Proceedings of the First Conference
Transformables 2013.In the Honor of Emilio Perez Piñero
18th-20th September 2013, School of Architecture Seville, Spain
EDITORIAL STARBOOKS. Felix Escrig and Jose Sanchez (eds.)

Mobility and transformability in architectural structures. Proposal of a transformable system of telescopic and x-articulated bars: cinematic, geometric, and structural analysis

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Summary: Systems of bars in x with intermediate hinge, also called SLE (scissor like elements), are suitable for the adaptability approach from the perspective of structural mobility. They are the starting point for new solutions: transformable M-SLE. It has been proved possible to obtain different formal alternatives with a single structural solution, by making modifications to add a DOF (degree of freedom) to the SLE base unit.
In this research a new transformable typology is studied: telescopic bars, articulated in x. This proposal, based on the new MP-SLE (modified prismatic SLE) typology, combines two mechanisms of transformation: the scissor system with telescopic bars. It should be able to offer a wide variety of shapes without changing the span to cover, and unlike foldable structures, with only two stable positions, the new proposal offers several intermediate configurations.
The object of study is a deck arch formed by several SLE units with 4 telescopic bars driven by pneumatic actuators.
Through kinematic analysis (study of mobility), geometrical analysis (search for possible configurations and limits) and structural analysis (resistant feasibility) of the proposal with the new MP-SLE transformable unit, its critical issues of dimensioning and construction have been identified. This enables announcing possible solutions and defining future lines of research.

Keywords: *transformable structures, telescopic bars, scissor like elements, adaptable structure systems, kinetic architecture, deployable arches*

INTRODUCTION

Adaptability defines the ability of an element to accommodate to changing requirements. In architecture, it arises not only as a formal search, but as a holistic concept that encompasses the whole work, meeting different needs in one space. Recent advances in construction technology, robotics and materials science have increased the interest in this type of architecture: foldable and convertible. This adaptability is based on four fundamental concepts: flexibility of use, transformability of space, mobility of elements and interaction with the environment. The systems of bars in x with intermediate hinge, also called SLE (scissor like elements), are suitable for the adaptability approach, from the perspective of structural mobility [1].

The objective of this work is to study the feasibility of a new type of system of bars in x with intermediate hinge for transformable structures, starting from the analysis of existing SLE units for folding structures. The structure based on the new typology MP-SLE (modified prismatic SLE) should be able to offer a wide variety of configurations without changing the span to cover.

This new MP-SLE would allow the realization of Indeterminate Architecture, an architecture in a continuous process of definition and redefinition, so far an utopian concept, as the ideas viewed by ArchiGram in the 60s or the animate forms of intelligent spaces (by authors such as Greg Lynn and Tristan d'Estrée Sterk).

BACKGROUND

The typology of the SLE unit determines the morphology and movement of the resulting structures. There are three typologies of SLE for folding structures, depending on the shape of the bars and the position of the intermediate joint: centered or symmetrical scissors, asymmetrical or polar and angulated or type Hoberman. Their joining allows generating lines and grids, arches and vaults, and domes respectively, all extensible. The polar unit is the only one to move from one line to a curvy figure, but does not allow three-dimensional displays [2].

These SLE are the starting point for new M-SLE solutions for transformable structures. Other authors have proposed alternatives: Yenal AKGÜN (Izmir Institute of Technology Turkey) [3] proposes to add a hinge on each bar of the x, which allows changing from straight to angulated scissor like elements; and Daniel Rosenberg (MIT Massachusetts Institute of Technology) [4] proposes to replace the central hinge between the bars for an oblong union, to switch from a symmetric to an asymmetric unit. As shown in the former investigations, only by making changes to the SLE base unit, it is possible to change the shape, to obtain different formal alternatives with a single structural solution.

NEW PROPOSAL FOR A TRANSFORMABLE UNIT

Starting from the three base units for folding systems (degrees of freedom DOF= 1) and adding another DOF to the unit (DOF> 1), folding and transformable systems are obtained simultaneously. The mechanism that allows the transformation of the base units is a central hinge (which allows rotation between bars). In this job a new typology of transformable is studied: telescopic bars articulated in x. The proposal uses two mechanisms of transformation: a scissors system combined with the use of telescopic bars, which allows switching from a symmetric to an asymmetrical unit by changing the length of the bars. The object of study is a deck arch formed by several SLE units (or units of scissors) with 4 drive telescopic bars driven by pneumatic cylinders. (see Table 1)

The methodology applied for the analysis and evaluation of the proposal can be summarized in the following phases: kinematic analysis, geometric analysis and structural analysis.

