Engineering Structures 174 (2018) 561–572

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Numerical analysis and cable activation in hybrid bending-active structures with multiple cables

Marios C. Phocas*, Kristis Alexandrou

Department of Architecture, Faculty of Engineering, University of Cyprus, 75 Kallipoleos Str., P.O. Box 20537, 1678 Nicosia, Cyprus

ARTICLE INFO

Keywords:
Bending-active structure
Hybrid system
Finite-Element Analysis
Nonlinear analysis
Load-deformation behavior
Structural efficiency

ABSTRACT

Recent applications of bending-active structural principles have facilitated the development of unique, material and energy efficient, free-form lightweight systems. The systems are realized through the application of an interdisciplinary design, computational fabrication, exclusive assembly techniques and construction. These aspects are directly linked to the form-finding process through the bending-active members' activation. A number of design and construction parameters necessary for the morphological objectives succession, as well as the consideration of the deformation behavior of the systems, have raised the challenge of associating generative configuration parameters with their respective post-formed load-deformation behavior. Along these lines, the present paper examines the design of a planar hybrid bending-active system that consists of a single elastic member interconnected with cable elements at equal length intervals of 1 m. The three-stage development of the system consists of its assembly in planar arrangement (i) and erection (ii) following an initial uniform cables' length reduction, in connection with the appropriate kinematic constraints of the ground supports. In a consecutive post-tensioning stage (iii), the supports are fixed and the cables' length is further reduced to provide higher system prestress conditions and a differentiated span to height ratio. In a preliminary stage, the system load-deformation behavior under uniformly distributed vertical load is investigated at the end of its erection (ii&Q) and post-tensioning stage (iii&Q). The analysis examines seven system configurations with increasing number of cable segments, from two to eight. For the eight cable segments system, fourteen alternative post-tensioned configurations, emerging from individual, or group, cable activation, are investigated in their load-deformation behavior. The analysis provides insights into the configurability of the hybrid systems and their load-deformation behavior. In conclusion, the paper discusses design aspects that contribute towards structurally efficient configurations of the hybrid system series.

1. Introduction

Soft-mechanical principles, conceptually derived from the study of natural systems behavior patterns, have increasingly shown in recent years, their potential in succeeding a vast diversity of morphological adaptation. At the same time, they provide a promising outcome in terms of energy performance, stability, material minimization and aesthetics [1]. Flexible motion principles have been transferred in architecture through the versatile behavior of locally differentiated structural member regions with special morphological features that allow for large elastic deformations [2]. In this frame, elastically deformable members may act as structural components with enhanced capabilities in their kinematics. For instance, planar bending-active members of relatively thin section prompt controllable elastic deformations, while they preserve geometrical reversibility, achieving, in this way, different configurational transitions [3]. The embedded energy stored inside the material's molecular structure, allows bending-active members to compose reconfigurable mechanisms that are able to undergo geometrical deformation without the provision of additional energy. During deformation, the residual forces, caused by the bending-active members, increase the residual stresses of the structure and therefore allow it to be self-stiffening [4]. This behavior offers potential new forms of flexibility, adaptiveness and deformation using the memory effect in structural members. The characteristic features of bending-active members in structural applications are mostly prevalent in their application as linear or surface members. These refer to the bending behavior of the members, the configurability and the erection process of the system.

Precedents of lightweight structures, that utilize the members' high bending capacity, can be found in strained gridshells and plydome

---

* Corresponding author.
E-mail address: mcphocas@ucy.ac.cy (M.C. Phocas).

https://doi.org/10.1016/j.engstruct.2018.07.089
Received 2 March 2018; Received in revised form 20 June 2018; Accepted 30 July 2018

pavilions [5]. These types of structures are formed through controlled, externally induced deformations of individual members or global system assembly techniques [6]. In a post-formed stage, the structures are stabilized and stiffened through additional deformation manipulation, or secondary members' superposition. In the case of strained gridshells, a series of identical straight members is used to construct the planar lattice surface, purposely bended, to generate a three-dimensional curvilinear configuration [7]. At the post-formed stage, the strained shell structure is anchored to the ground and stiffened though diagonal bracing, or a prestressed interconnecting cable network [8]. In a similar way, a plydome structure is constructed from identical slender plates, partially fastened together to obtain a global polyhedral shape. The amount of the overlapping area between two adjacent plates defines the degree of the members' self-induced single curvature tilting [9].

The significance of gridshell structures lies within the design and construction principles adopted, enabling the production of structural systems characterized with modularity, low self-weight, ease in constructability and configurability [3]. The form-finding process of bending-active structures results into global three-dimensional shell shapes that are often similar to synclastic curvatures. In terms of construction, the utilization of the members' high capacity in bending enables the self-generation of organic shapes, providing, in this respect, a viable alternative to cold-formed members. This results in reduction of fabrication energy and costs. Construction expenses are further reduced through the transportation ease achieved over conventional prefabricated free-form assemblies, due to respective reductions in the overall transportation volume of the members. By extent, the use of universal joint connections in strained gridshells simplifies the construction stages and maintains the projects' economy within a lower balance [10].

