Deployment aspects of a tensegrity-ring pedestrian bridge

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Summary

Tensegrity structures are spatial systems that are composed of tension and compression components in a self-equilibrated prestress stable state. Although tensegrity systems were first introduced in 1950s, few examples have been used for civil engineering purposes. In this paper, tensegrity-ring modules are used for a deployable pedestrian bridge. Ring modules belong to a special family of tensegrity systems composed of a single strut circuit. Assembled in a "hollow-rope" structure, ring modules were shown to be a viable system for a tensegrity pedestrian bridge. Furthermore, ring modules are deployable systems that can change shape by adjusting cable lengths (cable actuation). This paper focuses on the deployment of a tensegrity-ring pedestrian bridge. A geometric study of the deployment for a single module identified the solution space that allows deployment without strut jamming. The optimal deployment path is identified amongst hundreds of possible solutions. Moreover, the number of actuators required and their placement in the module are determined by the deployment path that is applied. Cable-based actuation often has the drawback of having to control too many cable elements. Therefore, a deployment path that minimizes the number of actuated cables was found. The number of actuated cables is further reduced by employing continuous cables. A first generation prototype made of aluminium struts and steel cables was used to verify experimentally both findings. The structural response during unfolding and folding is studied numerically using a modified dynamic relaxation algorithm. A well-known dynamic-relaxation algorithm is extended to accommodate clustered tensegrity structures (tensegrity systems with continuous cables). The deployment-analysis algorithm applies cable-length changes first, to create mechanisms allowing deployment and then, to find new equilibrium configurations. Deployment is thus carried out through an equilibrium manifold. The deployment-actuation step size is identified as a critical parameter for successful deployment. Large deployment steps lead to instable configurations while small steps are computationally expensive. Due to mechanism-based deployment, the total energy in the structural system remains nearly constant during deployment. Elastic potential energy due to cable tension is the highest energy identified while kinetic energy and the work of torque friction on strut-to-strut joints are relatively low. Finally, internal forces increase during deployment but remain low compared with service self-stress values showing that deployment is not a critical phase for the design of the bridge.

Keywords

Tensegrity structures, deployable structures, adaptive structures, pedestrian bridges, dynamic relaxation.

Theme

Tensegrity structures

1. Introduction

Tensegrity structures are spatial pin-jointed systems composed of axially loaded elements in a self-equilibrated

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pretension stable state. Since the introduction of the tensegrity concept during the 1950s, tensegrity systems have received significant interest from scientists and engineers [1-4]. In structural engineering, tensegrity systems offer an attractive solution for lightweight structures due to a high strength to mass ratio. However, there are few examples of tensegrity systems used for civil engineering purposes such as the roof of the velodrome in Aigle (Switzerland) [5]. Furthermore, tensegrity structures are attractive systems for active/adaptive structures and deployable structures as small amounts of energy are required for control and adaptation [6]. Adaptive structures are dynamic structures that can interact with complex environments using embedded actuated elements. A five-module active tensegrity structure was constructed and studied by Fest [7]. Advanced computing techniques enabled the structure to improve service performance using previous experiences and perform self-diagnosis, self-repair as well as vibration control [8-10].

Deployable structures are a sub-class of adaptive structures as active control can be used to control the shape of the structure (from compact to expanded or inversely) and to enhance service performance. Deployable tensegrity structures were first introduced by Furuya who studied deployment approaches for a tensegrity mast [11]. Since, both telescopic struts and tendon control have been used for the deployment of tensegrity systems [12-14]. Tibert and Pellegrino argued that tendon control is more complicated than using telescopic struts [15]. Therefore, they proposed the use of foldable struts and self-locking tape spring hinges instead. Furthermore, they identified the lack of stiffness during deployment and low bending stiffness as obstacles to practical applications for deployable tensegrity masts. Sultan and Skelton showed that cable control allows tensegrity systems to remain close enough to its equilibrium manifold throughout deployment and hence permitting deployable systems to maintain stiffness [16]. However, most of these studies do not explore actuation strategies using continuous cables and do not take into account loading.

This paper presents the deployment of a tensegrity-ring pedestrian bridge using cable control. The deployment-solution space is explored and continuous cables are used to decrease the number of actuators. Static analysis is performed using a deployment-analysis algorithm based on a modified dynamic relaxation method. Deployment is based on a series of intermediate equilibrium configurations. Evolution of the internal forces and energy of the system is investigated for both unfolding and folding.

