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Kinematics analysis of deployable and reconfigurable bar-linkage structures

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ABSTRACT

In terms of a sustainable future of the built environment, flexibility, structural efficiency, modularity and transformability gain significance. Deployable and reconfigurable structures that are able to be easily erected in different locations and respond to varying functional, environmental or loading conditions through shape transformations facilitate new research directions in achieving a corresponding interactive and optimized behavior. Related to deployable and reconfigurable modular structures are linkage-based systems. A concept of a spatial structure that builds upon flexibility and controllability through modularity and simple actuation requirements is considered in the current paper. The spatial structure is composed of identical planar linkages, horizontally arranged at an axial distance of 2.5 m, and rigidly interconnected through secondary members. Each linkage is assumed to be composed of 6 and 9 rigid aluminum bars with lengths of 1.5 and 1.0 m respectively, and a sliding block. The basic bar-linkage structure has one end fixed to the ground and the other end, to a sliding block. A single linear motion actuator detached from the structure, acts on the sliding block, while all intermediate joints are equipped with brakes. The deployment and reconfiguration approach involves the selective releasing of one intermediate joint in each step, to define a generic 1-DOF system. The simulations conducted refer to three system typologies: a bar-linkage, a bar-linkage with a secondary system of struts and parallel continuous cables to the links and diagonal ones. In both latter cases the cables participate in the actuation of the system and two motion actuators are required. The approach has been examined from an initial, almost flat configuration of the linkages to a specific target arch-like one with span of 4.5 m. The comparative evaluation of all six systems kinematics is primarily based on the criteria of maximum brake torques at the joints, axial cable forces and relative sliding distance of the rolling support during the system transformations. The studies demonstrate the feasibility of the proposed deployment and reconfiguration approach and reveal the potential of transformable structures that needs to be further examined through systematic design, prototyping and testing.

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1. INTRODUCTION

Adaptation constitutes an important and integral design tool in the architectural and construction field, as it recognizes that the future is not finite and change is inevitable. Adaptive structures have important characteristics that may contribute to sustainability, as these are intended to respond readily to different functions, the users changing needs, external loading and environmental stimuli (Christoforou *et al.* 2015). Technological evolution has offered many tools, such as control systems, sensors and actuators, materials and structural components, which provide a feasible option for shape-controlled architecture and unique opportunities. Structural modularity, through the use of basic and identical modules, allows a high degree of adaptability and flexibility to be achieved with regard to the specific morphological outcome (Phocas *et al.* 2019; Phocas, Alexandrou and Athini 2019). Deployable systems incorporate the concept of modularity in their components and are capable of large configuration changes in an autonomous way. Such systems comprise tensegrity, scissor-like element and bar-linkage structures. In general, shape-control systems comprise self-erectable and reconfigurable structures that extend beyond their time-dependent transformations and could potentially minimize the whole life-energy, which refers to the embodied energy of the material, as well as the operation of the structure and the building. In contrast to conventional fixed-shape structures, which ensure that the system stiffness and material strength meet the required limits to cope with external loading, reconfigurable structures are designed through self-weight minimization to carrying loads whose magnitude varies very little (Sterk 2006). A system that incorporates characteristics of deployability, reconfigurability and modularity on a syntax of sustainability is highly desirable in providing flexibility with regard to the morphological outcome by exploiting basic modules.

In this framework, deployable and reconfigurable structures are capable to erect from an initial to a target position and further adjust their shape through motion control with computational assistance (Phocas, Christoforou and Matheou 2015). Deployable structures have the ability to transform themselves from a small, packaged and compact state to a large, open and deployed configuration (Jensen 2005). Usually such systems are used for temporary structures due to an easy storage and transportation. Main characteristics of these structures are light-weight, rapid assembly and disassembly, easy storage and transportation (Doroftei, Oprisan and Popescu 2014). Many structural examples have been applied in the field of architecture, such as tents, yurts and shelters, which adapt to changing external climate factors and fulfill the indoor needs of the users through modification of their geometric morphology. Among these structures, tensegrity and scissor-like systems have attracted great interest and have been developed in late years for various architectural and engineering applications involving deployability (Pellegrino 2001).

