The structural design and construction of a cable bending-active structure

M. C. Phocas, O. Kontovourkis & K. Alexandrou
Department of Architecture, University of Cyprus, Cyprus

Abstract

Bio-inspired adaptable systems derived from nature on the basis of elastic kinematics are related to the design of material efficient structures in terms of self-weight minimization and adequate stiffness. The use of bending principles in primary structural components enables the achievement of a variety of initial geometries and their subsequent stabilization through prestress, as well as the capability of the members of sufficiently low thickness to undergo reversible deformations with low bending stresses. The cable bending-active structure presented in the current paper consists of two parallel series of bending-active PETG-members with initial inverted curvatures forming continuous elastic curvilinear elements, which are horizontally interconnected through cables. Following the construction design and manufacturing of the structural members, the load-bearing behaviour of the structure is investigated in a preliminary nonlinear static analysis with regard to the internal forces and deformation control, in order to achieve suitable prestress values of the cables and geometric characteristics of the bending-active members. The dual responsiveness of the prototype envisages providing an experiential component for the pedestrians and effective adaptability of the structure in its load-bearing behavior.
Keywords: kinetic structures, adaptable structures, hybrid systems, bending-active members.

1 Introduction

The development of contemporary lightweight, modular and deployable structures is influenced by both architectural form demands and structural optimization criteria in terms of aesthetics, stiffness and economy [1]. In extent, kinetic structures require besides minimum self-weight that is related with

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aspects of structural modularity, also constructability, connectivity and provision of feedback about load transmission with changes in stiffness and shape, in accurately testing the geometrical shape limits of the structural system. Kinetic structures may obtain different forms according to the methods of embedded computation applied for kinetic activation and structural control. In this frame, hard mechanical approaches require often designers to deal with high-energy costs and complex kinetic mechanisms [2].

Natural systems are of particular interest in the design of adaptable structures as far as their principle integral characteristic is concerned, that of a multi-layered, finely tuned and differentiated combination of their components [3]. In this frame, adaptability refers to the property of self-transforming systems to accommodate to different conditions. Recently a number of research activities concentrate on the application of new soft materials in architecture that are characterized by their passive elastic properties derived from nature. Such materials may constitute mechanisms with autonomous, adaptive physical behaviour. Compared to technical linkage systems, bending-active mechanisms replace local hinges by elastic deformations of their members and thus distribute the acting forces over a wider area in which bending takes place. This alternative approach renders the possibility to form complex single- or double-curved primary structures from straight or planar members. Sufficiently thin component thickness thereby allows for small bending radii and thus results in low bending stresses. The application of bending-active members has been originally demonstrated with a pavilion prototype construction with birch plywood lamellas at the University of Stuttgart in 2010 [4] and the kinetic shading elements development for the Biomimetic Media Façade of the Thematic Pavilion at Expo 2012 in Yeosu, South Korea [5].

For optimized resistance to time-varying external forces, structural rigidity can be either increased by the combination of bending and tension prestress stored within individual elements, or by coupling of multiple elements to a hybrid system [6]. The crane model originally proposed by Frei Otto [7], of a central flexible curved element that may obtain different configurations through three sets of longitudinal cables, provides such an adaptive hybrid bending-active system. Another example is the hybgrid prototype structure of three polyethylene terephtalate glycol, PETG lamellas interconnected by struts with variable length [8]. Further developments of adaptive hybrid structures, consisting of primary bending-active members and a secondary system of struts and cables with closed circuit and variable length, have been proposed in [9, 10]. In these prototype developments, the cables have a dual function: to stabilize the primary members and to provide the structure with controlled transformability for obtaining different configuration states throughout the adaptation process.

Serviceability criteria in reconfigurable structures with bending-active members and excessive loading conditions may be satisfied through active deformation control of the members. The extremely light, prototype bridge structure in [11] relies on active deformation control since its mass and stiffness become time-variant with changing pedestrian traffic. As far as hybrid systems are concerned, studies on the active control of cables vibrations have been conducted in [12]. The mechanism of tendon control of strings and cables is presented in [13]. The applied concept of active control with pneumatic muscle actuators for a stress ribbon footbridge is presented in [14].