2. Tensegrity-ring module and footbridge design

Tensegrity-ring module topology was first presented in 1976 [17]. Ring modules are class II tensegrity systems composed of a single strut circuit. Their topology is based on straight prism geometry with an empty space in the middle. Therefore, Motro applied the term "ring module" for their description [18]. Ring modules can be further specified according to their corresponding straight prism. A cable-based deployment is guaranteed by their topology [18]. Cable actuation is used to create finite mechanisms that will allow the module to change length and therefore unfold or fold. The structural response of a deployed pentagonal ring-module was studied by Dung [19]. He concluded that cable stiffness is more important for the overall stiffness compared with strut stiffness. The folding of a single module was studied using FEM applying nodal displacements and allowing slack cables. Although the deployment motion is similar, this method is not suitable for studying deployment actuation.

For a footbridge application, elementary self-stressed ring modules are assembled according to a "hollow rope" concept [18], where the empty space is used as walking space with the addition of a deck. Previous work from the authors showed that the pentagonal ring-module system is viable for a footbridge [20, 21]. In the case of a deployable footbridge, the bridge is composed of two parts of two modules each. In this study, each part of the bridge has an 8 m span. The two parts deploy from both sides of the bridge joining in middle. Figure 1 shows an illustration of a pentagonal tensegrity-ring module and the structural system of the footbridge in service and during deployment. Bridge-module topology includes struts with a length of 5.42 m and two families of cables with lengths of 2.77 and 3.66 m respectively. In order to allow deployment, boundary conditions must allow the required in plane movements (longitudinal movements are blocked). On the contrary, all boundary nodes are blocked during service.

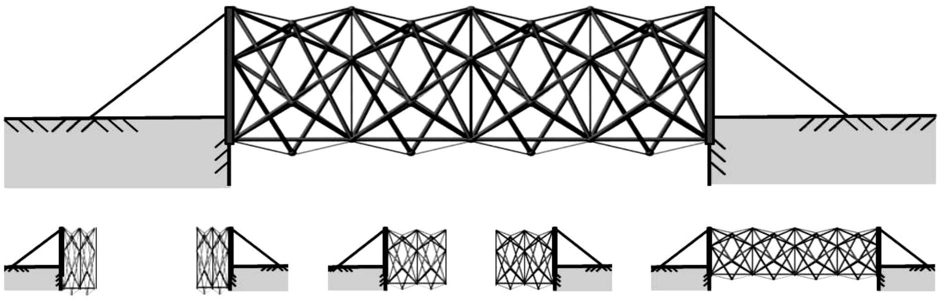

Figure 1: illustration of the structural system of the deployable “hollow rope” tensegrity footbridge

3. Geometric study of the deployment

The deployment of the pentagonal ring module is described with a minimum of three movements and consequently three geometric parameters. The first movement is the translation of the two pentagonal faces (front and back face of the module) along the longitudinal axis of the module. The distance between the two faces defines the module length *L*. Therefore, parameter *L* increases with unfolding with a maximum value L_{max} corresponding to the deployed length (L_{min} corresponding to the folded configuration). The second movement is the transverse rotation θ between the two pentagonal faces. The third movement is the radial expansion of the pentagonal faces described by the radius *R* of their corresponding circumscribed circle. The last two movements allow struts (that do not change length during deployment) to fit inside a new module length. Therefore, both the transverse rotation θ between the two pentagonal faces and the radius *R* of their corresponding circumscribed circle increase with folding. The transverse rotation θ starts from zero reaching a maximum value θ_{max} for the folded length, while the radius *R* starts from a minimum value $R_{\min}$ corresponding to unfolded length. The values of the triplet $\{L, \theta, R\}$ define the module geometry at any position during deployment. However, there is no explicit relation between these parameters since many paths can lead to the same module length. If a deployment path is chosen for a known deployed topology, parameters θ and *R* are related. Consequently, only *L* and θ are required to describe the deployment of the module. Figure 2 shows the deployment-solution space for a module of the deployable tensegrity footbridge. The bridge module has a deployed length of 4 m and a radius of approximately 3.1 m. The solution space allowing deployment without any strut jamming for a single module is given in white. The isometric curves inside the white space represent the closest strut distance varying from 5 to 45 cm (inside to outside). The folded configuration of the bridge module has a length of 60 cm and is obtained with a 0.37 rad (21°) rotation. Two deployment paths are highlighted on figure 2: the path with minimum jamming risk and the path with minimum actuation. Both paths are valid for unfolding and folding. The path with minimum jamming risk is based on the highest distances between struts. However, this path requires the actuation of all 30 cables in a module. Therefore, paths requiring less actuation are explored. The minimum actuation path is found to be similar to the path with minimum jamming risk. An increased folded length of approximately 80 cm and lower transverse rotation θ are the main differences. However, deployment actuation is minimized with a set of 10 non-actuated cables in this path reducing the number of actuators to 20. Non-actuated cables remain in tension throughout the entire path.