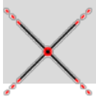
		rotation		displacement			
		between bars	bending bars	between bars	of the bar		
	SLE-centered	x				1 DOF	foldability
	SLE-polar	x				1 DOF	foldability
	SLE-angulated	x				1 DOF	foldability
	M-SLE-akgün	x	x			2 DOF	foldability + transformability
	M-SLE-rosenberg	x		x		2 DOF	foldability + transformability
	MP-SLE-proposal	x			x		

Table 1. Study of the DOF of the SLE units.

KINEMATIC ANALYSIS: STUDY OF MOBILITY

The analysis of the mobility consists of identify the number of degrees of freedom of the system proposed. This calculation has been made using the F. Freudenstein and R. Alizade formulation ($M = JT - \lambda \cdot L + q - jp$).

In conventional static structures, mobility is M = 0, which means that the system is a rigid structure without any additional element for fixing the system. Typically, scissor articulated systems are rigid structures if they have their ends linked.

The transformability in the proposal has been limited to a two-dimensional structure with 4 drivers at the ends as control elements to define and set each of the positions, and four central prismatic bars to ensure compatibility of movements. The mobility resulting from the proposal is M = 4. Having more actuators requires more control elements, increasing the complexity of the system considerably. (see Fig. 01)

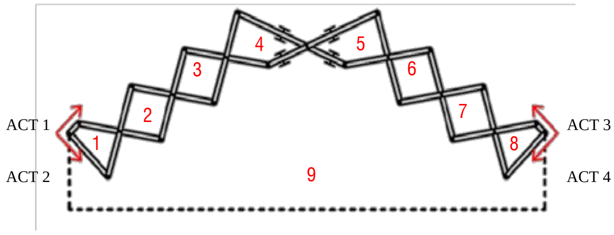


Fig. 01 Proposal scheme, with MP-SLE.

GEOMETRIC ANALYSIS: SEARCH FOR POSSIBLE CONFIGURATIONS AND LIMITS

The study of the transformability of the proposal is based on the application of the principles of parametric design. Through the use of self-created software (see Fig. 2), the relationships between INPUT parameters and the possible resulting geometric OUTPUTS that can be generated have been established. In the proposed design, the input geometrical data is: the span of the arc, the number of units, the length of the bars, the lengthening / shortening of the actuators (0b to 2b, where b is the length of the mid-bars), and the angle of the end bars in the supports. From these variables, all the output configurations can be obtained, defined by the length of the resulting bars, the curvature of the final configuration, the height of the maximum and minimum nodes, the distance between nodes, and the angle of rotation in the hinges.

Three symmetrical configurations have been studied. Configuration A is rectilinear, and occurs when lengthening or shortening equally the 4 actuator ends. Configuration B has 1 curvature, when the length of the actuators is symmetrical on both sides. And configuration C has 2 curvatures, when the actuators are extended in opposite to each of the sides. (see Fig. 3 and Fig. 4)

The results are represented in dimensionless graphs, according to the L/b ratio (ratio between span / bars length).

