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A preliminary study on a variable section beam through Algorithm-Aided Design: a way to connect architectural shape and structural optimization.

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Abstract

This paper presents a simple strategy in order to search for the ideal shape of a generic variable section beam through algorithm-aided design; the latter makes it possible to interconnect the morphological requirements dictated by all the disciplines that contribute to the architectural / structural composition. At this aim, a specific optimization procedure is codified by Grasshopper software. The search for the minimum middle rise of the beam is posed as a single-objective optimization problem, while suitable architectural/geometrical constraints are considered for gaining the optimal shape. The dimensions and characteristics of the beam are taken from an existing structure (nowadays demolished), the BRAZIL PAVILION at the OSAKA Expo (1970) designed by Paolo Mendes da Rocha. The structure was characterized by an important structural span, that was covered by adopting advanced technological methods, shapes and materials.

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Keywords: Paulista School, Algorithm-Aided Design, Structural Morphology, Structural Optimization

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1. Introduction

There are different ways for looking, studying and telling an architecture; each has its own identity, history and each can be analyzed under different points of view. An architectural project involves multiple disciplines, all necessary for the definition of the "final product" (see Fig. 1.).

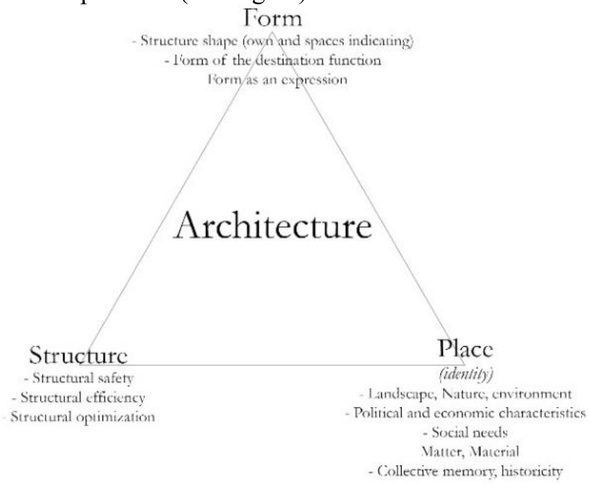

Fig. 1. disciplines that compete in architectural composition.

This type of research is based on the assumption that there is a unique problem to which the figure of the designer must give multiple answers, starting from a precise and determined form (because it has that morphology) up to the structural and decorative features. The answer will be satisfactory in a way that is directly proportional to the designer's ability to integrate different disciplines and to make them converge towards a single result: the final architecture. In this framework, the role of structural components becomes more significant in the case of large spans to be covered. The proposed study deals with particular architectural typology, on which the efforts of many designers concentrated in the last decades, experimenting new shapes and materials, such as laminated wood and prestressed concrete.

1.1. Shape and Structure: the Paulista architectural tradition

The theme of covering large spaces has always deeply interested the designers, representing an exciting challenge for combining the various aspects of a building. The design challenge becomes even more bould when the space is "delimited", "created" and "designed" only from roofing; this specific condition leads the designer to think outside the traditional design schemes.

The above concepts are well explicated in the Paulista architecture (from Paulo Mendes da Rocha). The clarity of concrete volumes, from project to construction, and the integration of the building in the landscape are basic and permanent features of the Paulista architecture. The Paulist architects motivate their architecture in its entirety, starting from the choice of the material that is not exclusively motivated by a desire of "poverty" and aesthetic "discretion", but is also dictated by the search for a coexistence between the structural element and the shape of the architecture, expressed through the exaltation of construction components. In particular Paulista architects combine concrete and steel - and again propose a mixed materiality, which maintains the association of both materiality, the elemental force of expressiveness. So, architecture becomes the art of matter and expresses a worldview that speaks of solid values.

There is no doubt, therefore, that the works of the Paulist School find in their structural design - in reinforced concrete, but also in steel or in the concomitance of the two - their personal raison d'être, whose results, often surprising, lead to an inseparable identification [4]. The Paulist architects do not ask themselves how to construct their buildings from a constructive point of view, since the architectural form is the result of suggestive structural choices. In the School, there's no reasoning for parts, but it is reasoned in a uniform manner. It comprises the "integral reasoning", compared to the integral calculation: many small parts define a unique and continuous element (see Fig. 2.).