A small scale physical model made of aluminium hollow tubes and steel cables was used for experimental validation of the deployment-solution space (figure 3). Alluminium tubes have a length of 1 m resulting in a deployed module length of 75 cm. Joints were designed to allow all required movements for deployment.

The computed solution space and minimum actuation path for the physical model are given in figure 3. The measured path is similar to the computed path with a systematic error of approximately 0.05 rad (3°) in transverse rotation. Folded and unfolded lengths remain the same for both paths.

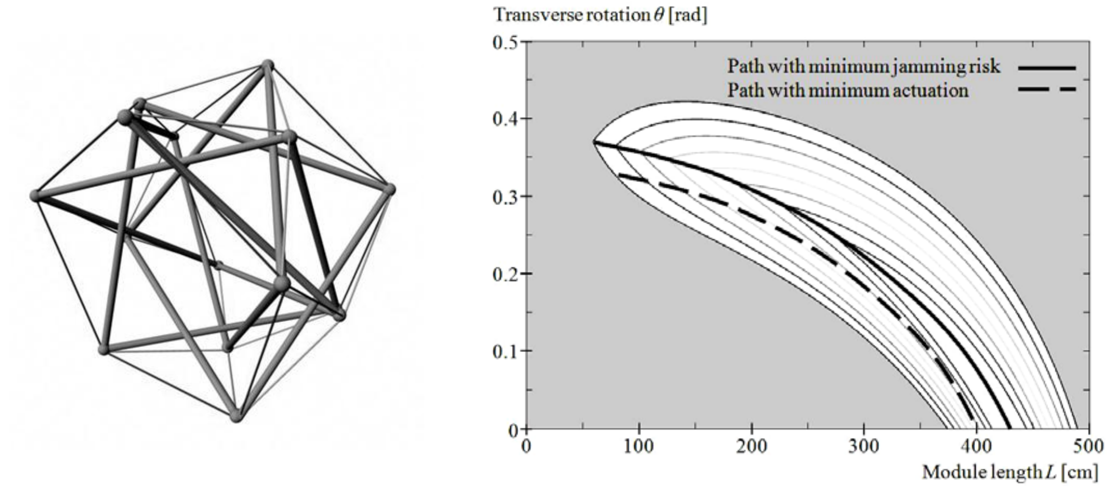

Figure 2: illustration of the pentagonal ring module and the deployment-solution space for the bridge module

In order to further reduce the number of actuators, continuous cables can be used in the module. Continuous cables can replace only cables with identical actions during deployment without any abrupt changes of direction. Moreover, continuous cables may run in more than one module. However, the integration of continuous cables in a tensegrity system affects the number of independent self-stresses states and the number of internal mechanisms in the system. Therefore, continuous cables cannot be applied without prior studying the new configuration [22]. Continuous cables are thus applied only to a limited set of 10 actuated cables (replaced by 5 actuated continuous cables) and not applied to any non-actuated cables. Consequently, the number of actuators is set at 15 for a single module. Deployability with continuous cables was also verified experimentally on the small physical model. Both unfolding and folding were successfully conducted without strut jamming.

