which allows the members to remain in tension/compression due to an increase in the stress, as shown in Fig.1.

Figure.1. Mechanical stability of structures

Due to these patterns, no structural member experiences a bending moment, thus producing exceptionally rigid structures for their mass and for the cross section of the components. Motro (2010) described tensegrity as a system in a stable, self-equilibrated state containing a discontinuous set of components in compression inside a network of components in tension. Changes in length of struts and cables can be made through various actuation strategies. Strut-based actuation, employing telescopic members, has been used in active tensegrity control applications. Research has mainly concentrated on theoretical studies on the mechanics involved, by conducting tests mainly on small-scale models rather than full-scale structures. The pre-decided tension in cables and compression in bars are known as unilateral properties of the components. They are classified as class 1, where bars do not touch, and class *n*, where at most ‘*n’* of the bars connect at joints. The process of finding an equilibrium configuration, termed as form-finding, is a key step in the design of a tensegrity structure. Form-finding is the process of finding equilibrium and a stable geometry.

History: The beginnings of tensegrity concept go back to 1921, when the Russian artist Karl Loganson contributed some work to Russian Constructivism exhibit. Artist Kenneth Snelson was the first to create the innovative 'X-piece' sculpture in 1948. In 1949 Fuller commissioned a mast as a tensegrity structure, shown in Fig 2. The Skylon tower of 1951 follows typical Tensegrity concept. But, there are variations such as the 18- metre Needle Tower of 1968, which involves more than three cables meeting at the end of a rod. These cables define the position of the end of the rod which is considered as a well-defined point in space and the other additional cables are simply attached to this well-defined point. Eleanor Hartley describes visual transparency as an important aesthetic quality of these structures. The simplest three-dimensional example is the T-3 structure.

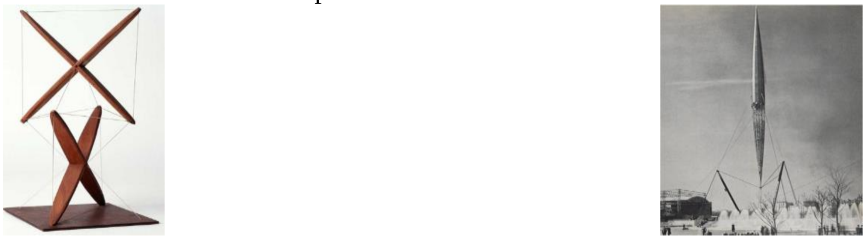

Figure.2. Fuller's mast as a tensegrity structure

Merits and Demerits: There are several merits on which these structures receive new attention from mathematicians and engineers: a) As the load is distributed in the whole structure, there are no critical points of weakness. b) They don't suffer torsion and buckling of any kind of torsion and due to space arrangement and short length of compression members. c) Forces are transferred naturally, and consequently, the members position themselves precisely by aligning with the lines of forces transmitted in the shortest path to withstand the induced stress. d) They are able to vibrate and transfer loads very rapidly and hence absorb shocks and seismic vibrations which makes them applicable as sensors or actuators. e) They can be extended endlessly through adding elementary structures. f) Structures with tensegrity principle are highly resilient as well as economical. (g) An increase in the use of tensile members can lead to large stiffness-to-mass ratio. (h) They use longitudinal members arranged in an unusual and non-orthogonal patterns to achieve strength with small mass. (i) They are deployable and can be easily transported. (j) They are easily tuneable. (k) They can be more reliably modelled. (l) They facilitate high precision control and might lead to major advances in the precision of controlled structures.

Some disadvantages of tensegrity are: a) Problem of bar congestion in larger size designs i.e., when the arc length of a strut decreases, the struts start running into each other. b) Fabrication complexity is also a hurdle for floating compression structures. Spherical and domical structures are complex, which can lead to problems in production. To support critical loads, the pre-stress forces should be high enough, which is difficult in larger constructions. c) Adequate design tools are not available for their design. d) Larger structures cannot withstand loads higher than the critical, related to their dimensions and pre-stress.

Applications: Tensegrity towers can have the following applications:

Lightning conductors: As it is not required to have these elements in a completely static situation and they tolerate certain small movements, they could serve perfectly for this application. It is depicted in Fig.3.

