1. INTRODUCTION

The inseparable combination of form, material and function constitutes the main design agent in bending-active structures. Such structures provide a wide range of curved, free-form geometries by elastically deforming their members. The elastic deformation is handled through a form-finding procedure, in which form and force counteract. The inherent elasticity of the structure's members allows form variation, whereas its inner stress state determines the load bearing capacity of the system. The form-finding procedure leads to a plethora of new structural forms of curved geometries. Imposed external forces act as actuation components for the elastic members, yielding various form-found shapes, while also allowing further reversible configurational transitions. By extension, active structural systems, are able to react to any kind of stimuli by manipulating the structure response, such as internal flow of forces, deformations and vibrations (Sobek and Teuffel (2001). Contemporary means of analysis and simulation may accelerate the calculation phase, increase the accuracy and enable experimentation in the development of the systems.

Alternative material utilization in bending-active structures has already generated new potentials in the field of adaptive architecture. New materials with specific mechanical properties allow geometrical variation and multiple states of equilibrium, leading to morphologically free innovative structures. In general, active-bending processes pair material elasticity with adaptivity through reversible elastic deformations of the bending-active members. Elastic members act as structural components with enhanced capabilities in their kinematics, providing different configuration transitions, while maintaining geometrical reversibility (Phocas and Alexandrou 2018a). Elastic deformation principles open up a new range of possibilities for lightweight and adaptiveness. The main benefit of elastic materials in bending-active structures, is that of gaining motion through the flexibility of the structure, whereas fewer parts are needed to accomplish a specific mechanical task. Their capacity to store energy in the deformed flexible members, provides them the ability to correlate energy and motion. Thus, bending-active kinematics define a deformation sequence that takes into consideration geometrical relationships in addition to internal forces. The latter may be responsible for the motion or the resulting transformation (Schleicher *et al.* 2011). In pliable systems, adjacent elements can transmit forces and torque. Therefore, a deformation of an element can lead to the deformation of an adjacent element. The transmission ratio to the adjacent elements depends on their geometry, material characteristics and the properties of the hinge-zone between them (Schleicher *et al.* 2011).

In active structural systems, different geometrical configurations can be created under various stresses, in order to react to variable external influences. The adaptation to different load cases can be achieved using linear and stiffness actuators. Linear actuators provide force and deformation adaptation through direct variation of the element's length. On the other hand, stiffness actuators attain adaptation indirectly, by an adjustment of rigidity (Sobek *et al.* 2006). In elastic systems, transformation occurs as long as the force remains active, since the members have the ability to repossess their initial form, when the force is released. Recent examples illustrate how motion derives through elastic deformation. The kinetic façade of the Korean Expo Pavilion (Knippers and Speck 2012), demonstrated that convertibility can be facilitated by large deformations. Furthermore, highly-adaptable systems can be developed, using nature as an inspirational source. An example of biologically inspired elastic kinematics is the case study of Flectofin (Lienhard, Schleicher and Poppinga 2012; Schleicher *et al.* 2015).

The utilization of bending-active principles in gridshell structures enables an inventive way to achieve adaptation in form. In general, elastic gridshells offer large spans with low material quantities. By utilizing the bending flexibility of the members, the planar grid deforms elastically, reaching its target curved geometry. A number of elastic gridshells implemented over the last years revealed the potential of utilizing bending principles in larger scale structures (Du Peloux *et al.* 2015; Harris, Haskins and Roynon 2008; Kelly *et al.* 2001; Liddel 2015). Elastic gridshells are also promising in terms of shape adaptation and reuse of a structure for different purposes. By extension, by integrating linear actuators in bending-active gridshells, multiple and no predetermined shapes can be derived, with regard to different requirements. In the example of the Hybgrid adaptable system, adaptivity derives by pairing the continuous elastic planar strips with strut actuators. The curvature of the strips alternates by changing the length of the struts. In the “2 Landscapes” pavilion, six telescopic bars provided translational and rotational motion to the overall gridshell system (Filz and Naicu 2015).