The design of a controlled cable bending-active footbridge structure presented in the current paper reflexively addresses the above mentioned considerations with regard to structural lightweight and modularity, natural systems inspired adaptability derived from the elastic material properties and controllability of stiffness and shape for satisfying serviceability criteria in excessive loading conditions. The preliminary design and the numerical analysis of the structure with regard to different geometrical and mechanical characteristics of the members are presented. The static behaviour of the system is clarified on the basis of the elastic structural design of the members and the geometrical nonlinearity of the tension-only members.

2 Preliminary design

In structural configurations initially investigated through physical models, the primary elements consist of pairs of continuous PETG lamellas with dimensions of 700/25/2 mm, joined at nine points and bended to form continuous elastic curvilinear elements (fig. 1). In the first two alternatives eight units are stabilized at midspan through struts. The kinematics of the systems is induced by cables with closed circuit and variable length, passing through the units at the perimeters. In both cases the transformability of the structure was found to be symmetrical and limited. In a third alternative, units of 700/25/2 and 900/25/2 mm dimensions for the primary and secondary lamellas respectively, are only stabilized through a cable with closed circuit and variable length, passing through at mid-height of the upper lamella. Although the system exhibited non-symmetrical deformability, it lacked stability and controllability. In a final alternative the stabilisation of the units is achieved with short length cables interconnected at the upper, middle and lower unit points. The kinematics of the system is enabled through respective length adjustments of the cables at the respective system segments. This system consists of a higher number of secondary members and connections. On the other side, the discretization of the tension-only members enables higher controllability in its kinematics.

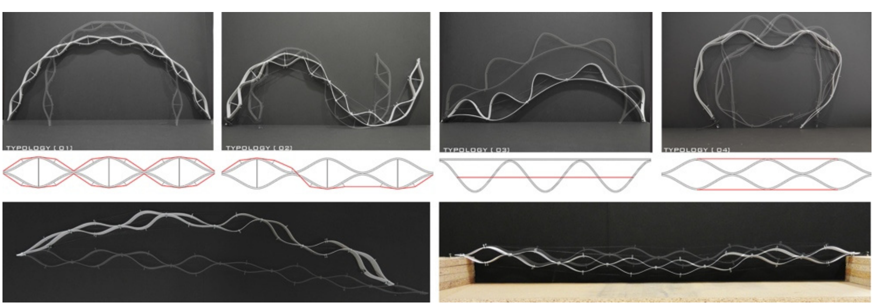

Figure 1: Configuration case studies of kinetic cable bending-active structure.

The selected system configuration of the two hinge-supported girders consists of pairs of inversely curvilinear PETG lamellas resulting in eight hinge connected rhomboid units. The units are stabilized by rows of three horizontal cable pairs at their respective upper, middle and lower points (fig. 2(a)). The units have 1.375 m axial length and 0.5 m height. The flat rectangular sections used have dimensions of 250/20 mm and the cables, a diameter of 20 mm. The total span of the structure amounts to 11 m. The structural system has been compared in its load-bearing behaviour to three similar systems with the same overall span: a pantograph structure of scissor elements providing five rhomboid units of 2.2 m axial length and 0.5 m height, which are stabilized through horizontal upper, middle and lower cables (fig. 2(b)); a hybrid system of a girder consisting of rigidly connected beams, strengthened by a secondary system of five struts with 0.6 m overall length and cross cables that connect adjacent upper and lower strut points (fig. 2(c)); a hybrid system of hinge-connected beams stabilized by a secondary system of five struts, interconnected through cross and horizontal upper and lower cables (fig. 2(d)). All respective structural members have been assigned with identical sections for comparison of the systems structural behaviour. In the pantograph structure the primary members consist of rectangular steel hollow sections with dimensions of 150/50/5 mm. In the hybrid systems the bending and compression members consist of tubular hollow sections with dimensions of 170/5 mm.