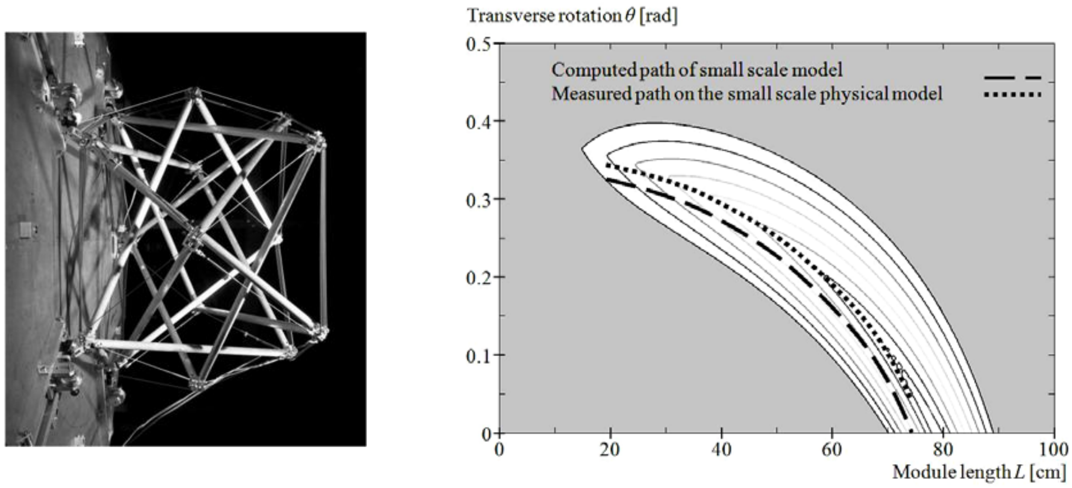

Figure 3: small scale physical model and its corresponding deployment-solution space and path

4. Numerical analysis the deployment

The geometrical study identifies the deployment-solution space including the minimum actuation path but provides no information about the structural response of the tensegrity system or actuation forces. Therefore, a structural analysis of the module during unfolding and folding is conducted with dead load as unique loading. Friction and dynamic effects are excluded of the structural analysis. The analysis is performed using a deployment-analysis algorithm that was conceived based on the actuation required and a modified version of dynamic relaxation method. Dynamic relaxation is a static analysis method particularly suitable for highly non-linear structures such as tensegrity systems. Its modified version integrates the action of continuous cables in the system [23]. Module topology, element characteristics and actuation are required as input for the analysis. For the bridge module, struts have an external diameter of 11.4 cm and a 0.6 cm thickness. Cables have a cross-sectional area of 1.76 cm^2. Both struts and cables are considered made of steel. The deployment is based on the creation of a series of finite mechanisms allowing the module to change length. Since tensegrity modules are stable systems, cable actuation is used to create a suitable finite mechanism. Actuation is implemented as an increase or decrease of the length of actuated elements. After each actuation cycle, a new equilibrium configuration with a new length is found. The deployment step depends on the actuation step chosen. Large actuation steps result in unstable configurations, while small actuation steps are computationally expensive. In the case of the tensegrity footbridge, only cables are actuated with a mean actuation step of 2 mm. Individual actuation steps can be applied to each actuator if required, leading to a better control of the shape of the tensegrity system. Constraints such as strut jamming and maximum values for internal forces as well as geometrical relationships can be integrated to control the topology of the equilibrium configuration obtained. In the case of the footbridge, strut jamming and internal forces are checked during the deployment to avoid problematic configurations. The repeated sequence "*mechanism creation - new equilibrium – constraint*" leads to unfolding or folding the module. An overview of the deployment-analysis algorithm is given in figure 4. If a deployment path is predefined, actuation should match the path. If no path is selected, random actuation can be applied. However, random actuation may converge into a problematic topology (strut jamming). In such case, the algorithm will stop and provided a description of the event. If the module completes the deployment sequence reaching a predefined unfolded or folded length, a complete description of the deployment including the deployment-path and internal forces during unfolding and folding is provided.