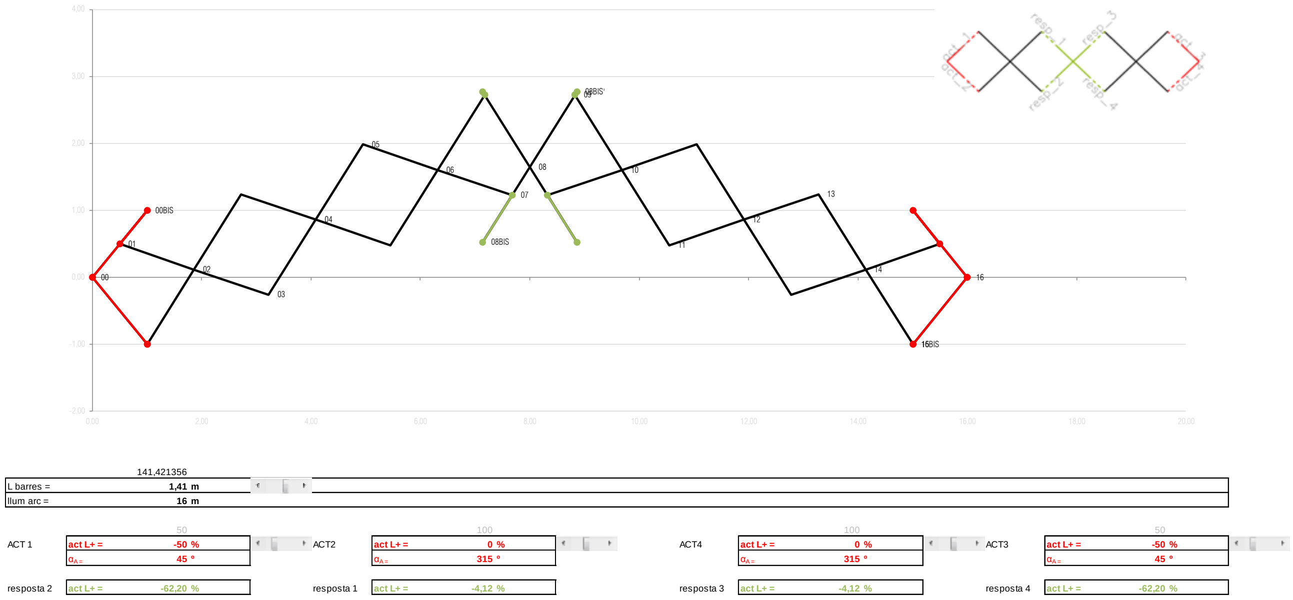


Fig. 02 Software for the geometric analysis.

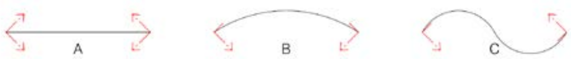


Fig. 03 Configurations studied.

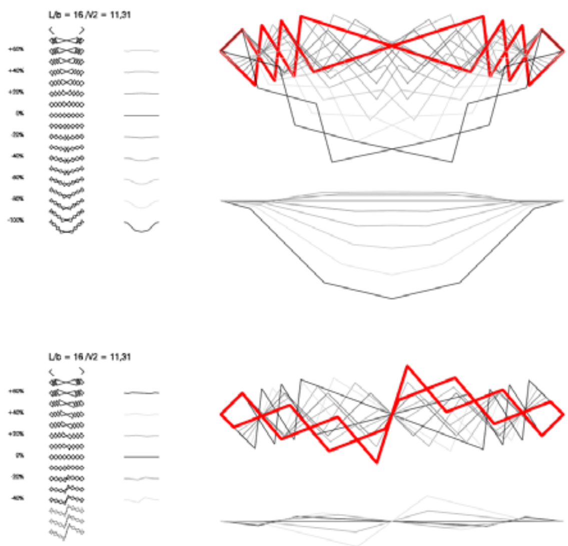


Fig. 04 Transformation process.

Feasibility study according to the L / b ratio (n=8)

The graphs show the relation of lengthening or shortening of the upper and lower side actuators regarding its initial length, identifying the feasibility of the system: green corresponds to viable geometries, others are non-possible geometries. The geometry is not possible when the distance between upper and lower nodes is greater than the sum of the two mid-bars (white), when the resulting central telescopic bars are elongated more than twice its length (red), or when bars intersect (blue).

For Configuration A and B, the horizontal axis represents actuators 1 and 3, and the vertical axis actuators 2 and 4. For configuration C, the horizontal axis corresponds to actuators 1 and 4 and the vertical axis to actuators 2 and 3. In all cases, actuators 1 and 3 are the superior actuators, and 2 and 4 the inferior ones.

The above flat graphics display the set of possible combinations for each type of configuration A, B, and C. (see Fig.5) (see Table 2)

Geometric viability limits geometric n = 8

n = 8	**9,94**	**< L / b <**	**13,56**
	16 / 1.61	< L / b <	16 / 1.18

Optimal ratio L/b

L/b = 12	35% + 38.75% + 13.5%	**= 87,50**
L/b = 11.31	25% + 37% + 11.75%	**= 73,75**
L/b = 10	20% + 28.75% + 9,50%	**= 58,28**

Table 2. Geometric limits and optimal ratios.