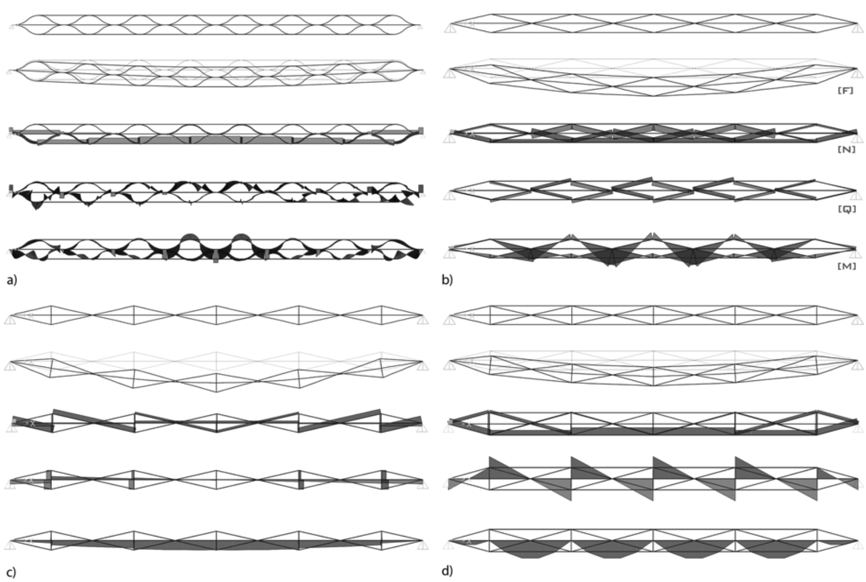

Figure 2: Comparative preliminary analysis of kinetic systems: (a) Cable bending-active system, S1; (b) Pantograph system, S2; (c) Hybrid system with continuous girder, S3; (d) Hybrid system with hinge-connected primary beams, S4.

The structural systems have been investigated in their load-bearing behaviour with the Finite-Element software program SAP2000 based on a vertical uniform load of 2.5 kN/m (Q). In the 2-dimensional, nonlinear analyses the cables have been initially modelled as frame objects with zero compression limit to represent the actual behaviour of flexible tension-only members. The maximum absolute system responses for the uniform vertical loading considered in the analyses are included in table 1.

The cable bending-active structure develops relatively high axial forces, primarily in the lamellas and the lower cables. The bending moments developed are insignificant. The maximum vertical deformation of the system amounts to 14.41 cm, i.e. 1.31% of the overall span. The pantograph structure works primarily in compression and bending, at the connection points of the primary members to the horizontal middle cables. The respective internal forces amount to 48 and 259% of the cable bending-active structure forces. The maximum vertical deformation of the system amounts to 6.27 cm, i.e. 0.57% of the overall span. The hybrid system with continuous girder develops the highest bending moments, 728% of the respective value of the cable bending-active structure, as well as the highest maximum vertical deformation compared to all other systems. Given the selected high relation of the bending stiffness of the girder to the stiffness of the system, the secondary system does not practically induce any substantial decrease of the bending moments of the primary member. Furthermore, the hybrid system with hinge-connected beams is primarily characterized in its load-bearing behaviour through axial forces in the beams and tensile action by the lower cables. The maximum axial force developed in the members, of 158.46 kN amounts to 84% of the respective cable bending-active structure force. The maximum vertical deformation of the system amounts to 14.50 cm, i.e. practically equal to the maximum response of the cable bending-active structure. In extent, certain advantages sought after in the cable bending-active structure that was further investigated, refer to its inherent material deformability that would enable reversible deformations with relatively low bending stresses and therefore, a high degree of geometrical transformability in its kinematics.

Table 1: Maximum absolute system responses for uniform vertical loading (Axial force: N, Shear force: Q, Bending moment: M, Vertical deformation: U).