Communications: In situations where the margin of displacements is not very strict, tensegrity towers can be employed to support antennas, receptors, radio transmitters, mobile telephone transmitters as shown in Fig.4.

Wind parks: The lightness of these towers, as shown in Fig.5, could minimize the visual impact of these energetic installations.

Figure.3. Lightning towers

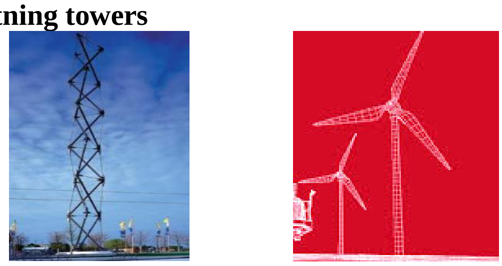

Figure.4. Towers used in communication **Figure.5. Wind Towers as Tensegrity Towers**

Aesthetic elements: They enhance the visual landscape of an area. The Tower of Rostock demonstrates this aspect.

Roof Structures: An important example of this is the stadia at La Plata in Argentina, based on a concept by architect Roberto Ferreira.

Outer Space Structures: Since the beginning, one of the most recurring applications found for the floating-compression has been its speculated use in moon-colonies which are foldable, extremely light, Omni-triangulated, pre-stressed, etc.

Smart Structures: Being static, civil structures should actively adapt to changing needs, such as load modifications, temperature variations, support settlements and damage occurrence.
Bridges: Double grid systems have resulted in the use of Tensegrity to bridge construction like Kurilpa Bridge in Brisbane, Australia, the world's largest.
Configuration and Form-Finding: Finding an equilibrium configuration of a tensegrity structure is known as form-finding. The difficulties in form-finding problem are to find the self-equilibrated configuration that satisfies specific properties required by the designers in an efficient way. This geometric research resulted in a large number of configurations classified as diamond, circuit and zig-zag by Pugh (2016). A zig-zag configuration is depicted in Fig.6.

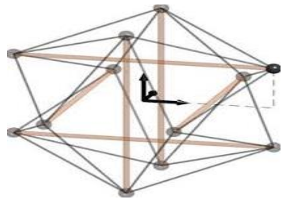

Figure.6. Zig-zag Configuration

The existing methods are of two broad families, kinematical and statical. There are three kinematical methods, which determine the geometry of a given tensegrity structure by maximising the lengths of the struts while keeping constant the given lengths of the cables:
Analytical approach: An approach which takes advantage of the symmetry of structures was introduced by Connelly and Terrell.
Non-linear optimisation method: The simplicity of the kinematical method for structures with v-fold symmetry is mirrored by the static method. But, for non-symmetric cases this formulation becomes infeasible due to the large number of variables required.
A pseudo-dynamic iterative method: The method of dynamic relaxation that had already been successfully used for membrane and cable net structures was put forward by Motro and Belkacem as a general form-finding method for tensegrity structures.

The four statical methods decide the likely equilibrium configurations of a tensegrity structure with a given topology, i.e. a given number of nodes and connecting elements between them:
Analytical solutions: Kenner used node equilibrium and symmetry arguments to find the configuration of expandable octahedron. More complex, spherical tensegrities with polyhedral geometries, i.e. the cuboctahedron and the icosidodeca-hedron, were also analysed using this approach. Connelly and Terrell have used an equilibrium approach to find the pre-stress stable form of rotationally symmetric tensegrities. They used force density, i.e. force divided by length, as variable for each element.
Force density matrix method: First proposed by Linkwitz and Schek in 1971, it uses a simple mathematical trick to transform the non-linear equations of the nodes into a set of linear equations. A basic principle in the analysis of the stability of structures is that the total potential energy functional should be at a local minimum for a given configuration to be stable.
Energy minimisation approach: It produced a matrix identical to the force-density matrix and introduced the concept of super-stable tensegrities. A basic principle is that the total potential energy functional should be at a local;
Reduced Coordinates Method: It searches for equilibrium configurations of a set of rigid bodies, i.e. the struts of the tensegrity structure, connected by cables whose lengths should be determined. A reduced set of equilibrium equations for the struts are determined by virtual work, making use of symmetry conditions, and are then solved in symbolic form. Introduced by Sultan (2009), it considers a tensegrity structure whose b elements consist of M cables and O struts. The struts are considered as a set of bilateral constraints acting on the cable structure.
Active Tensegrity: Active tensegrities are those structures which can control their shape and adapt to changing tasks as well and environments, by changing their self-stress, whereby they continue to satisfy their safety and serviceability criteria. Extensive research works are underway to study theoretical aspects of control of tensegrity structures whose geometrical behaviour is non-linear and coupled. There are three objectives in controlling the tensegrity structures, namely, maintaining the shape, minimizing deflections and structural optimization. Many authors have reported on shape maintenance using control. By changing strut lengths, Djouadi (1998) controlled the vibrations of four tensegrity modules that form a cantilever beam. Sultan (2009), by changing cable lengths, controlled the shape of a one-module structure and using symmetrical motion based on Lagrangian dynamics, they controlled the height of the upper level under loading. Fest (2003), experimented on a three-module manually-adjusted structure and reported that nonlinear geometrical behaviour occurs for cases of: i) small deflections, ii) loads being applied to several joints and iii) combinations of telescopic struts being adjusted. Festin 2004 designed a fully active, asymmetric tensegrity structure with five modules by embedding a control system based on stochastic search.