Amplitude of transformation (n=8)

The following table shows the study of the amplitude of transformation for a structure of 8 units SLE, showing for each of the limit permissible configurations: the lengthening or shortening of the resulting central telescopic cylinders, the angle between the central bars of the system, and the maximum height of the system, depending on the span of the structure. (see Table 3)

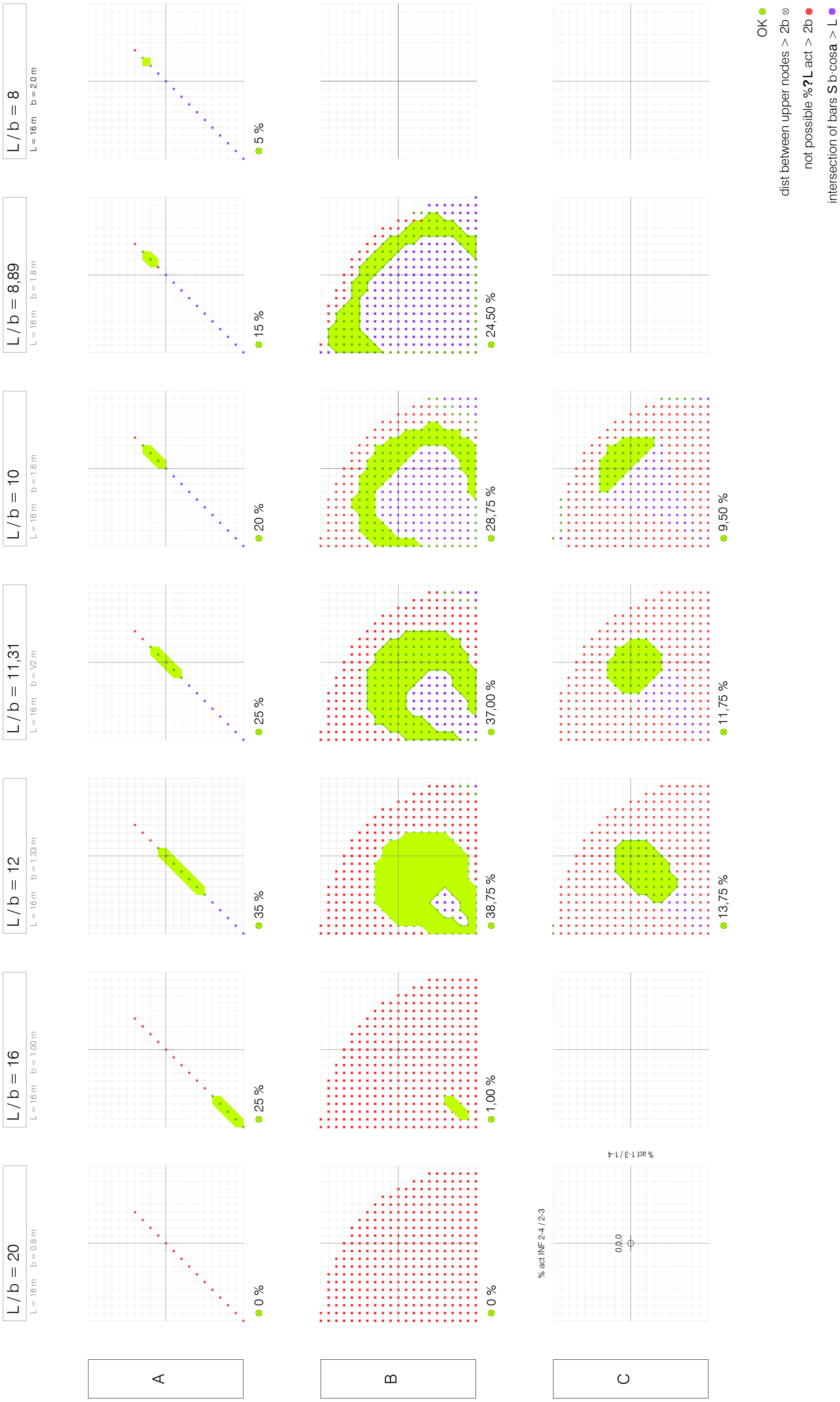


Fig. 05 Feasibility study according to the L/b ratio (n=8)