Structural System	Primary Members			Tension-only Members			U [cm]
	N [kN]	Q [kN]	M [kNm]	Upper N [kN]	Middle N [kN]	Lower N [kN]	
S1	181.06	25.50	5.67	5.35	91.93	188.40	14.41
S2	86.14	19.40	14.66	0	4.51	59.69	6.27
S3	8.15	11.04	41.28	12.84	-	19.50	28.58
S4	75.12	2.97	1.57	1.31	42.40	158.46	14.50

3 Construction design

The construction design of the structural members and connections enables minimum self-weight, standardization and mass customization, as well as ease of fabrication, assembly and erection [15]. Essentially, three structural element types comprise the primary components: The PETG lamellas, metal sleeves at the middle unit connection points and metal sleeves at the upper and lower unit points.

In principle, the assembly logic of the structure is reflected in its components design. Pairs of primary planar PETG lamellas are articulately joined at nine points through metal sleeves of 5 mm thickness and bended inversely to form curvilinear, interconnected rhomboid units. The units are initially stabilized through pairs of steel cables anchored on steel plates of 10 mm thickness that pass through the metal sleeves. The upper and lower cables are anchored to steel plates welded on the outer sides of metal sleeves at the respective unit points. The middle steel plates are also responsible for the primary and secondary structure supports through respective horizontal and vertical steel plate extensions welded on the former, fig. 3. The secondary structures comprise the horizontal truss connecting adjacent primary structures at a distance of 2.0 m, at the units mid-height for the diaphragm at the horizontal plane, and the horizontal deck beams supporting the deck plates over elastic extension spring joints. Spring elements may be also provided at the end connections of the horizontal cables of the balustrades for enabling the members to remain straight and taut during operation of the footbridge. Furthermore, active viscous dampers with spring elements may be applied at the end connections of the lower cables. Application of the technology depends on the respective operation mode of the structure and serviceability criteria set in excessive loading conditions.

Figure 3: Cable bending-active structure design: (a) Primary components design; (b) Primary structure hinge support; (c) Typical metal sleeve joint at units mid-height.

The primary structure assembly process following discrete steps of the lamellas bending and interconnection through the metal sleeves, the units stabilization through the horizontal middle cables, the anchorage of the upper and lower cables and the integration of the secondary deck structure is exemplified in fig. 4.

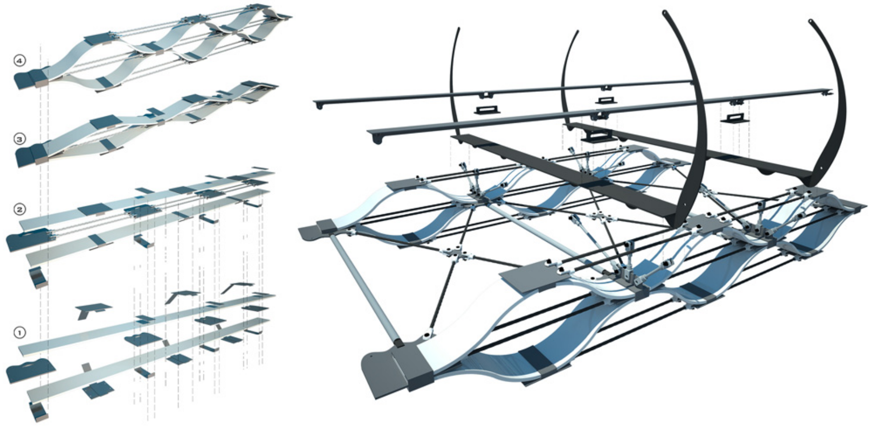

Figure 4: Structure assembly process.

The structural components were developed in scale 1:10 (fig. 5). The digital fabrication process builds upon the advantages achieved through the modularization of the structure and the clearly articulated construction design principles. The detailed prototype's transformations resulting from the elastic materials and kinetic structures behaviour can be furthermore triggered in the actual physical model through embedded technology, in order to obtain controlled adaptive behaviour.