The beneficial construction and design features of bending-active, instead of conventional, structures come at a cost when dealing with construction duration. The erection of strained gridshells, for example, necessitates the use of external infrastructural support or mechanical actuators for pulling, pushing, or lifting the structure into the desired position. The erection process of the Mannheim Multihalle gridshell for example, was performed using a series of forklifts and scaffolding units, for gradual pushing and supporting the structure's upward bending [5]. In the example of the Weald and Downland Museum gridshell, the non-deformed, horizontally assembled, lattice structure was elevated at a higher level, left to gravity and further weighted at the edges and pulled towards the ground level to form the doubly curved shell [10]. An alternative erection is based on the use of mobile crane and light auxiliary columns, as practically applied for the erection of the Essen Pavilion [8]. Some of the most frequently applied erection and forming approaches are also known as 'pull up', 'push up' and 'ease down' [8]. Despite the diversity of applicable techniques, almost every major gridshell project has suffered from excessive erection duration. In addition, most of the erection approaches induced high concentrated stress or full-span compression forces to the constituent members, causing the structure to experience breakages. Although modern examples have reduced the amount of breakage failures through the use of modern machinery and tools, this issue remains an important aspect of consideration when dealing with the construction of bending-active structures [11].

Reflecting upon the aforementioned aspects of bending-active systems erection, the present paper investigates an alternative approach for structural activation of single elements in the case of synclastic shapes. The activation approach is based on the hybridization of bending-active members with a secondary system of cable elements used as alternative form-finding and deformation actuation means, which may also act as self-stiffening and stabilization elements [12,13]. In hybrid 'tension-compression' rigid-bar systems, in which all members are pin-joined together, pretension is principally introduced for stability reasons. Typical structures that belong to this category include tensegrities and tension trusses. The application of cable pretension has been also widely used for cable stiffened systems, such as beam string, or hybrid string structures. In these cases, the cables are also responsible for the rigid members' bending moment reduction [14]. Cable stiffened structures are highly suitable for long span applications with minimized structural self-weight [15]. In hybrid rigid-bar structures, no form-finding process is necessary. In contrary, hybrid bending-active structures require their form-finding process and final configuration to be monitored. The role of the cable in the hybrid system becomes integral [16–18]. The activation process through the cables' length reduction may follow a gradual and uniformly induced deformation distribution, in dissolving the stress concentration effect of elastic members. The amount of the cables' axial stress is assumed to be directly proportional to the elastic members' deformation. The cable action may serve both, in activating the erection of the system, as well as in improving post-formed stability and load-deformation.

The aim of the paper is to clarify the reconfiguration of a low-stiffness bending-active strip interconnected with cable elements at equal length intervals of 1 m. The cables aim towards an alternative erection process and control the elastic member's shape and internal stress distribution. This optimization process is divided into an erection and post-formed stiffening process. The system is assembled in planar arrangement (i) and erected (ii) through uniform cable length reduction to reach half the initial non-deformed length $L_0/2$. Once the system is erected, the ground supports are fixed. In a consecutive post-tensioning stage (iii), the cable length is further reduced, in order to enable the system to reach higher prestress values and differential span to height ratios. The structural model used for the Finite-Element Analysis (FEA) is described in Section 2. The preliminary analysis presented in Section 3, examines seven system configurations with increasing number of cables, from two to eight. Following the erection and post-tensioning stage, the systems are vertically loaded (ii&Q and iii&Q). In the case of the eight-segment model, the length reduction of cable elements is further examined in Section 4, in a post-tensioning stage (iii) for the acquisition of different configurations. Different activation scenarios of individual or group cable length reduction are applied and compared in Section 5. The resulting configurations of the system, and the amount of prestress achieved, are assessed with regard to the system's post-tensioned load-deformation behavior.

2. Elastica arch and analysis model

An elastica arch describes the elastic deformation curve of a slender single span beam in its post buckling state. According to the Bernoulli-Euler law, the elastica may be understood as respective elastic curves that generate a minimum of potential bending energy in a constrained system [19]. This proves the inseparable interdependency of mechanical behavior and form-finding in bending-active members [20]. The problem of form-finding "minimum potential energy constraint bending curves" may be used, based on the equilibrium of forces acting on a member by applying nonlinear FEA. The bending moment M at a differential segment of a largely deflected beam with continuous section, is proportional to the change in curvature $1/r$, as follows [3]:

$$\frac{1}{\mathrm{r}(\mathrm{x}_0)}=\frac{\mathrm{M}(\mathrm{x}_0)}{\mathrm{E}\cdot\mathrm{I}} \tag{1}$$

For flat sections, the width has no influence on the bending stress, which can therefore be expressed in proportion to the thickness t and curvature $1/r$. Therefore, the following bending stress curvature relation may be established:

$$\sigma(\mathrm{x}_0)=\frac{\mathrm{E}\cdot\mathrm{t}}{2\cdot\mathrm{r}(\mathrm{x}_0)} \tag{2}$$

In Eq. (2), both curvature $1/r$ and cross-sectional thickness t have a linear influence on the residual stress caused by active bending. The area moment of inertia I is therefore limited by a given minimal