Tensegrity structures comprise spatial, reticulated and lightweight units that are composed of compression members and cables (Fuller 1962; Bel Hadj, Rhode-Barbarigos and Smith 2011). Such self-stressed systems provide stability through the composition of compression and tension elements that are characterized by their physical properties in providing embedded active control. The specific typology refers to autonomous and self-supported systems that can effectively transfer loads acting on the structure (Gantes 2001). This type of systems is used in modules connected to each other through telescopic bars. The edges of the bars are connected with the cables, or anchored with other bars. In this way, shell structures can be produced in short time, in larger and different shapes. The deployment of tensegrity structures may be achieved in two ways: by changing the length of the compression members, i.e., by using telescopic bars with linear motion actuators, or by changing the length of the cables (Hanaor 1998; Duffy *et al.* 2000; Tibert 2002; Adam and Smith 2008). In general, this structural type of systems has the capability to be transformed from a flat and closed position to an expanded and stable one, and is suitable for transportation and reuse.

A further group of deployable structures is based on the well-known concept of the lazy tong system. The basic component of this system is the so-called scissor-like element (SLE). The planar SLE consists of two bars connected to each other with a rotational joint. The upper and lower end nodes of a scissor unit are connected through unit lines, which are parallel and remain so during deployment (Maden, Korkmaz and Akgün 2011). A different length of the bars, as well as different nodes of their connection induce variable forms of SLEs. Scissor-like deployable structures have been originally proposed by the Spanish engineer, E. P. Piñero, who developed a foldable theatre in 1961 (Pinero 1961). Even if SLEs need additional stabilizing elements like cables or other locking devices, it is possible to design self-stable structures in the erected configuration without any additional members. This can be achieved by adding inner SLEs to the initial secondary units. In general, SLEs are mechanisms that only have one degree-of-freedom (1-DOF), which enables the internal spreading of movement from one member to another. These systems are capable to transform by following a sequence of stages, changing physically from one form to another. This kind of transformation offers indeterminacy solutions and potentials, if we consider the in-between stages that SLEs produce and the range of possible shapes in the retracted and deployed positions. However, the application of the systems principally follows a two-stage form, from the closed to the open, deployed one, while acting as a structural mechanism during deployment (Akgün *et al.* 2010).

In most reconfigurable structures that have been developed so far, only individual target system configurations are realized through integration of ‘locking’ techniques and rigid locking mechanisms (Matheou *et al.* 2018). In order to succeed different configurations of intermediate positions, actively controlled bar-linkage structures with a fixed and a sliding support have been proposed (Phocas, Christoforou and Dimitriou 2020). The deployment and reconfiguration of the system takes place through a linear actuator positioned on the support and the selectively releasing of one intermediate joint in each step. The so-called ‘crank-slider’ approach of the bar-linkage system provides various target system configurations, while enabling flexibility and controllability through modularity and simple actuation requirements respectively. This can be achieved by a systematic work of the members, which are all interconnected and able to reconfigure the shape of the whole system through linear motion. The actively controlled linkage systems rely on a reduced number of actuators that are detached from the main structure body, while aiming at preserving minimum self-weight, structural simplicity, and reduced energy consumption. Along these lines, the current paper examines the kinematics of two linkage structures of 6 and 9 rigid aluminum bars with lengths of 1.5 and 1.0 m respectively, and a sliding block. The structural systems consist of three typologies: a bar-linkage, a bar-linkage with a secondary system of struts and parallel continuous cables to the links and diagonal ones. In both latter cases the cables participate in the actuation of the system and two motion actuators are required. The approach has been examined from an initial, almost flat configuration of the linkages to a specific target arch-like one with span of 4.5 m.

2. EFFECTIVE CRANK-SLIDER APPROACH

The basic structural and kinematics element of a planar linkage system consists of n-serially connected rigid links with pivot joints between them, as shown in Fig. 1. The two ends of the structure are supported on the ground, through a pivot joint on one end and a linear sliding block on the other end. Brakes are placed on each joint, as well as a linear actuator, on the ground, fixed to the sliding block. The proposed reconfiguration concept is based on stepwise adjustments of the joints, where in each step, the brake of one intermediate joint is selectively released, while the pin joints at the supports are always kept unlocked. Through this procedure, every angle of the n-bar linkage system is transmitted and adjusted to its target position step by step, converting the mechanism into a generic 1-DOF system and in particular, in an ‘effective crank-slider’ (ECS) system. A reconfiguration of the mechanism can be accomplished through different control sequences and the optimal one can be elected based on specific criteria, such as maximum required brake torques, actuator motion, etc. In the case of a system with n bodies (including the ground and the slider block), a complete reconfiguration will require a number of (n−3) intermediate steps, given that during the final step the four remaining joint variables will be adjusted simultaneously.