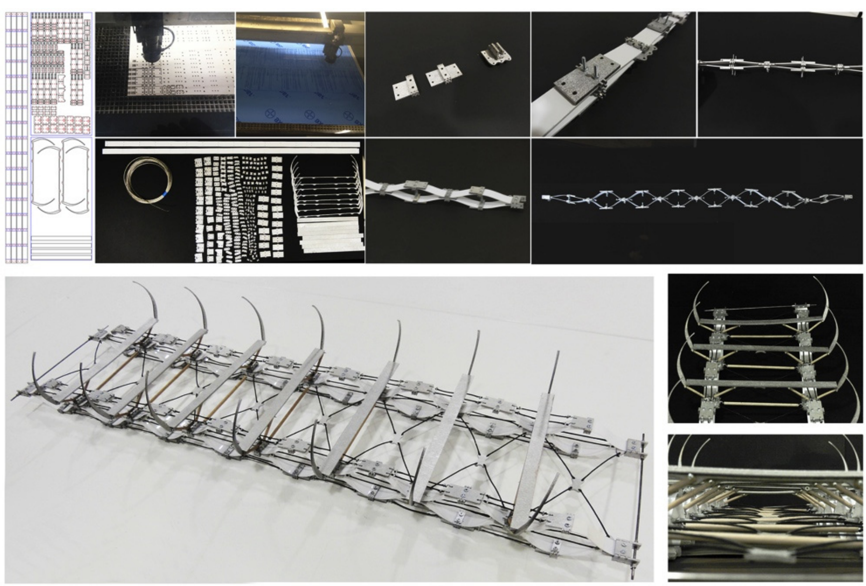

Figure 5: Digital fabrication of components and assembly of small-scale physical model.

4 Cable bending-active structure performance

The investigation of the cable bending-active structure initially refers to suitable prestress values for the cable members. Subsequently, for a selected cables prestress case, the structures behaviour is investigated with variation of the section thickness of the bending-active members.

4.1 Cables prestress analysis

The optimization of the cable bending-active structure is primarily based on the shape design of the cables and their prestress. The cables have been assigned with different prestress values for providing improved structural stabilization under external loading and maximum vertical structural deformations reduction at mid-span under the vertical uniform load of 2.5 kN/m (Q). Cable elements were used to capture both the catenary nature of the tension-only members and their geometrical nonlinear characteristic behaviour. Initially, suitable selection of the respective target pretension force in the cables, neutralizes the structures bending deformation at mid-span with regard to its self-weight. The initial tension forces in the cables are associated with the shape of the members, whereas the upper, middle and lower cables obtained maximum values of approximately 3, 25 and 45 kN respectively. The prestress values of the middle and lower cables have been independently differentiated for each cable row, in order to cover a range of 10 to 220 kN target pretension forces, while keeping the prestress values in the other tension-only member rows constant. Typical deformations of the structure with increase of the prestress values of the lower cables are shown in fig. 6.

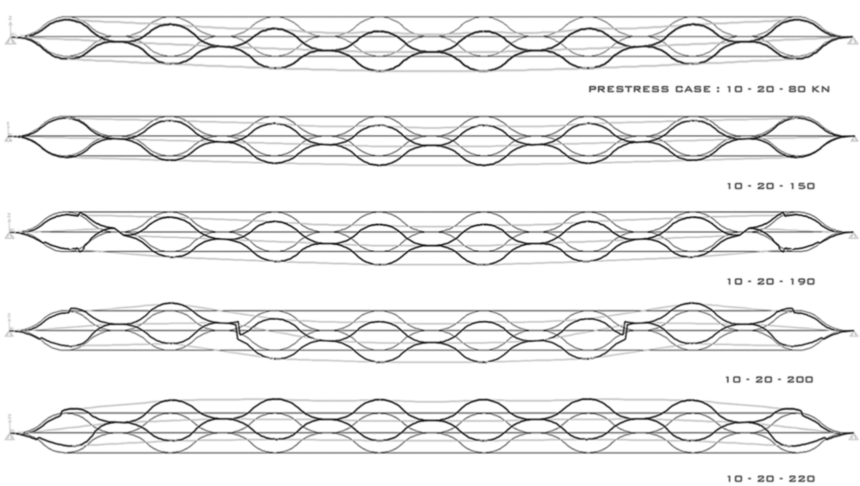

Figure 6: Cable bending-active structure deformation behaviour with different cables prestress values.