The development of gridshells with transformability capabilities is based on a step-by-step process of an initially undeformed planar grid. An adaptive bending-active plate gridshell has been developed by Phocas, Alexandrou and Zakou (2018), whose configuration is actively controlled by telescopic bars interconnecting the elastic strips and cables of variable length connecting the supports. In further achieving different possible configurations of passive elastic systems, hybridization of the elastic members with a secondary system of struts and cable segments has been proposed (Kontovourkis *et al.* 2017). Along these lines, the current paper proposes a reconfigurable hybrid bending-active gridshell, based on actively controlled segmentations. The design concept includes the planar deployment of the elastic members, the vertical erection of the gridshell leading to its symmetrical form-found configuration and subsequently, the activation of controlled joints and respective cable segments for achieving differentiated target configurations.

2. HYBRID GRIDSHELL

The aim of the current paper is to outline the prospects for further configurational transitions of a bending-active gridshell initially presented in Anastasiadou and Phocas (2019). The current research suggests the segmentation of the elastic members and the introduction of controlled joints. In general, adequate materials for static bending-active structures should offer a ratio of σ_{Rd}/E > 2.5 (with σ_{Rd} strength [MPa] and E elastic modulus [GPa]). When it comes to adaptive bending-active structures, additional requirements for fatigue control limit further the acceptable permanent elastic stress; a respective ratio of σ_{Rd}/E > 10 is recommended in (Lienhard 2014). In this respect, fiber-reinforced polymers (FRP) and certain types of timber and high strength metals are most appropriate for application in bending-active structures (Phocas and Alexandrou 2018b).

The proposed hybrid gridshell consists of four segments of interconnected elastic GFRP (glass fiber-reinforced polymer) strips in span direction. The system segments are interconnected in each strip by three controlled joints and a secondary system of struts and cable segments with variable length. The position of the joints along the strips was selected according to the target configuration of the system. Two joints are placed at midlength of the strips between the second and third strut, whereas the third joint is placed at midspan, Fig.1. The joint connections are actively controlled through electromagnetic brakes; they act as fixed connections during erection and moment free ones during reconfiguration of the system. Thus, once the system has been erected in its symmetrical configuration, further differentiated target configurations may be obtained through the release of the joints and activation of respective cable segments. In the latter stage, the shape adaptation and stress-control of the hybrid gridshell are directly related to the length of the cable segments and the deformation behavior of the elastic members. Thus, the integration of the controlled joints aims at achieving further active shape control of the structure, utilizing reversible elastic deformations of the bending-active members.