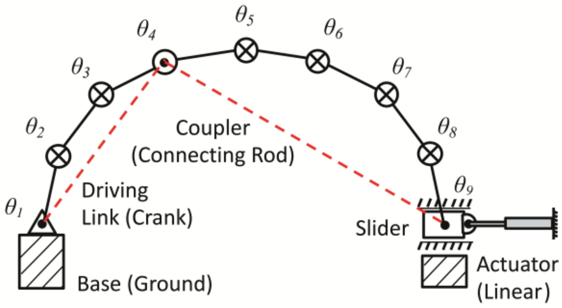

Fig. 1 ECS approach that is the basis for the stepwise deployment and reconfigurations of the system with n serially connected rigid links (⊗: locked joint, ʘ: unlocked joint, △: pivoted–to–the-ground joint, □: slider joint, —: physical link, – –: effective link) (Phocas, Christoforou and Dimitriou 2020)

A spatial structure is assumed to be composed of identical planar linkages, horizontally arranged at an axial distance of 2.5 m, and rigidly interconnected through secondary members. Two basic linkage structures of 6 and 9 rigid aluminum bars with lengths of 1.5 and 1.0 m respectively, and a sliding block have been applied, in three possible typologies: a bar-linkage, a bar-linkage with a secondary system of struts and parallel continuous cables to the links and diagonal ones. The approach has been examined from an initial, almost flat configuration of the linkages to a specific target arch-like one with span of 4.5 m. The stepwise reconfigurations of the 6- and 9-bar linkage based on the ECS mechanism are presented in Fig. 2 and Fig. 3.

	JOINT 1	JOINT 2	JOINT 3	JOINT 4	JOINT 5	JOINT 6	JOINT 7	JOINT 8
STEP 1	△	⊙	⊗	⊗	⊗	⊗	⊙	□
STEP 2	△	⊗	⊙	⊗	⊗	⊗	⊙	□
STEP 3	△	⊗	⊗	⊙	⊗	⊗	⊙	□
STEP 4	△	⊗	⊗	⊗	⊙	⊗	⊙	□
STEP 5	△	⊗	⊗	⊗	⊗	⊙	⊙	□

Fig. 2 Scheduling table for the control sequence realizing the required shape adjustment on a linkage with 6 serially connected members, based on the ECS approach (⊗: locked joint, ʘ: unlocked joint, △: pivoted–to–the-ground joint, □: slider joint). Dashed-line encirclements denote the effective coupler links. The red coloured symbols represent the currently adjusted joints

	JOINT 1	JOINT 2	JOINT 3	JOINT 4	JOINT 5	JOINT 6	JOINT 7	JOINT 8	JOINT 9	JOINT 10	JOINT 11
STEP 1	△	⊙	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊙	□
STEP 2	△	⊗	⊙	⊗	⊗	⊗	⊗	⊗	⊗	⊙	□
STEP 3	△	⊗	⊗	⊙	⊗	⊗	⊗	⊗	⊗	⊙	□
STEP 4	△	⊗	⊗	⊗	⊙	⊗	⊗	⊗	⊗	⊙	□
STEP 5	△	⊗	⊗	⊗	⊗	⊙	⊗	⊗	⊗	⊙	□
STEP 6	△	⊗	⊗	⊗	⊗	⊗	⊙	⊗	⊗	⊙	□
STEP 7	△	⊗	⊗	⊗	⊗	⊗	⊗	⊙	⊗	⊙	□
STEP 8	△	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊙	⊙	□

Fig. 3 Scheduling table for the control sequence realizing the required shape adjustment on a linkage with 9 serially connected members, based on the ECS approach (⊗: locked joint, ʘ: unlocked joint, △: pivoted–to–the-ground joint, □: slider joint). Dashed-line encirclements denote the effective coupler links. The red coloured symbols represent the currently adjusted joints

The proposed system is expected to have reduced energy consumption compared to a corresponding linkage with multiple motion actuators installed on the joints (number of actuators must be equal to number of DOF). In the latter case, the actuators constitute additional lumped masses on the joints, and they would have to be moved together with the rest of the structural elements during reconfigurations, consuming extensive amounts of energy.