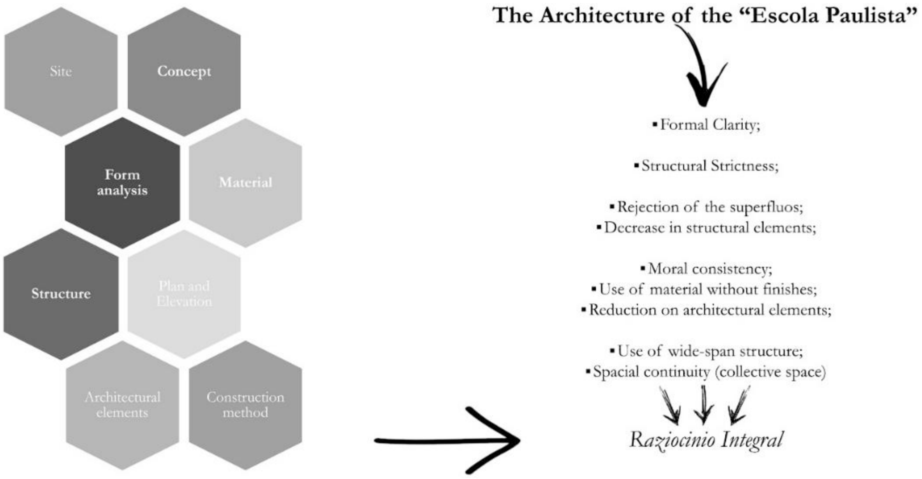

Fig. 2. The "Raziocinio Integral" in the Paulista School.

The resulting project appears to be indivisible in its constituent "*pedaços*": structure, installations, vertical connections, horizontal paths. A possible way to make the design process "undivided", exactly as in the Paulista architecture, is represented by the *computational design*. It is one of the most powerful algorithmic modeling tools for generating and controlling complex shapes at any scale: from architecture to design (see Fig. 3).

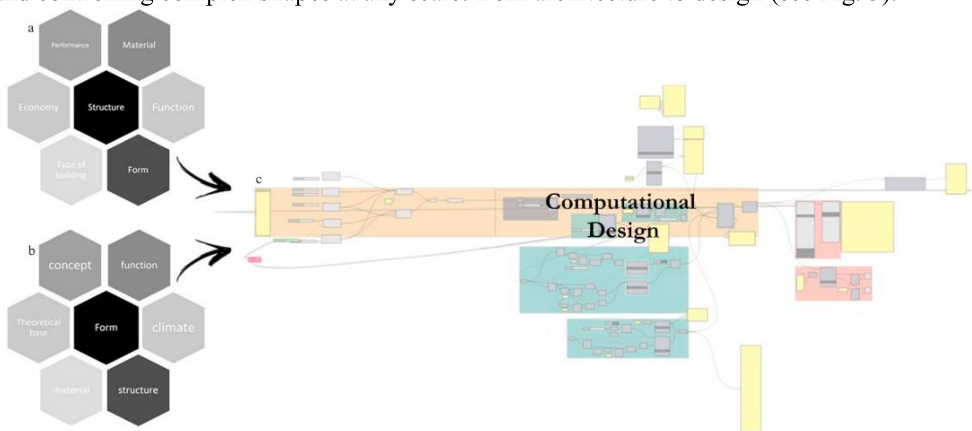

Fig. 3. (a) The relationship between structure and other elements of analysis; (b) Some of effective factors on architectural composition; (c) Example of knot diagram (Algorithm) produced by the factors of the architectural composition.

Within the process, it is possible to simultaneously manage the individual parts of an architectural project through dimensional (and therefore geometric) parameters that allow the development of architectures, by maintaining under control all aspects of form and structure throughout the whole design phase.