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The maximum absolute system responses for the uniform vertical loading considered in the numerical nonlinear analyses under different prestress values of the lower cables are included in table 2. A certain divergence of 21.62 and 11.24% with regard to the maximum axial force in the lower cables and the vertical deformations of the structure respectively, are registered by modelling the tension-only members as cable elements without prestress compared to the initial modelling of the elements as frame objects with zero compression limit, i.e. S1 in table 1. This is attributed to the fact that the nonlinear analysis with cable elements includes both, tension-stiffening and large deflections nonlinearity in the members' response. In principle, the lower cables seem to control effectively the deformations of the system. An increase of up to 200 kN target pretension forces in the lower cables, and constant prestress of 10 and 20 kN of the upper and middle cables respectively, succeeds in practically neutralizing the maximum deformations of the system at mid-span. This is accompanied by an increase of 288 and 225% of the axial forces and bending moments in the primary members respectively. Further prestress of the lower cables induces inverse deformations of the system. Supplementary analyses conducted based on a differentiation of the middle cables prestress levels indicated no substantial influence on the internal forces of the members. In these cases, the maximum vertical deformation of the structure decreases only to approximately 14.5% for a respective prestress increase of the middle cables from 40 to 150 kN and a constant prestress of 10 kN of the remaining tension-only members. The analysis results suggest a target pretension force of 10, 20 and 190 kN, to be applied in the upper, middle and lower cables of the system respectively, prestress case: 10-20-190. The selected prestress level reaches approximately 43% of the maximum elastic tensile stress of 140 kN/cm^2 of the lower tension-only members with a section diameter of 20 mm. Furthermore the system responses suggest that an additional target pretension force in the lower cables of up to 30 kN could be provided by an active control system, where limitation of the vertical deformations of the structure under excessive moving loads is necessary.

Table 2: Maximum absolute cable bending-active system responses for uniform vertical loading Q and different prestress values of the cables.

Cables Prestress Case	Primary Members			Tension-only Members			U [cm]
	N [kN]	Q [kN]	M [kNm]	Upper N [kN]	Middle N [kN]	Lower N [kN]	
0-0-0	53.36	20.97	2.40	8.74	84.31	147.66	12.79
10-20-40	90.49	35.06	3.84	24.67	143.97	249.16	14.80
10-20-80	103.46	39.62	4.16	41.79	140.20	267.77	10.05
10-20-150	131.23	49.38	4.84	80.56	152.02	337.65	4.16
10-20-190	149.48	55.81	5.28	105.98	167.23	391.58	1.30
10-20-200	154.14	57.45	5.40	112.35	171.53	405.36	1.89
10-20-220	163.54	60.77	5.63	124.98	180.88	433.37	3.41