A common problem that comes up with deployable and reconfigurable structures refers to the kinematic bifurcation (Chen, Feng and Sun 2018). While the structure is transforming along a determined path, at a singular configuration it may follow its initial path or divert into one of the bifurcation paths (Park and Kim 1999). In this context, motion planning requires to consider the kinematics of the basic crank-slider mechanism and its singular configurations. The specific mechanism when encounters a fully extended or fully retracted position, it reaches its limit positions, where the slider may not move any further. In that case, any force applied to the slider side cannot turn the crank and when slightly disturbed, the crank is possible to move in either direction. Likewise, when the connecting link becomes perpendicular to the slider's joint axis the system assumes a 'dead configuration'. At this particular posture the crank cannot move the slider whose motion may unpredictably resume in either direction. As part of motion planning (i.e., definition of the scheduling sequences) it is important to establish that all intermediate configurations, including the transitions between them, keep away from passing through singular configurations or their vicinity. Whereas the proposed implementation of the ECS method involves a primary linear motion actuator associated with the slider block, an auxiliary (optional) actuator installed at the base rotational joint may intervene to effectively prevent the mechanism from entering into an unwanted bifurcation path. This actuator may also be used for load-sharing purposes.

3. SIMULATION STUDY

The simulation study refers to the preliminary kinematics analysis and the Finite-Element-Analysis (FEA) of two planar linkage systems with 6 and 9 rigid bars, each of 1.5 and 1.0 m length respectively. Thus, both linkage systems have the same initial overall length of 9.0 m in their unpacked, almost flat position, and the same span of 4.5 m in the target configuration of a symmetric arch. These systems have been examined in three different typologies, namely in a simple (SS), hybrid (HS) and cross hybrid (CHS) one. In particular, each linkage consists of serially interconnected members with rotational joints between them, which have the ability to lock and unlock in each transformation step, in order to achieve the target configuration of the system. The supports consist of a pivot joint and a linear sliding block. One linear motion actuator is associated with the sliding block. Structural reconfiguration of each linkage is achieved through the acting of the respective support as a slider; once a target position has been obtained, the actuator locks in place, thus transforming this support into a pin connection as well. This provides the respective kinematics of the system to acquire the target deformation, with specific angles between the bars. Each linkage has a reconfiguration that involves an initial form, $\theta_{i,n}$, and a target configuration, $\theta_{f,n}$. The configurations are defined by the following position vectors, which demonstrate the individual joint angles (internal to the linkage).

$\theta_{i,6}$ = $[5, 175, 180, 180, 180, 180, 0]^T$
$\theta_{f,6}$ = $[74, 171, 151, 108, 151, 171, 74]^T$ degrees
$\theta_{i,9}$ = $[5, 175, 180, 180, 180, 180, 180, 180, 180, 0]^T$
$\theta_{f,9}$ = $[76, 175, 172, 161, 136, 136, 161, 172, 175, 76]^T$ degrees

The following specific requirements were also considered:

- Every rotational joint is installed with brakes except the two joints at the base.
- The only actuated joint is the last joint which is linear and associated with the sliding block.
- Joint position adjustments start from the left side of the linkage and move towards the right.

- During each step of reconfiguration, one joint angle is completely adjusted to its target value.
- No rigid bar can move below the horizontal ground level.
- In the hybrid typologies, no contact between any cable and a rigid bar is allowed during reconfiguration.

3.1 Kinematics Analysis

A preliminary kinematics analysis of the planar bar-linkages has been conducted with the software program Working Model 2D. The dynamic analysis was based on numerical integration of the linkage model, based on the Kutta-Merson method. The respective time step is automatically adjusted during the course of the simulation.