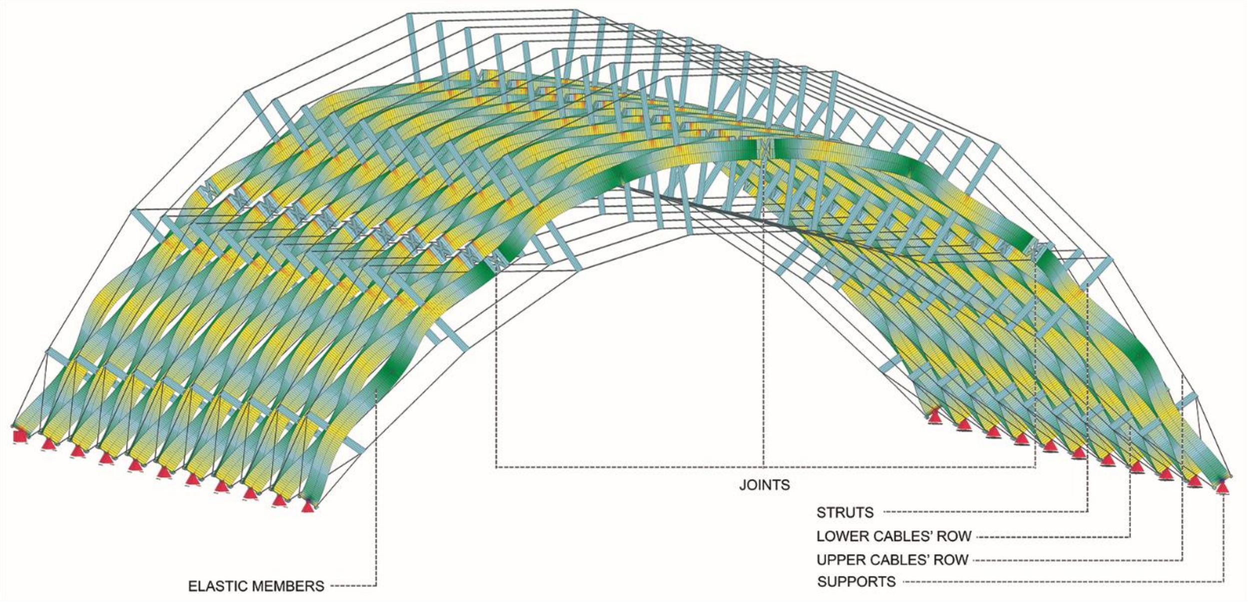

Fig. 1 Hybrid gridshell

3. GRIDSHELL DEVELOPMENT

The planar deployment of the gridshell is handled through auxiliary contracting cables connecting the supports. The cables' length reduction induces bending to the elastic members, enabling the deployment of the gridshell. The resulting deployed grid has overall dimensions in its flat form of 12.4 x 10 m and 22 support points at the ends. By completion of the planar deployment, cables of variable length connecting the supports are actuated, which enable the erection of the structure. By decreasing the cables' length, the structure lifts-up, and obtains its symmetrical target configuration. The erected structure has span of 9.6 m and length of 10 m. Cable segments connecting the upper and lower edges of the struts are applied once the structure has reached its form-found shape. By completion of the vertical erection, the joints are released and further reconfigurations of the gridshell can be then achieved. The structure's reconfigurations are handled through different scenarios of cables' actuation. The gradual shrinkage of the cables connecting the edges of the struts allows rotations of the joints on the global Y-axis and subsequently, bending deformations of the elastic members leading to configurational transition of the whole system. Depending on the expected system reconfiguration, different scenarios of cables' activation on the upper and lower row are applied in achieving the respective curvature at the gridshell's segments. By reducing the cables length on the lower row, the respective segments of the gridshell move upwards. Respectively, by reducing the cables length on the upper row, the gridshell tends to move downwards, gaining a reverse curvature. Different scenarios of cables activation can be selected, based on the respective functional, morphological, structural, etc., demands. The following case study seeks to increase the system height at midspan, and at the same time yield reverse curvature of the edge segments. In order to reach this form, the upper row cables were actuated up to the gridshell's edge joints. Respectively, the lower row cables were actuated at the gridshell's center, Fig. 2. The target reconfiguration of the system is determined at the stage where the maximum stresses of the elastic members reach 90 % of the respective material's yield strength, i.e. 450 MPa, in preserving adequate stress reserves to the system, when further subjected to external loading.

