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Sensitivity analysis of tensegrity systems due to member loss

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ABSTRACT

Tensegrity systems typically contain a large number of members, and possess a high degree of statically indeterminacy. However, a number of members are critical to system integrity and serious strength reductions can be produced by loss of any of them. Furthermore, when these members are lost suddenly, their forces are shed in a dynamic manner into the structure, causing more severe damage. This paper presents a numerical study on the sensitivity of tensegrity systems to both gradual and sudden member losses, taking into account both geometric and material nonlinearities. Also, other parameters, considered in this work, include the self-stress level, slenderness ratios of struts and damping ratios. The conclusions, drawn from this study, can in turn, lead to the suggestion of some guidelines for the design of such systems.

1. Introduction

Tensegrity systems are innovative systems in the spatial structures field and refer to a special type of tensile structures that can offer an alternative to traditional space structures. A tensegrity structure is defined as "a system in a stable self equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components" [1]. These systems exist under pre-stressed (self-stressed) configurations. The initial stresses contribute to the system's rigidity and stability.

Tensegrity systems have specific advantages that merit their consideration for use as engineering structures. First, most tensegrity structures are lightweight structures, making them suitable for various space applications [2]. Second, their members can serve simultaneously as sensors, actuators and load carrying elements. Therefore, having incorporated sensors and actuators, tensegrity structures have considerable promise as smart structures [2]. Third, for using as a mechanism in the folding process, the lengths of the tension links (cables) can be easily adjusted. The folding and deployment capabilities of these systems will allow the use of tensegrity systems as deployable space structures with promising future aerospace applications. Fourth, tensegrity systems are capable of large displacement, belonging to the class of flexible structures [3].

There are also several disadvantages that must be overcome to make tensegrity structures useful. First, most tensegrity systems are not conventionally rigid; they usually exhibit an infinitesimal mechanism and must be pre-stressed to resist deformation in the direction of the mechanism [4,5]. Second, tensegrity systems generally tend to be susceptible to vibration because of the infinitesimal mechanism [5]. Third, tensegrity systems only exist under specific geometries. The nodal positions cannot be specified arbitrarily for a tensegrity structure. Thus, some positions cannot be achieved with a tensegrity structure [6].

Tensegrity systems are mainly statically and kinematically indeterminate systems. They typically contain a large number of members, and possess a high degree of statically indeterminacy. The stability analyses performed on these systems have indicated that despite of high redundancy, buckling of a strut (or set of struts) or rupture of a cable may cause a progressive collapse to occur [7,8]. In fact, in the case of local collapse in which strut snap-through or cable rupture is occurred, a large amount of kinetic energy is released at a local region of the structure, which can cause the overall collapse of the system.

There are some researches regarding the effect of member loss on the ordinary space trusses, studied by many researchers as Hanaor [9], Murtha-Smith [10], El-sheikh [11] and Malla [12]. It was illustrated that a loss of a member in a critical truss area was more serious than a loss in another area. Since this phenomenon was rapid, dynamic effects could develop, leading to a further damage in the space truss. Ben Kahla and Moussa [13] have performed a numerical investigation into the effect of sudden rupture of a cable component in a beam-like tensegrity system, without applying external loads, using nonlinear dynamic time history analysis. Oppenheim and Williams [5] examined the dynamic behavior of a simple elastic tensegrity structure. It is confirmed, analytically and numerically, that the energy decay

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of such a system is slower than that of a linear-damped system. Abedi and Shekastehband [7] have studied the stability behavior of continuous strut square grids with node-to-node connection of simplexes under static loading conditions, taking into account the effects of post-buckling response of the struts and post-yield response of the cables. Nevertheless, so far no study was conducted to confirm and examine the effect of member loss on the nonlinear behavior of double layer tensegrity systems under external loads.

In tensegrity systems, a number of members are critical, with the loss of any of them likely to produce serious strength reductions. When a member is lost suddenly in tensegrity system which is under load, e.g. due to the failure of a faulty connection, the energy stored in the system is released and this induces a state of transient vibration about the new equilibrium position. The members of the system will therefore experience transient forces and displacements greater than the values derived from static analysis, and consequently, there is the possibility that these dynamic forces may cause buckling of a struts or rupture of a cable. Failure of a second member will cause further vibration resulting in progressive collapse of other members before a new equilibrium state is reached. It is, therefore, important to account for the dynamic effects caused by the member loss in the evaluation of response of these systems in the cases that member loss occurs.

In practice, members of a tensegrity system may be lost due to a poor member node connection. In fact, having one or more faulty connections in a structure, containing hundreds of connections, is a realistic possibility. The existence of geometric imperfections (e.g. lack of fit) may cause this to occur prematurely under a small portion of the total design load. In such a case, it can be argued that this member has in effect been lost [11].