The deployment process of the systems succeeds by selectively releasing one intermediate joint in each step. Once the specific joint is adjusted through respective displacement of the sliding block by the linear motion actuator, then it remains locked. The process is repeated until all joints of the system are adjusted. In the case of actuation provided through the cables, i.e., in the hybrid and cross-hybrid system, only one of the two cables needs to be pulled towards the deployment direction in each step for the transfer of motion to the actuated joint; specifically, in the current examples, in the hybrid system, the lower one, and in the cross hybrid system, the one that passes through the lower strut next to the fixed support. The other cable only requires some pretention to remain stretched. Furthermore, application of two individual cables and their corresponding actuators is expected to provide capability of the system to reconfigure to further target positions and increased geometrical stiffness during operation of the structure.

The deployment steps of the simple planar linkages with 6 and 9 bars from their initial to the target position are shown in Fig. 4 and Fig. 5.

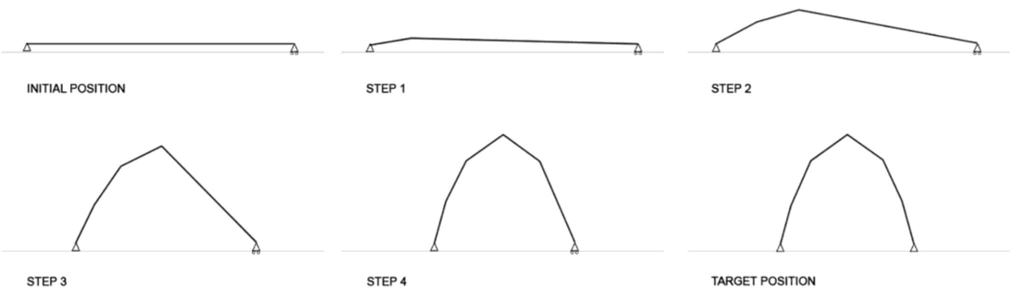

Fig. 4 Deployment sequence of the 6 bar-linkage, SS

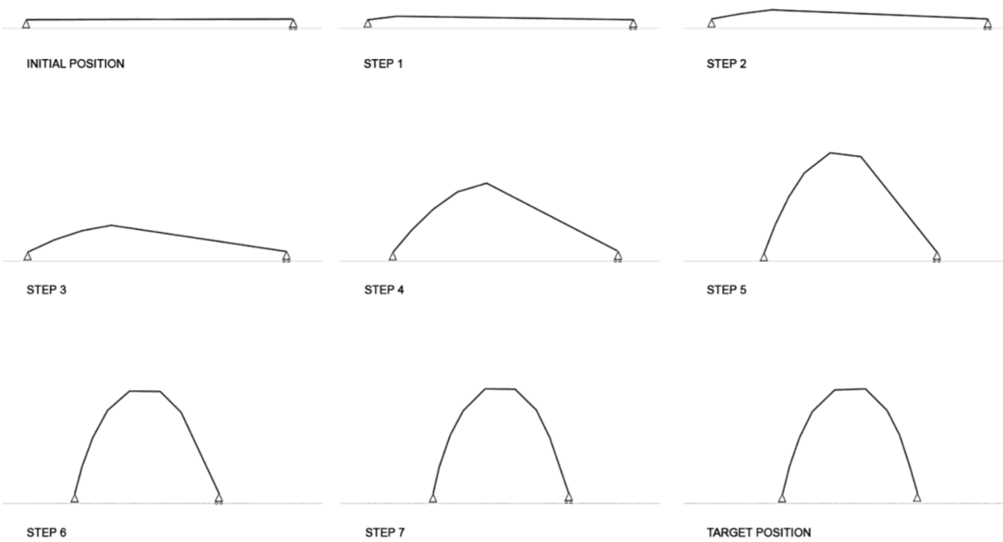

Fig. 5 Deployment sequence of the 9 bar-linkage, SS

The deployment process of the hybrid and cross hybrid linkage systems with 9 bars is presented in Fig. 6 and Fig. 7.