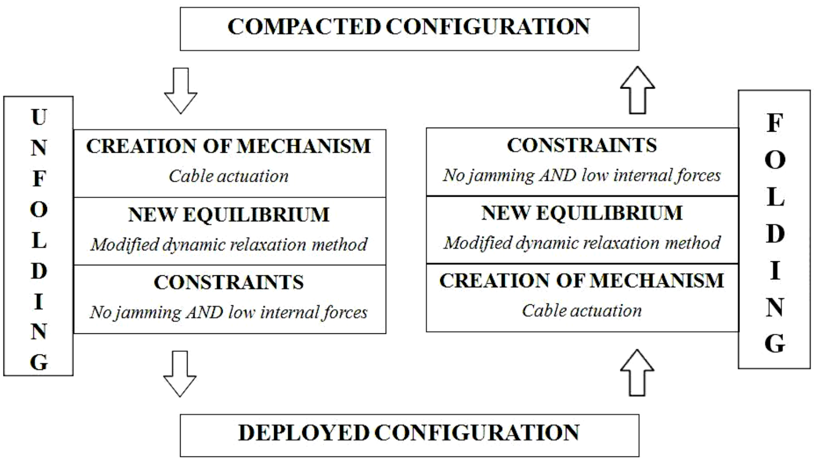

Figure 4: deployment-analysis algorithm: creation of mechanism, new equilibrium and constraints applied

Figure 5 shows the computed deployment path and the evolution of internal forces during unfolding and folding for a single part of the deployable tensegrity footbridge (incl. two pentagonal ring modules). Structural members are separated in struts, actuated cables and non-actuated cables. Two curves are given for every member type corresponding to its maximum and minimum value in internal forces. The deployment path on figure 5 shows that geometrically (in terms of total length *L* and transverse rotation *θ*) the same exact path is followed for unfolding and folding the bridge. However, internal force graphs reveal that intermediate equilibrium configurations for unfolding and folding are not exactly the same. This suggests that intermediate configurations may have the same deployment length with a different self-stress state. The folded configuration of the bridge has a length of approximately 2.8 m. Folded length is increased compared with results from the geometrical study due to the presence of two successive modules but also due to loading. For all members, internal forces increase with unfolding and decrease with folding. Due to the creation of mechanisms for deployment, internal forces in the tensegrity footbridge remain in low levels as dead load is the only loading applied. Furthermore, forces in actuated cables are lower compared with non-actuated cables. Non-actuated cables are in tension throughout entire deployment process (during the mechanism creation too). The highest values of internal forces for all members are observed for the fully unfolded length. These values correspond to the service self-stress state which provides the necessary stiffness for the structure under service. Service self-stress state is lost with deployment actuation. Member strength is set at 177 kN for struts (buckling strength) and at 199 kN for cables (tensile strength).