Fest (2003), followed by Adam (2008), demonstrated the possibility of utilizing control to maintain relationships between nodal points. Adam's work involved the selection of multiple objectives such as slope, stress, stroke and stiffness.

The second objective of minimizing deflections has also been studied by some authors. Djouadi (1998), by means of instantaneous optimal control, was able to minimize deflections. With respect to the third objective, i.e., structural optimization, Adam, Raja, and Milenko Masic (2005), are the researchers whose works are found to have been predominantly reported in the literature. Adam (2008), developed an algorithm which satisfied multiple objectives. Masic and Skelton (2005), through an initial selection of parameters like pre-stress forces of the members, showed that the Linear Quadratic Regulator (LQR) control output could be optimized. All these works aim to create simultaneous control and optimization of a tensegrity structure. These objectives can be accomplished in one of three ways, namely, search methods, H-Controller and LQR algorithms.

2. METHODS & MATERIALS

Methods of Analysis: Analysis of tensegrity structures involves the process of investigation of their geometrical and mechanics, termed as static and dynamic analysis, respectively. In the backdrop of the controversy of the origin of the field (presumably 1921), it was not before nearly half-a-decade had passed by, that a detailed study on them was made when Fuller in 1975 and Pugh in the following year gave detailed reports on static analysis. A theoretical framework for dynamic analysis was later established using Maxwell's rule which states that a truss having *b* bars and *j* joints will be stiff if b =3j-r where r is number of reactions.

In the year 1978, using linear algebra, Calladine obtained the number of "incipient" modes of low-order stiffness depending upon the number of bars, joints and independent states of self-stress. Pellegrino and Calladine in 1986, showed that composition and analysis of an equilibrium matrix, linking the nodal loads to the member forces, provided deeper insights into the properties of structures. Hanaor (1992), and Liao analyzed Double Layer Tensegrity Grids (DLTG) based on flexibility approach. They used first order linear analysis method for the same. Hanaor, experimentally investigated a 3-unit span DLTG comprising seven triangular prismatic units and reported that the actual response was non-linear and higher than that predicted by the linear model. Sultan et al. used the principle of virtual work to formulate the general pre-stressability conditions for tensegrity structures expressing the conditions as a set of nonlinear equations and inequalities, and found the state of stress of the structure to depend only on scalar parameter i.e. the pretension coefficient. Murkami and Nishimura (2001), using the modal analysis, reported infinitesimal mechanism modes at pre-stressed configurations increased proportionate to the square root of the amplitude of the pre-stress mode. Further, they derived initial configurations and pre-stress modes for regular truncated icosahedral and dodecahedral tensegrity modules. A classification of the infinitesimal mechanism modes into subspaces based on the natural frequencies was also accomplished by them. Cesar (2001) and Crane (2005) combined virtual work and geometry of lines so as to determine the equilibrium position of a tensegrity structure subjected to external forces and external moments by static analysis. They considered anti-prism tensegrity structures, assuming struts as mass-less, of same length, with only one external force applied per strut and no dissipative force acting on the system and arrived at a Matlab-based solution using Newton-Raphson method and a verification using Newton's Third Law.