4.2 Bending-active members section analysis

Maximum absolute system responses for the uniform vertical loading and the cables prestress case of 10-20-190 have been investigated with different thickness values of the bending-active members as shown in table 3. By decreasing the upper lamellas thickness, the internal forces of the members decrease, except for the axial forces in the middle cables that increase insignificantly, as well as the structures vertical deformations at midspan. As far as the development of the axial forces in the cables is concerned, maximum values are derived in the lower cables. In particular, by decreasing the upper lamellas thickness from 20 up to 5 mm and constant lower lamellas thickness of 25, 20 and 15 mm, the maximum axial forces in the lower cables decrease insignificantly by up to 4, 4 and 3% respectively. Also, by decreasing the lower lamellas thicknesses from 25 to 15 mm and constant upper lamellas thicknesses of 20, 15, 10 and 5 mm, the maximum axial forces in the lower cables decrease by up to 1, 3, 4 and 4% respectively. A maximum tension force in the cables of 411.1 kN is obtained with 20 and 25 mm thickness of the upper and lower lamellas respectively. In addition, by decreasing the upper lamellas thickness from 20 up to 5 mm and constant lower lamellas thickness of 25, 20 and 15 mm, the maximum vertical deformation increases by up to 184, 177 and 146% respectively. On the other side, by decreasing the lower lamellas thicknesses from 25 to 20 mm and constant upper lamellas thicknesses of 20 and 15 mm, the maximum vertical deformation increases by up to 8 and 4% respectively. In the cases of constant upper lamellas thicknesses of 10 and 5 mm, the maximum vertical deformations increase by up to 3 and 5% respectively. A maximum systems deformation of 5.26 cm was obtained with 5 and 20 mm thickness of the upper and lower lamellas respectively.

Table 3: Maximum absolute cable bending-active system responses for uniform vertical loading Q and different PETG lamellas thickness.

Lamellas Thickness [mm]		Primary Members			Tension-only Members			U [cm]
Upper	Lower	N [kN]	Q [kN]	M [kNm]	Upper N [kN]	Middle N [kN]	Lower N [kN]	
20	25	142.00	63.40	6.40	116.83	165.96	411.10	1.76
15	25	133.30	59.41	6.22	105.44	177.34	406.74	2.25
10	25	115.98	52.32	5.72	75.44	197.70	401.30	3.10
5	25	89.22	41.60	5.13	24.56	217.50	394.80	5.00
15	20	129.21	54.54	5.52	102.87	180.71	400.96	2.35
10	20	112.25	48.45	5.33	75.40	198.77	395.35	3.18
5	20	85.18	38.20	4.73	26.65	216.70	388.54	5.26
15	15	120.15	48.00	4.54	92.33	185.33	392.43	1.95
10	15	104.95	43.56	4.65	70.74	197.80	386.75	2.60
5	15	79.30	34.90	4.40	27.90	210.80	380.00	4.80

4.3 Dynamic system behaviour

The dynamic system properties have been defined by taking into account the coupling nature of the dynamic modes, the involvement of different deformations in the mode shapes and the associated mass participation factors for the respective configurations. The dynamic analysis takes into consideration the geometrical modification of the cables due to the systems' deformations and the effect of the applied loads along the deformed geometry, i.e. P-Δ effect. The cable bending-active structure with geometrical section characteristics as in S1 and without prestress in the cables has a vertical natural frequency of $f_1 = 0.28$ Hz. Increase of the prestress values of the cables according to the cases described in section 4.1, leads to respective increase of the predominant vertical natural frequencies of the system, from 0.10 to 0.53 Hz, corresponding to the lowest and highest prestress case respectively. With further variation of the upper lamellas thickness, the vertical natural frequency of the system may have a divergence of up to 43, 64 and 79% for constant lower lamellas thicknesses of 25, 20 and 15 mm respectively. The selected systems vertical natural frequency of $f_1 = 0.49$ Hz registered in the first eigenmode for the prestress case 10-20-190 with section dimensions of 250/20 mm for both lamellas, proves the system to be tuned away from the critical range of excitation frequencies, i.e. $1.25 \leq f_i \leq 2.3$ Hz for vertical and longitudinal vibrations [16].

5 Conclusions

The design of a cable bending-active structure has been presented in the current paper, attributing to considerations of adaptability and structural interaction to external moving loads. The kinetic structures curvilinear typology results from the elastic properties of its primary members and their stabilization, through horizontal interconnecting tension-only members. The construction design and manufacturing of the structural members and connections aimed at a high degree of structural modularization and mass customization. The structural behaviour under vertical uniform loading has been investigated for different pretension levels of the connecting cables and section thicknesses of the bending-active members. The present prototype development as such envisages providing technologically intelligent kinetic structural systems that effectively adapt to external conditions, in interactive and experiential way.

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