Computational design allows to generate complex structural shapes through the definition of a node diagram (algorithm) able to describe the mathematical and geometric relationships of a model (see Fig. 3(c).). The three-dimensional model developed by the algorithm can be modified in real time by varying the parameters defined during the construction of the diagram, with immediate advantages in terms of formal exploration and of form control / rationalization. [2]

As a direct consequence of the associative logic, it is possible to create conceptual and effective links between the different levels of the in-depth planning. Details can so be easily redefined and modified at a small-scale, in order to be successively translated into a large-scale. The computational design is therefore the application of computational strategies to the design process. While designers traditionally rely on intuition and experience to solve design problems, computational design aims at improving this process by codifying design decisions using computer language. The goal is not necessarily to document the final result, but rather the steps necessary to create that result. [8]

1.2. Brazil's Pavilion in Osaka

In the Brazilian Pavilion in Osaka (Expo 1970) (see Fig. 4.) the architect Paulo Mendes da Rocha realized a large roof that could create much more than an itinerant architecture: it was a communication effort related to a specific territorial condition. The design of the pavilion was based on the idea of landscape enclosed in architectural forms without physical boundaries: the support points were in fact imperceptible ("the point of contact between heaven and earth where in the middle is the space of man) and among these, the shape of the arch stood out, representing the expression of a primordial geometry. So, the arch shape of the main beams did not only reproduce the load path but was primarily dictated by a design choice.

The pavilion was therefore born as a meeting place for the community, without pre-established rules, where a strong compositional freedom was accompanied by a deep knowledge of structural techniques: in a 80×50 m^2 lot, the roof occupied a 32.5×50 m^2 area, supported by the only four pillars - three hidden and a fourth in correspondence of the intersection between two orthogonal arches.

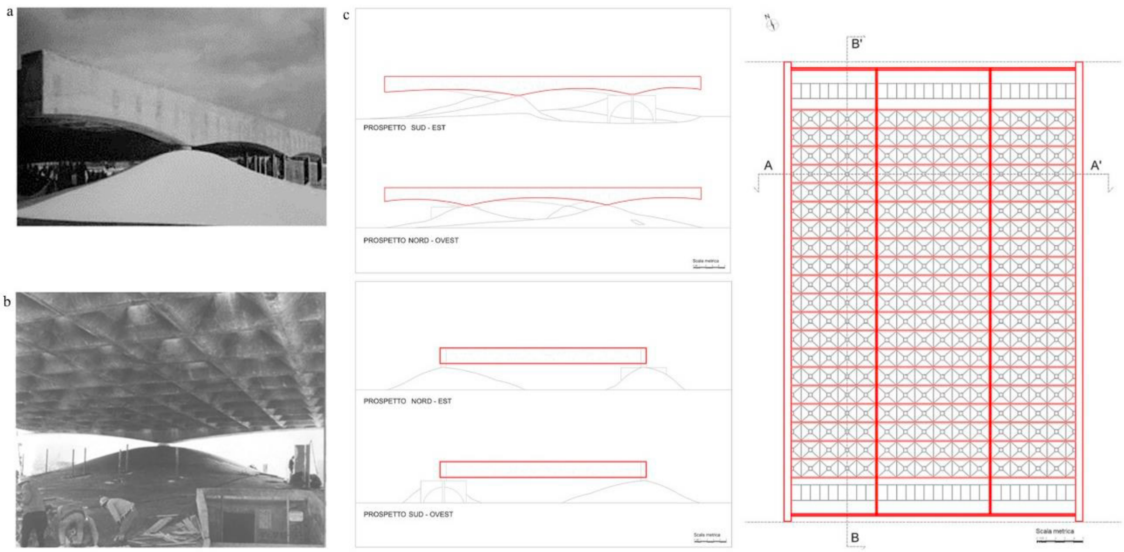

Fig. 4. (a) Brazil's Pavilion, Expo of Osaka (1970); (b) Brazil's Pavilion during construction phase; (c) Oriented elevations and plan - Brazilian Pavilion at Osaka Expo (1970).

Through a redesign procedure (see Fig. 4(c).), it was possible to recognize all the elements constituting the structural system of the pavilion, to be successively implemented in the structural calculation software.

2. Parametric design and optimal solution

The main variable-section beam represented in Fig. 4(c). is the object of this study. The simply-supported middle portion of the beam was modelled in the workspace and parametrically conceived (Fig. 5(a)). That is, the structural behavior can be recalculated in real time if geometrical parameters are changed. The beam geometry, loads, material properties and constraints were suitably coded, in the form knot diagram (Fig. 5(b)).