Most important research on tensegrity dynamics has been mainly focused on the study of the force-displacement relationship, i.e., how the structure changes its shape under the action of external forces, studying oscillation damping and frequency or geometric deformations. This study is necessary from viewpoints, namely, to study the behaviour of a structure subjected to external perturbations as also to find out the new stable configuration under such conditions. The first view consists in considering the structure to be at an equilibrium configuration experiencing small perturbations around it, not taking into account any dynamic issue, but just the geometry of the tensegrity structure. Final stable configuration under external perturbation can be found. The changes in the shape of the structure so as to reach that configuration are not uncovered. The second view regards the structure to be at an arbitrary position, experiencing large deformations. Fig. 7 illustrates the same.

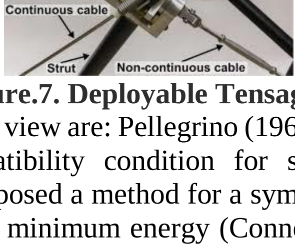

Figure.7. Deployable Tensagrity

Some of the studies based on the first view are: Pellegrino (1965) analyzed the behaviour of the system using the equilibrium condition and the compatibility condition for small perturbations around an equilibrium configuration. Oppenheim and Williams proposed a method for a symmetric structure which takes into account the fact that all equilibrium configurations have minimum energy (Connelly (2011). Either Newtonian or Lagrangian formulation has been used to arrive at the force-displacement relationships which are valid in any configuration. The former is based on Newton's second law of motion and simpler too. It may be used to completely characterize tensegrity structures by either the Euclidean position of a given point (i.e. the centre of mass) and its orientation or by the Euclidean position of each vertex (assuming the mass of each bar to be concentrated in its vertices. Kanchanasaratool and Williamson (2004), among many others, studied a 6-bar tensegrity platform. They developed a simplified particle system model with unitary point masses at the nodes which are subjected to geometric constraints. Skelton (2014) found a simplified version for a class-1 tensegrity shell, by formulating a non-linear system of equations and finding an analytical expression. The same was extended to structures with 'n' rigid bars, further by using matrix differential equations instead of vector differential equations. It was shown by de Jager and Skelton (1998), that a lineraized version of the model around an equilibrium configuration can itself be used in practical applications. However, most of the dynamic models found in literature for structures are based on Lagrangian formulation. Joseph Louis Lagrange described the movement of a mechanical system as the solution of a system of second order differential equations, called the Euler-Lagrange equations. Motro (2003) determined the transfer function between an input excitation and the structure oscillations. Sultan (2009) and Sultan used Lagrange formulation for Saddle, Vertical and Diagonal (SVD) cables. Murakami (2001), Murakami and Nishimura (2016), modelled the dynamic behaviour of a tensegrity structure taking into account additional non-linear effects.

As for the second point of view, wherever empirical data are available, model estimation techniques can be used. Bossens (2014), developed a method to identify a linearized dynamic model of a tensegrity structure around a stable configuration. The two-stage SVD tensegrity structure used by Sultan (2009), can be parameterized by the position and orientation of the top platform with respect to the bottom platform and the declination and azimuth angles of all the bars. Barnes (2014), classified the analytical methods for the simulation of such structures as incremental, iterative and minimization. Incremental and iterative methods use the matrix formulation of finite elements (Reddy (2010). Furuya (2003), presented a work consisting on dividing the structure in a large set of small, simpler, linked elements, and then apply the problem constraints to all of them. Belkacem (2016) suggested a dynamic relaxation method based on the minimization model, which is being widely used. Domer (1935), studied the tensegrity geometric non-linearities by using neural networks to improve the accuracy of the dynamic relaxation method and obtained a better fit of the real measured data.

Self Deployability: A system that can exist in two or more distinct configurations is termed deployable. One of these configurations is operational, and in this state the system is said to be 'deployed'. The other configuration is non-operational and is known as the "redeployed", which is usually used for transporting or storing the system. An n-strut tensegrity system can be designed to be deployable by using elastic ties for the leg ties, thereby forcing its struts together along their lengths and held in place by external forces. In this new configuration, the leg ties are stretched to the length of the struts and the tension in the top and bottom platform ties is removed. The system remains in this state until the external forces are removed, after which the internal force in the leg ties pulls the struts out until the system returns to its deployed tensegrity state. Fig.8 is a depiction of the components of such a structure.