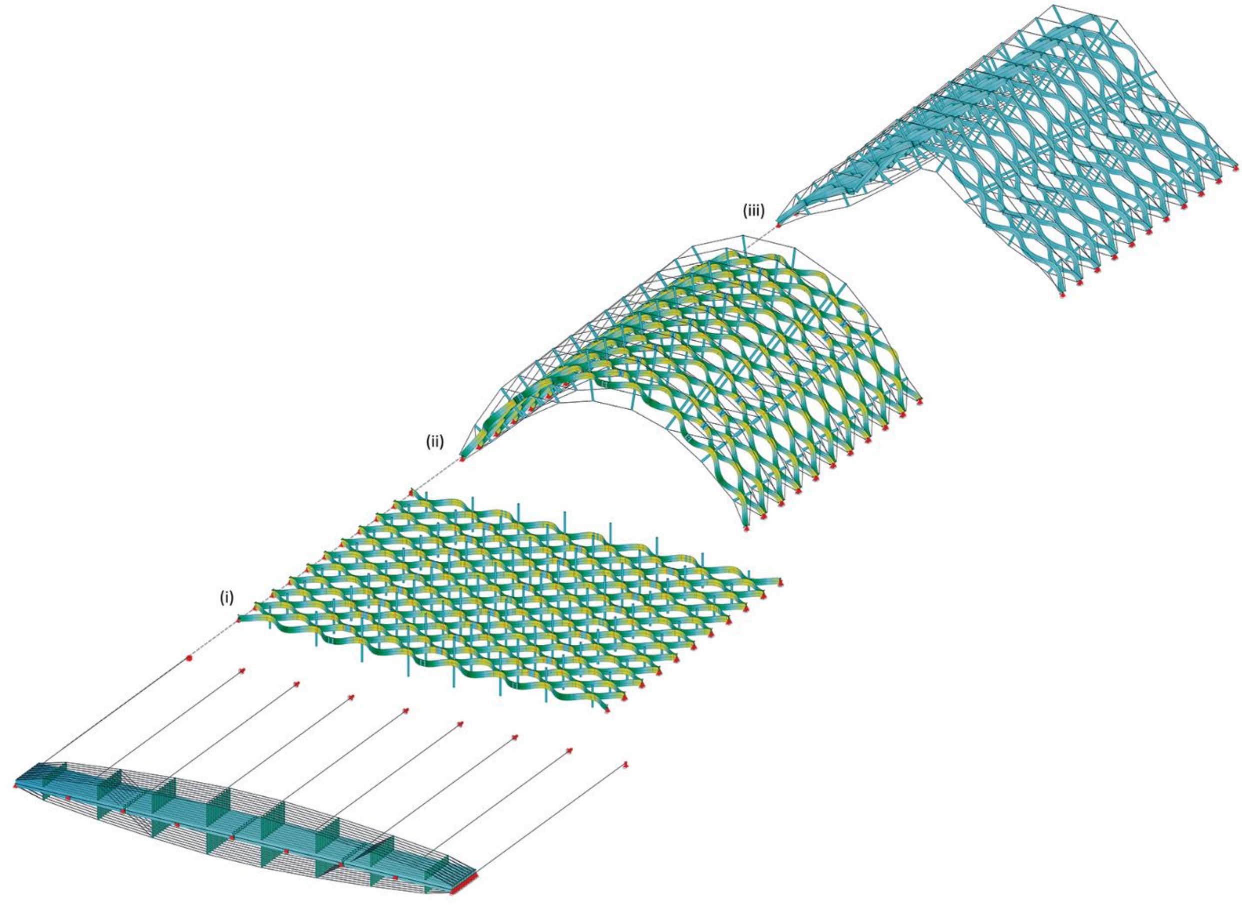

Fig. 2 System analysis stages; (i) planar deployment, (ii) vertical erection, (iii) reconfiguration

4. STRUCTURAL ANALYSIS

4.1 Analysis Model

The structural behavior of the hybrid gridshell was investigated with the FEA software SOFiSTiK®. The geometry of the system was defined in McNeel Rhinoceros program and exported to SOFiSTiK's main database. The elastic members were modeled as structural surfaces, and all other structural members, as beam elements. The bending of the structure was simulated by taking into consideration both the external forces and internal material stresses. The system simulations are based on the third-order theory, considering nonlinear geometrical effects and large displacements. The SOFiLOAD module was used for the definition of loads, while ASE was used as the general static analysis solver. SOFiLOAD and ASE were handled through the alternative text input tool, TEDDY. The analysis follows an incremental induction of bending deformations, where inner stresses of the material developed in each step are stored in the model. The elastic members are assigned to cross section dimensions of 200 x 6 mm and a GFRP material with elastic modulus of 30 GPa and yield strength of 500 MPa. The cables have 10 mm diameter and are assigned to prestressing steel Y1770 of 195 GPa elastic modulus and 1520 MPa yield strength. The struts consist of steel hollow sections of 60 mm diameter and wall thickness of 5 mm. The struts' length varies from 70 to 160 cm, successively increasing from the first segment up to midspan.