Generally, progressive collapse lasts for a short duration. Therefore, it is impossible to prevent progressive collapse in a structure once it occurs. This increases the importance of understanding response of the structure during member loss. One of the most effective methods to assess the vulnerability of a structure to progressive collapse is the alternate path analysis method. In this method, the defected structure is analyzed at specified load level (e.g. design load level) to investigate the performance of the structure under distributed loads due to member loss. Then, in order to avoid the propagation of local collapse, the structure is designed in a way to sustain local collapse (i.e. member loss) and produce a new path to transmit the loads [10].

In the present study, a numerical investigation into the static and dynamic response of tensegrity systems in the event of gradual and sudden member loss was carried out. The study includes progressive collapse in two configurations. The response and characteristic of the studied structures include load- deflection response in static analysis and displacement–time history of the configurations in the dynamic analyses.

The aims of the present study are as follows:

- Identifying the critical members by assessing vulnerability of tensegrity systems upon removing them;
- Determination of the collapse mechanisms of tensegrity systems due to gradual and sudden member loss;
- Evaluation of the effects of various parameters as self-stress level, slenderness ratio of struts and damping ratio on the progressive collapse of these systems.

2. Method of analysis

The tensegrity systems were analyzed using ABAQUS [14], a nonlinear finite element software package. Configuration processing was performed using 'FORMIAN' [15] together with supplementary software (Mechanical Desktop) by which the input data was interactively submitted as an ABAQUS input file. There are

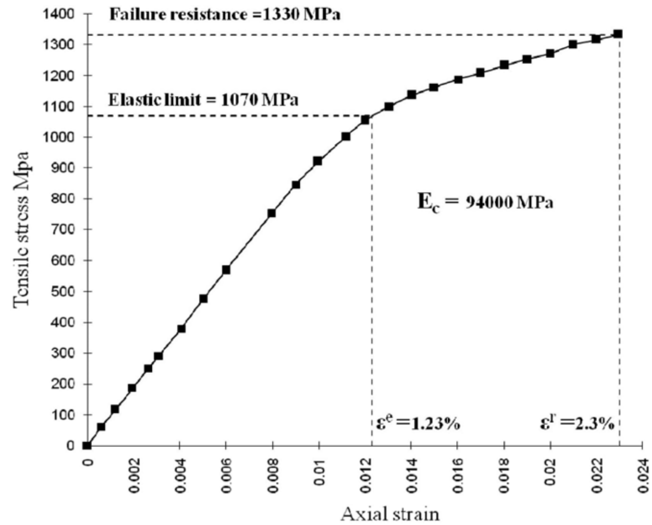

Fig. 1. The strain–stress response of the cables [16].

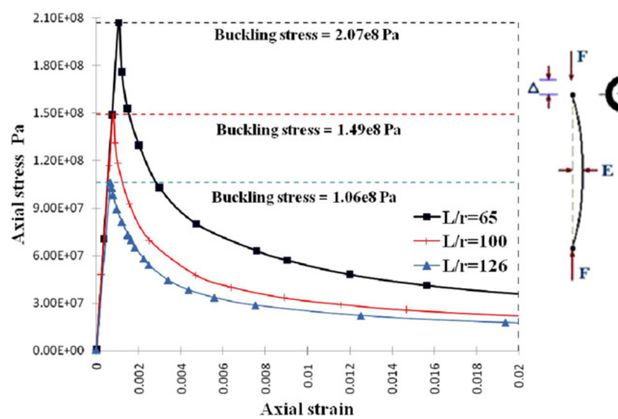

Fig. 2. The axial strain-axial stress responses of the struts with slenderness ratios of $L/r = 65$, 100 and 126 [7].

several main causes of geometrical and material nonlinearity in tensegrity structures. Therefore, material and geometrical nonlinear analysis should be undertaken [7]. The cables and struts were modeled as simple two-node truss elements with unilateral rigidity of tension and compression, respectively. The tension characteristic of the cables considered in the present study was as shown in Fig. 1 [16]. Fig. 2 illustrates the axial strain-axial stress responses of the struts with slenderness ratios of $L/r = 65, 100, 126$. These responses of the struts with three different slenderness ratios have been determined using material and geometric nonlinear analysis [7].

2.1. Modeling of member loss

In each analysis, only one member was removed from the overall tensegrity systems, and the systems were analyzed to determine the effect. Member loss could be realized either gradually over part of loading history on the model, or suddenly at any load level. The MODEL CHANGE option of ABAQUS is used to simulate removal of elements where it is necessary. If the loss of member is gradual, then the redistributions will be gradual, and static analysis should be adequate. However, if the member loss is sudden, then dynamic effects should be considered.

In the present paper, in each configuration for every member considered to be removed, two analyses were performed. First, with a member loss that took place gradually. In this stage, static