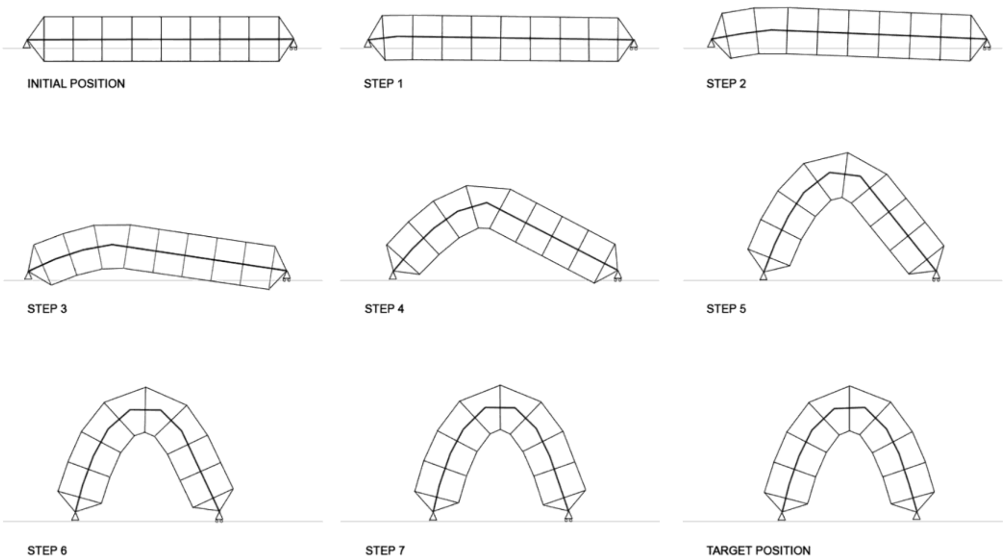

Fig. 6 Deployment sequence of the 9 bar-linkage, HS

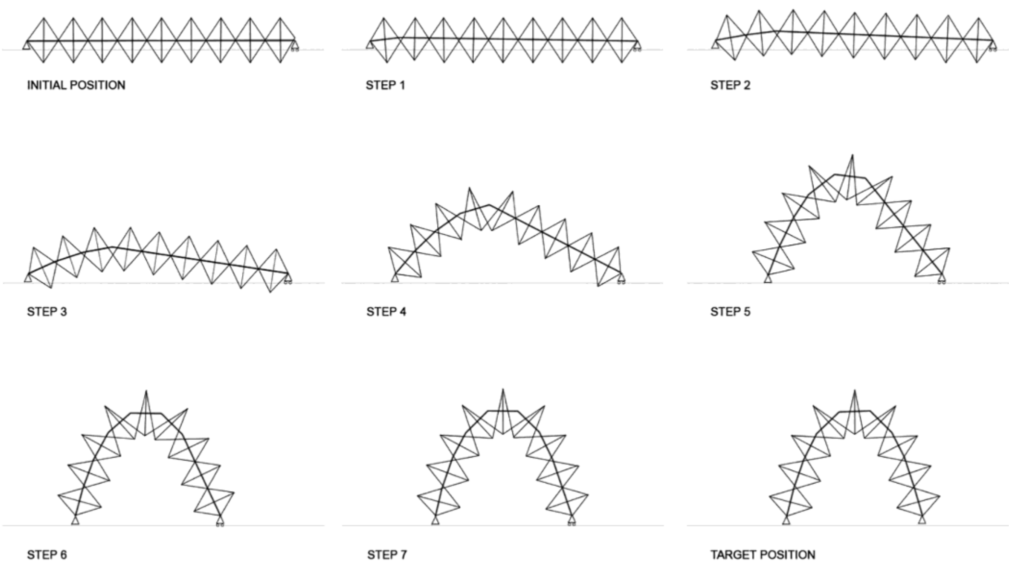

Fig. 7 Deployment sequence of the 9 bar-linkage, CHS

3.2 Structural Analysis

FEA of the systems in each reconfiguration step has been conducted with the software program SAP2000. The systems considered in the analysis are composed of perfectly rigid members of Aluminum with 69.6 GPa elastic modulus and 241.3 MPa yield strength. In the hybrid systems, the cables are assigned to steel S450 of 24.82 GPa elastic modulus, and a pretension of 2 kN. Throughout reconfiguration only self-weight has been assumed to act on the systems, and only slow motions are involved, i.e., inertial effects are negligible.