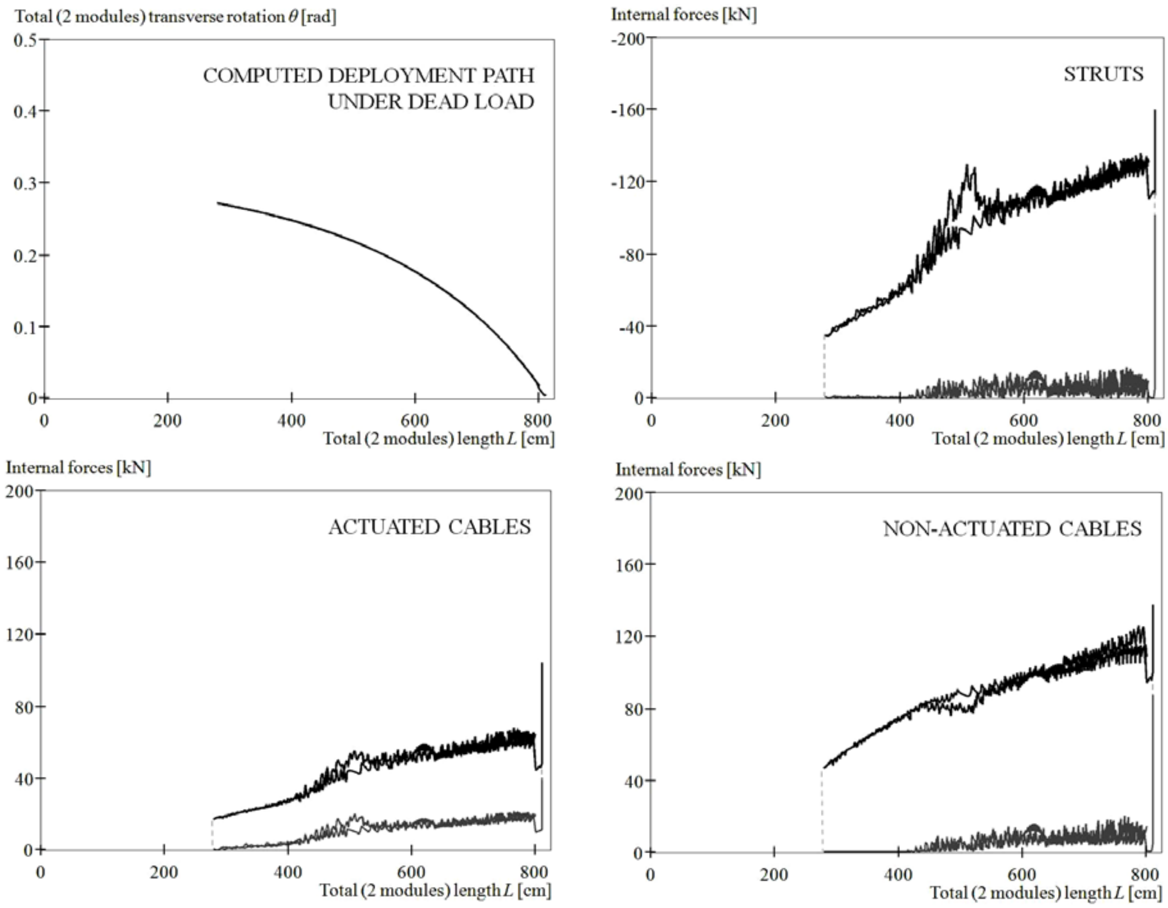

Figure 5: deployment path as well as minimum and maximum internal forces for struts, actuated and non-actuated cables for two bridge modules

Deployment may be a critical phase for the structural system since instabilities may occur. In the case of the tensegrity footbridge the deployment path is composed of a series of intermediate equilibrium positions. Contrary to other systems that are only stable in their unfolded and folded configurations, the proposed actuation scheme for the tensegrity footbridge allows the structure to explore the stiffness of intermediate stable configurations during deployment. The total energy of the system includes the gravitational potential energy and the elastic potential energy due to cable prestress as well as energy loss due to joint friction. Kinetic energy is neglected due to a quasi-static deployment actuation. Gravitational potential energy and the work of torque friction on strut-to-strut joint are found to be negligible compared with the elastic potential energy in cables as shown in figure 6. Friction is computed based on the relative rotation between struts during deployment and a friction coefficient of f_c = 0.2. The variation in energy between unfolding and folding reveals also that intermediate equilibrium configurations are not exactly the same in both directions. However, the total energy in the system is held approximately at the same level during unfolding and folding. Furthermore, the required deployment-actuation energy is not high.

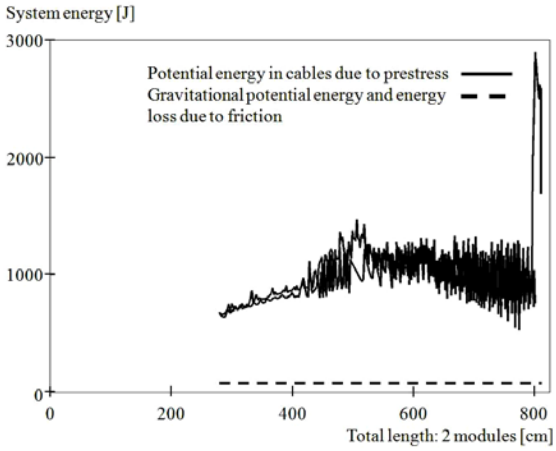

Figure 6: system energy in the tensegrity footbridge during deployment incl. gravitational and prestress potential energy as well as energy loss due to joint friction (kinetic energy neglected due to quasi-static actuation)

Conclusions

The deployment movement of the tensegrity footbridge can be described using three geometrical parameters. There is no explicit relationship between the parameters for deployment; many paths can lead to the same module length.

The deployment path that has the minimum jamming risk was identified based on the computation of strut distances. Nevertheless, this path requires the actuation of all 30 cables for a single module. A deployment path with minimum number of actuators was found based on observations on this path.

The number of actuators is reduced by 50% for a single module when minimum actuation path and continuous cables are employed. Deployment was successfully validated without strut interference in a small scale physical model.

The deployment path is composed of a series of intermediate equilibrium configurations. The deployment-actuation step size is an important parameter for the deployment analysis. Large steps result in unstable configurations, while small steps are computationally expensive.

Due to mechanism-based deployment, internal forces remain lower compared within service values. Consequently, actuated deployment is not critical for the design of the tensegrity footbridge.

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