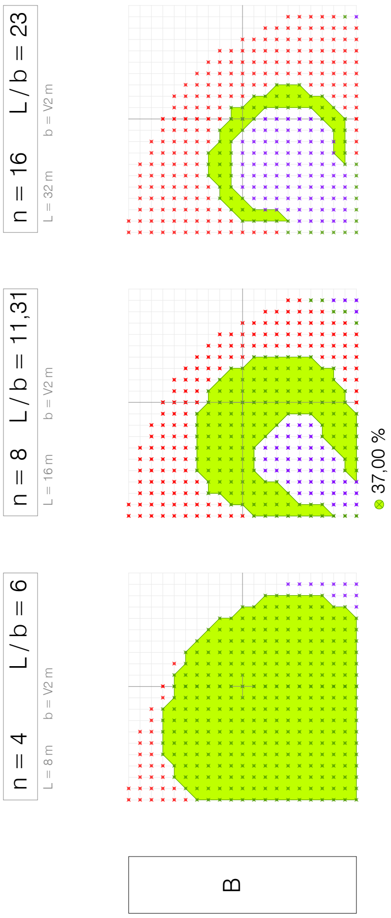
L / b = 12 **L=16m** **b=1.33**

		% act sup	act inf	% res 1-3	% res 2-4	α center	y max	y mx / L
A	% màx res	10	10	65,98	65,98	55,89	0	
	% mín res	-50	-50	-64,31	-64,31	164,22	0	
	α màx	-50	-50	-64,31	-64,31	164,22	0	
	y màx	-	-	-	-	-	-	
		% act 1-3	act 2-4	% res 1-3	% res 2-4	α center	y max	y mx / L
B	% màx res	-90	0	97,18	31,68	27,36	3,851	24,1%
	% mín res	-80	-70	-64,95	-98,9	155,96	1,274	8,0%
	α màx	-80	-70	-64,95	-98,9	155,96	1,274	8,0%
	y màx	-100	(-99)	75,89	75,18	0,231	**5,651**	**35,3%**
		% act 1-4	act 2-3	% res 1-4	% res 2-3	α center	y max	y mx / L
C	% màx res	10	20	98,57	82,27	50,39	0,12	0,8%
	% mín res	20	10	82,27	98,57	50,39	0,12	0,8%
	α màx	-30	-40	-77,17	-12,09	93,58	0,41	2,6%
	y màx	-90	-80	97,73	75,75	1,27	**2,04**	**12,8%**

Table 3. Amplitude of geometric transformation.

Feasibility study according to the number of units

The graphs show the relation of elongation or shortening of the upper and lower lateral actuators, identifying the viability of the system for configuration B. (see Fig. 6) (see Table 4)



Geometric feasibility limits

n = 4	**4,26** 8 / 1.88	**< L / b <** < L / b <	**7,92** 8 / 1.08
n = 8	**9,94** 16 / 1.61	**< L / b <** < L / b <	**13,56** 16 / 1.18
n = 16	**21,19** 32 / 1.51	**< L / b <** < L / b <	**24,8** 32 / 1.29

Table 4. Feasibility according to the number of units.

STRUCTURAL ANALYSIS: RESISTANCE FEASIBILITY

To study the resistant behavior of the proposal a linear static analysis of various models has been made, using WinEva program, since stability in moving structures is understood as a process rather than a state. This has been repeated depending on the geometry, the number of units and the lengths of the bars, in order to define the most influential parameters.

Four extreme configurations have been studied: configuration A, rectilinear; configuration B with 1 minimum curvature; configuration B with 1 extreme curvature; and configuration C with 2 curved configurations. These studies have been repeated for sets of 4, 8 and 16 units, and for various L / b ratios. Below is a sample diagram of axial, shear and bending moments, the maximum deformation of each model and the tension in the bars. The results will be summarized in future studies, linking several of these parameters. (see Table 4)