4.2 Systems' Performance

In the vertical erection stage, the overall static height of the erected structure reaches 3.42 m at midspan, whereas the height at the edges of the structure, at strip mid length between the second and third strut, reaches a value of 1.28 m. The reconfiguration of the structure increases the overall height at 3.64 m, whereas the structure's edges undergo reverse deformations, reducing thus the height to 0.98 cm, Fig. 3.

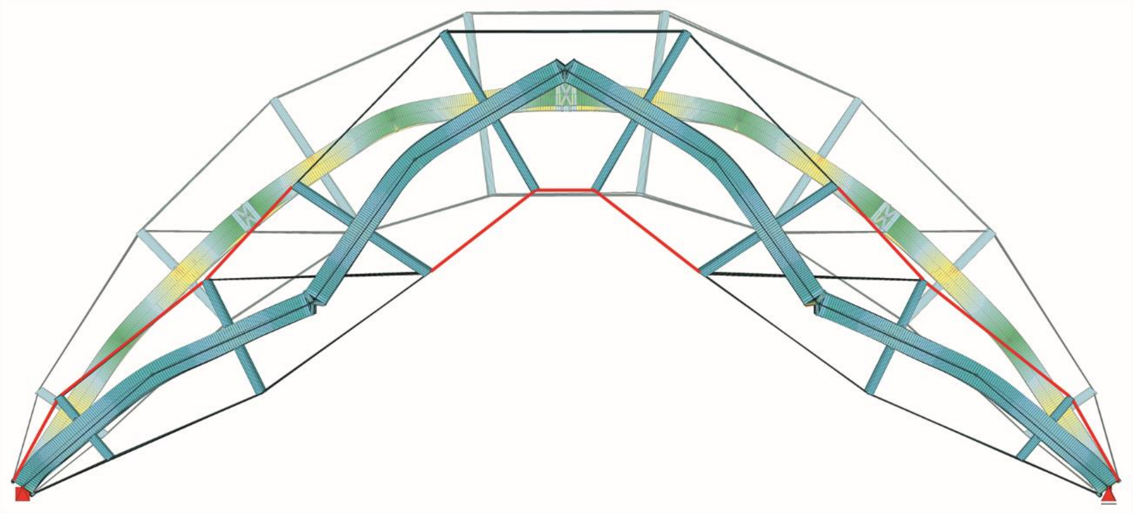

Fig. 3 System deformation behavior at the vertical erection and reconfiguration stage with activation cable segments in stage (iii) indicated with red color

4.3 Numerical Analysis Results

The numerical investigation of the gridshell was conducted for the above mentioned analysis stages. In the vertical erection stage, a total shrinkage of 301.50 cm has been applied to the cables connecting the supports in span direction. In this stage, the maximum cable's axial force amounts 0.78 kN. In the reconfiguration stage, a shrinkage of 50.0 cm has been applied to the respective activation cables. A maximum cable's axial force of 3.2 kN develops at the upper cable connecting the first strut with the support.