The beams consist of pairs of UPN140/60 aluminum sections placed at horizontal axial distance of 5 cm, the struts in the hybrid typologies, of circular hollow sections of 60.3/4.6 mm and the continuous cables, of 2 mm diameter. The struts with an overall length of 1.50 m, are symmetrically positioned on each side of the beams and rigidly vertically connected to the latter at mid-length. The cables pass through the pulleys located at both ends of the struts and travel along the structure with one end anchored to the ground support and the other end connected to the corresponding linear actuator. The self-weight of the beams in the linkage with 6 bars amounts to 49.44 kg, and with 9 bars, 49.50 kg. The self-weight of the struts amounts to 10.20 and 15.30 kg respectively, and the cables, 8.9 kg/m. The model assumes no geometric imperfections, nor any initial deformation of the system in each reconfiguration step, and ideal joints. Modelling of the joints is based on the direct stiffness method, i.e. the system is modelled as a set of idealized elements interconnected at the nodes, and the analysis makes use of the members' stiffness relations for computing the members' forces and displacements.

The highest maximum inner forces in the members, as well as the maximum relative cable length variation and relative displacement of the sliding block are presented for all system typologies in Table 1. The cross-hybrid linkage with 6 bars has the highest maximum bending moment, M, of 73.89 kNm in the 4th beam on the side of the sliding block, and the same system typology with 9 bars, the highest maximum axial force, N, of 8.87 kN in the beam connected to the sliding block. The highest maximum shear force, Q, of 0.88 kN is developed in the hybrid linkage with 9 bar, in the 4th beam, on the side of the sliding block. A higher maximum displacement of the sliding block of 2.66 m is registered in the deployment of the linkage system with 6 bars. Among the linkages with 6 bars, the cross-hybrid one has the highest maximum axial force of 6.74 kN in the beam connected to the sliding block, and the hybrid linkage, the highest maximum shear force of 0.79 kN in the third beam, on the side of the fixed support. Furthermore, the relative cable length variation is higher in the hybrid system typology. Among the linkages with 9 bars, the cross-hybrid one has the highest maximum bending moment of 1.19 kNm at the joint between the beams adjacent to the sliding block, but lower relative cable length variation. A direct comparison among the same system typologies reveals that the cross-hybrid linkage with 6 bars has the highest maximum bending moment and shear force in the beams. The same applies for the simple and hybrid linkage with 9 bars. With regard to the relative cable length variation, a higher number of bars favors lower values. In general, the highest maximum inner forces, as well as the lowest maximum relative cable length variations and sliding block displacements are developed in the systems with higher number of bars.

Table 1. Maximum torque (M_{max}), shear force (Q_{max}), axial force (N_{max}) and relative cable length variation ($\Delta l_{c,max}$) and sliding block displacement (Δl_{max}) of bar-linkages

Bar-linkage	**System typology**	**Members**	**Q_{max} [kN]**	**M_{max} [kNm]**	**N_{max} [kN]**	**$\Delta l_{c,max}$ [m]**	**Δl_{max} [m]**
6 (n=8)	SS	Beams	0.21	0.29	2.48		2.66
	HS	Beams	0.79	0.37	2.49		
		Struts	0.09	0.071	1.66		
		Cables			2.40	0.89	
	CHS	Beams	0.7	73.89	2.40		
		Struts	0.17	12.84	6.74		
		Cables			0.93	0.35	
9 (n=11)	SS	Beams	0.22	0.42	1.31		1.93
	HS	Beams	0.88	0.38	0.93		
		Struts	0.09	0.073	3.10		
		Cables			2.66	0.45	
	CHS	Beams	0.66	1.19	3.97		
		Struts	0.13	0.098	2.15		
		Cables			0.98	0.10	

4. CONCLUSIONS

The current paper presents a deployment approach for bar-linkage structures based on the ECS method. The simulation study conducted refers to the preliminary kinematics analysis and the FEA of two planar linkage systems with 6 and 9 rigid bars of 1.5 and 1.0 m length respectively. The systems have the same initial overall length of 9.0 m in their unpacked, almost flat position, and the same span of 4.5 m in the target configuration of a symmetric arch. Both linkage systems have been examined in three different typologies each, i.e., simple (SS), hybrid (HS) and cross hybrid (CHS) system. The numerical results obtained demonstrate the feasibility of the proposed ECS approach and reveal the potential of the kinematics approach that needs to be further examined through systematic design, analysis, prototyping and testing of different system typologies. Within this framework, effective designs may promote desirable features like modular assembly, self-erectability, reconfigurability and structural reliability under varying loading conditions.

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