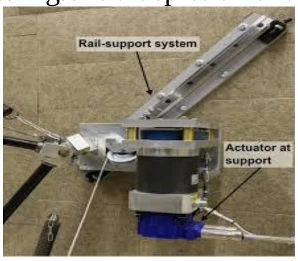

Figure.8. Components of a Deployable Structure

The capability of a system to return to its deployed state without external forces is called a self-deployable system and this makes an n-strut tensegrity an excellent platform for deployable systems in space as well as systems that need rapid deployment. The top and bottom ties of the tensegrity system can be replaced with elastic ties or elastic material, though this is no requirement for the system to be self-deployable. However, the system would still only require an external force to be transformed into the redeployed state and held in that configuration. Having known the geometry, the design of such a system involves

Once the desired geometry of the system is known, the first step in the design of a self-deployable tensegrity, based on its function, is to determine the materials to be used. The yield stresses and modulus of elasticity can be identified from material property handbooks or results of testing. If the materials to be use can vary, then the desired stiffness can assist in conducting the material selection. The material with the highest yield stress to modulus of elasticity ratio will obtain the maximum stiffness, whereas the one with a lower value may be selected if the maximum stiffness is not desired. Once the materials of the ties are identified, the geometric stiffness ratio of the tensegrity is calculated. The success of any deployable structure lies in the actual deployment; it does not matter how accurate or stiff the structure is in its deployed state if it fails to deploy.

The deployment of any structure relies entirely on the way the struts are unfolded; the unfolding rate must be easy to control. Knight lists four possible solutions for strut deployment, namely, hinged struts, sliding coupling struts, telescopic struts, and inflatable struts. Hinges of various types have been used on deployable systems for several decades. A simple and reliable hinge is the Tape-Spring Rolling (TSR) hinge. Its automatic locking capability makes it especially useful for this application. A sliding coupling, with a locking mechanism, is an alternative to the hinge. With sliding couplings it takes minimal force to deploy the strut but significant force to stow it again. However, sliding couplings are fairly new and also introduce stiffness non-linearities. Telescoping structures have not been used very often in space applications due to excessive weight and drive force required. The last option is to use inflatable struts. This approach can minimize the stowed volume, but the size and weight is comparable to the three previous schemes. An inflatable strut would use manufacturing and inflation techniques similar to those of inflatable antennas. After inflation, the struts need to be made rigid to ensure their structural integrity throughout the mission lifetime. A rigid strut would have a uniform cross-section and a minimum of stiffness non-linearities. One design issue, which is critical for deployable structures with cables, is snag prevention. There is a potentially large risk that the long slack ring cables get caught or looped around a strut during deployment. To avoid snagging they must be stowed in a clever way. Knight and Duffy studied the possibility of using highly elastic cables, which efficiently prevent snagging. However, in such an approach the structure is subjected to very high stowage forces and stiffness creep.

Stiffness: Stiffness of tensegrity structures arises from two sources, namely change of force carried by members as their length is changed and the reorientation of forces as stressed members are rotated. Both these sources play a critical part. Stiffness changes as the level of pre-stress in a member varies. For a particular stable tensegrity, increasing a low-level of pre-stress will increase the stiffness and for high levels of pre-stress, an originally stable tensegrity can be made to have zero stiffness or negative stiffness, or indeed be made unstable. Schenk (2007) had shown that the stiffness of tensegrity structures depends not only on connectivity, geometry and material properties of the structure, but also on the level of pre-stress that the structure carries, with the dimension-less parameter 'ε' playing a key role. Their major contribution is the suggestion of the parameter 'ε', and how the stiffness of two carefully chosen tensegrity structures vary as 'ε' varies from 0 to 1. Fig. 9 is a description of Zero stiffness tensegrity structures. They are structures with zero free-length springs, affine transformations (scaling/shear) and preserve length of conventional members.

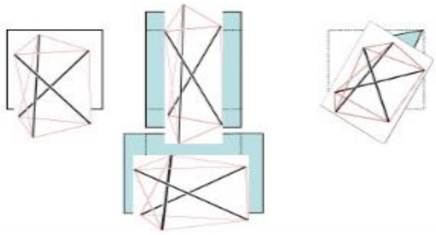

Figure.9. Zero Stiffness Tenssegrity

The role of pre-stress in stiffness of tensegrity structures is to postpone the slackening of cables. A high pre-stress could result in instability of the structure due to buckling and yielding of compressive and tension elements, respectively. Non-linear flexibility analysis is suitable for finding the most flexible directions of tensegrity structures and their dependence on different pre-stress levels. Increasing the buckling safety factor decreases the stiffness of the structure. The advantage of increasing the buckling safety factor is a higher capacity for pre-stressing. DalilSafaei (2011), has concluded from his studies that the structures composed of modules with separated states of self stress have higher stiffness values than the Snelson-type with just one state of self-stress for any number of modules.