comparative L/b ratio – shape

L = 16m q = 100 kg/m2 AB = 3 m ø180-15

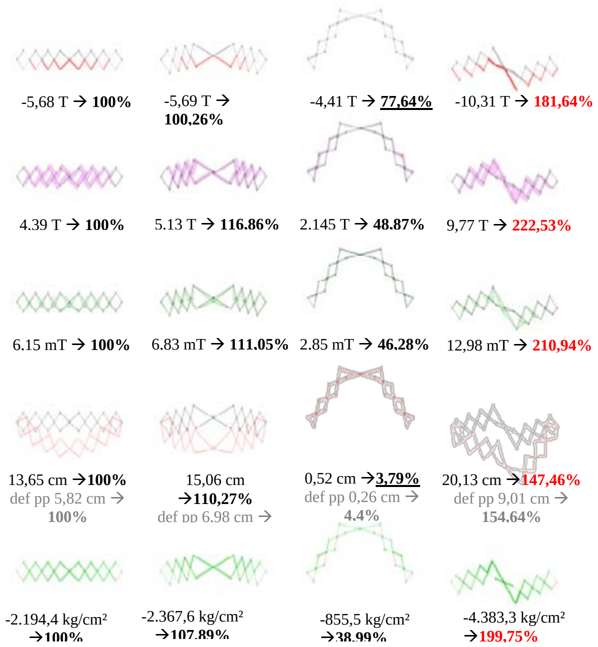


Table 4. Structural study: comparative L/b ratio - shape

CONCLUSIONS

The definition of geometry is a key factor in any transformable system, since not all configurations offer viable results. Geometric compatibility must be ensured during the development, for which parametric design is essential.

From the review, comparison and evaluation of the results obtained, the weak points of the proposal with the new transformable MP-SLE can be defined, possible solutions can be proclaimed and future areas of research can be defined; in order to materialize a transformable prototype with the system studied.

Studies of the feasibility of the system:

KINEMATIC ANALYSIS: STUDY OF MOBILITY

The key point in the variability of a system is its mobility: the more actuators, the greater the transformability the design offers. Anyhow, it is necessary to limit the degrees of freedom of the system, since the more control elements, the higher the complexity is.

Thus, it is feasible to create structures of variable geometry or transformable, making minor modifications to the SLE base unit, multiplying in this way the formal alternatives of a single structural solution.

GEOMETRIC ANALYSIS: SEARCH FOR POSSIBLE CONFIGURATIONS AND LIMITS

Geometric viability limits depend on the L / b ratio and the number of SLE units in the system.

For a different number of units equal amplitude is obtained for viability (3.6). For n = 4, 4.26 <L / b <7.92; for n = 8, 9.94 <L / b <13.56, and for n = 16, 21.19 <L / b <24, 8. Thus, in all three cases studied, the same set of points displaced in the vertical axis in the three-dimensional graphic is generated. Thus, setting a fixed variable (length of the bars or span cover), the margins for the other parameter for optimal viability can be set.

The optimum L / b ratio, the one that offers more diversity of formal possibilities, is L / b = 12 for systems of 8 units, with a 29.1% of all possible combinations of symmetrical actuators for A-B-C configurations. This percentage is low due to many geometrical incompatibilities: L / b ratio that do not support the combination of actuators at rest (0% -0%), intersection of bars (for small values of L / b) and the fact that the elongation of the resulting telescopic bars exceeds the 2b length (for high values of L / b).

Limit configurations also define the amplitude of transformation. For an arch configuration of 8 units, a core height of 37% of the arch span is obtained, whereas for a double-curvature configuration it is a 13% of the span. It can be concluded that, for B type configurations, the lower the L / b ratio, the greater the transformation amplitude. Whereas, for C type configurations, the larger the L / b ratio, the greater the transformability.

STRUCTURAL ANALYSIS: RESISTANCE FEASIBILITY

Shape is the most influential parameter in structural analysis. The arch shape works and distributes efforts optimally, while double curvature configuration doubles the deformation and tensions compared to the straight configuration. Thus, it is not necessary to study all possible configurations to dimension every system, but only the most unfavorable. However, since the dimensioning of the most unfavorable configurations leads to oversizing all other states, the inclusion of tensioners or canvas in the design will be considered, without affecting with this the transformability of the system, and improving its behaviour.

The angle of the supports is another parameter to be considered. Its variation allows the inclusion of more units, increasing the system's edge but at the cost of increasing the weight of the structure, thereby penalizing the resistant behavior. It is a must to find the balance between weight and singing for each case.

The lengthening and shortening of the actuator produces no efforts in the bars, but by changing the geometry of the system, the stress distribution and the behaviour of the structural elements vary. In a static analysis, those parameters which influence the resistance behaviour resistant, are identified. However, to analyze the behavior generated by transformations, a large displacement linear analysis would be required.

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