In the planar deployment stage, the maximum axial force N_{xx} of the elastic members amounts 86.18 kN/m, whereas in the vertical erection and reconfiguration, it increases by 15.85 and 318.15 % respectively. The maximum axial force N_{yy} gradually increases in each analysis stage, reaching values of 7.46, 38.99 and 162.04 kN/m respectively. The maximum shear forces V_{xx} also present a gradual increase during the gridshell's development, with the corresponding values been equal to 10.72, 16.69 and 35.07 kN/m. Similarly, the maximum shear forces V_{yy} exhibit an increase of 120.8 and 284.72 %, from the planar deployment to the vertical erection and the gridshell's reconfiguration, reaching values of 8.51, 18.79 and 32.74 kN/m respectively. The maximum bending moments M_{xx} present an increase of 176.74 % from the planar deployment to the vertical erection stage, whereas in the subsequent stage, i.e. system's reconfiguration, they remain constant. Similarly, the maximum bending moments M_{yy} increase slightly from the planar deployment to the vertical erection stage, reaching values of 2.37 and 2.69 kNm/m respectively, while they remain constant in the reconfiguration stage. In the planar deployment stage, the maximum stresses of the elastic members amount 395.5 MPa, and in the vertical erection stage, they reach 90 % of the material's yield strength, recording the value of 449.84 MPa. In both stages the maximum stresses develop at the system's midspan. Once the joints are released, the maximum stresses present a notable decrease, while in the subsequent stage of the system's reconfiguration, they increase gradually. The reconfiguration of the system is completed once the maximum stresses of the elastic members reach again 90 % of the material's yield strength. In the reconfiguration stage, the maximum stresses of the elastic members develop in the elastic strips' zones of the second struts in span direction, Fig. 4.

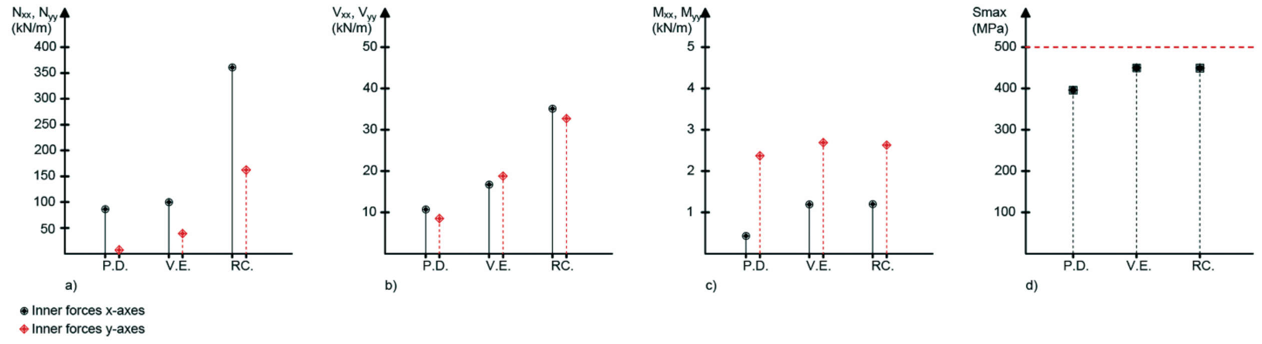

Fig.4 Numeral analysis results in planar deployment (PD), vertical erection (VE) and reconfiguration stage (RC) of the elastic members; Maximum a) axial force, b) shear force, c) bending moment, d) stress

CONCLUSIONS

The present paper investigates the deformation control and shape adaptation of a hybrid bending-active gridshell, by introducing the concept of elastic members' segmentation and their connectivity through controlled joints. The investigation focuses on the gridshell's reconfiguration potential, by examining a three-stage system's development, i.e. planar deployment, vertical erection and reconfiguration. The latter is achieved by releasing the gridshell's joints and activating respective cable segments. The shape adaptation is related to the cables' shrinkage value and the deformation behavior of the elastic members. The current research demonstrates the potential of the elastic gridshells to further adapt to different shapes, through the introduction of controlled joints and the cables' activation. Future work includes different joint location and cables actuation scenarios in achieving further configurations and the investigation of the gridshell's load-deformation behavior under external loading, involving simulations and experimental testing of small-scale prototypes.

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