Schenk (2007), stated that tension members with a zero rest length allow the construction of tensegrity structures that are in equilibrium. They investigated zero-stiffness modes introduced to tensegrity structures by the presence of zero-free-length springs. In the absence of external loads and constraints, affine modes are statically balanced zero-stiffness modes. Those modes involve changing spring lengths, but require no energy to move, even over finite displacements. For pre-stress stable tensegrities with a positive semi-definite stress matrix of maximal rank, we further showed that these are the only possible zero-stiffness modes introduced by the zero-free-length springs. It was further shown that such length-preserving affine transformations are present if and only if the directions of the conventional elements lie on a projective conic. This geometric interpretation revealed an entire family of tensegrity structures that can exhibit zero stiffness, and led to a simple method for determining the number of independent length-preserving affine modes.

Collapse: Collapse, or local collapse as it may also be called, is a phenomenon in tensegrity structures which is caused by the buckling of struts and/or rupture of cables and it affects a small portion of the system. This may propagate to other parts of the system, thereby resulting in the overall failure. This is known as progressive collapse. Further, behaviour of struts under compression such as snap-through, also termed as dynamic jump, and cable ruptures under tension may also result in abrupt structural collapse. Such member failures have a dynamic effect on the behaviour of the entire system, thereby releasing a large amount of kinetic energy, and hence it is imperative to consider dynamic effects like rapid redistribution of member forces and the inertia forces caused by the member failure, in the evaluation of the behaviour of the system. It has been shown, both experimentally and numerically, that the load level at the member-failure occurs has a dominating influence on the dynamic propagation of local collapse. This apart, self-stress level, slenderness ratio, effective-length factor of the struts and damping ratio of the structure are the other important parameters on the propagation of local collapse in tensegrity systems.

Numerical study on the propagation of snap-through and parametric analysis by Shekastehband (2012), have revealed various parameters having a significant impact on the progressive collapse of these systems. The studies by Shekastehband to examine the collapse behaviour of the tensegrity systems due to buckling of a strut at a critical load level have observed that the kinetic energy released due to the progressive collapse was so large that it led to the torsional buckling of the supporting beams. Shekastehband (2012) presented a numerical study on the progressive collapse behaviour of tensegrity structures due to the buckling of struts with a greater emphasis on the dynamic nature of the coupled member and nodal snap-through effects on the overall structural behaviour.

3. CONCLUSION

This paper has made a modest attempt at throwing light on the various research activities on tensegrity structures in the past. In this section, the author outlines directions for possible future work as found in the recent literature. Porta Josep and Sergi Hernández-Juan (2016) have pointed out the presence of configurations in path-finding, where the number of mechanisms, i.e., self-motions of the structure changes, wherein the kineto-static performance of the framework degrades, thus causing control issues. Such configurations are known as singularities. They have suggested two methods to deal with this issue; one is the usage of special planning and control procedures and the other one is avoiding the singularities. Furthermore, in order to deal with those integrity structures which need to move at high speed or interact with objects in the environment or interact with the ground, they have planned to use high-dimensional continuation tool.

Ashwear (2016) have observed that, while regulating the pre-stress level in each module, the ratio between the internal forces and the diameter of each component must be considered. This would reduce the amount of material used and hence the weight of the structure. It is interesting to study the proposed optimization problem. They have also proposed to separate at least the first 6 modes using different objective functions but with the same constraints. Ashwear (2014), in their study on influence of temperature on the vibration properties of tensegrities, have suggested that different damage scenarios and levels need to be investigated, for instance the effects of slacking in different cables and with different levels of reduction in tension. Cai Jianguo and Jian Feng (2015), as a form-finding method, have put forward certain advanced optimization models, such as Genetic Algorithms (GA), to be used so as to be applied on complex tensegrity structures, as part of their future work.

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