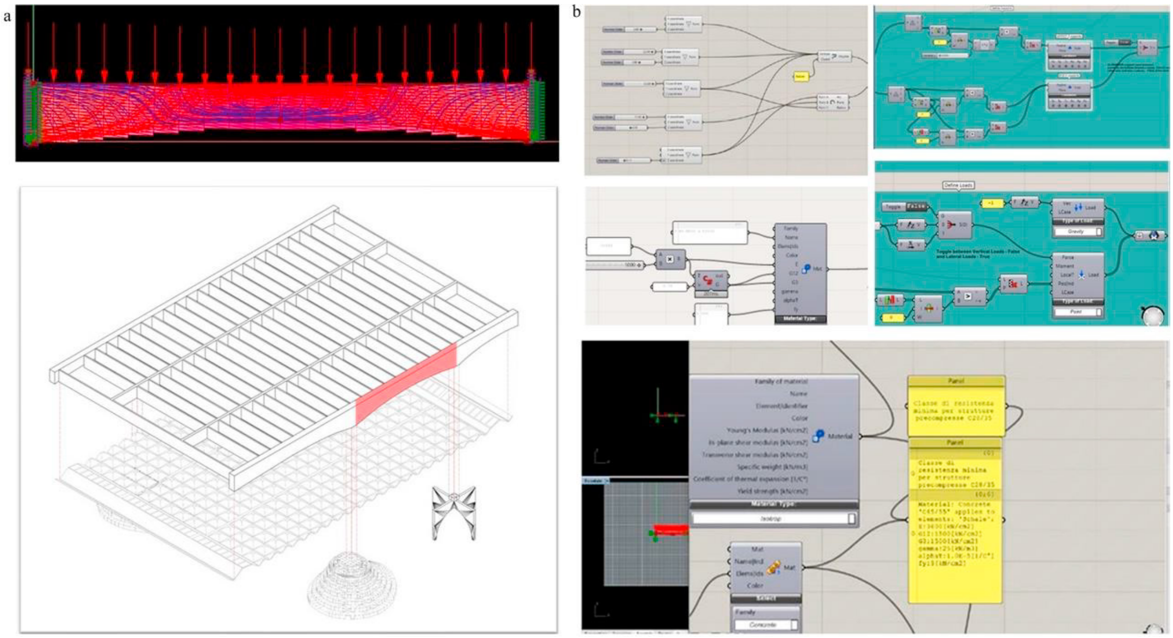

Fig. 5. (a) Portion of beam parametrically conceived; (b) Coding of geometry, constraints, material and load.

The dimensions of the beam cross-section, without any emptying, are: base b=0.9 m and height h=2.6 m. In this first analysis the material was hypothesized *homogeneous* and *isotropic*, with *linear elastic behavior* [11, 12]. The beam was modeled as a bidimensional body. It was subjected to a *uniformly distributed variable load* equal to 125 kN/m. The following mechanical properties, characterizing concrete, were considered: specific weight γ_c=25 kN/m^3; modulus of elasticity E_c=3600 kN/cm^3. A value of the span equal to 25 m was firstly assumed. After fixing the above configuration, linear-elastic analyses were carried out by Grasshopper software. In order to obtain the optimal shape, a specific optimization procedure was implemented. The optimization within the elastic framework is a classical problem that has been widely considered in the continuum analysis [13-15]. In this study the search for the minimum middle rise of the beam was posed as a single-objective optimization problem, while suitable architectural/geometric constraints were considered for gaining the optimal shape. More precisely the optimization problem can be formulated as follows:

Find the best shape of the beam that minimizes the middle rise, satisfying the following constraint:

$$y'(x) \geq 0 \ \forall x \tag{1}$$

The term “rise” defines the maximum deviation from the undeformed geometry of a beam subject to bending; The height y’(x) at midspan represents the potential emptying of the beam (see Fig. 6.) (the maximum domain value of the variable y’(x) corresponds to the maximum height of the beam from the original design by Paolo Mendes da Rocha i.e. h=2.6 m).

The length of the beam on the x axis is variable for each test carried out; in this case the length of the beam corresponds to L=25 m and the main axis for emptying the beam is in the middle span i.e. L / 2 = 12.5 m (y’).

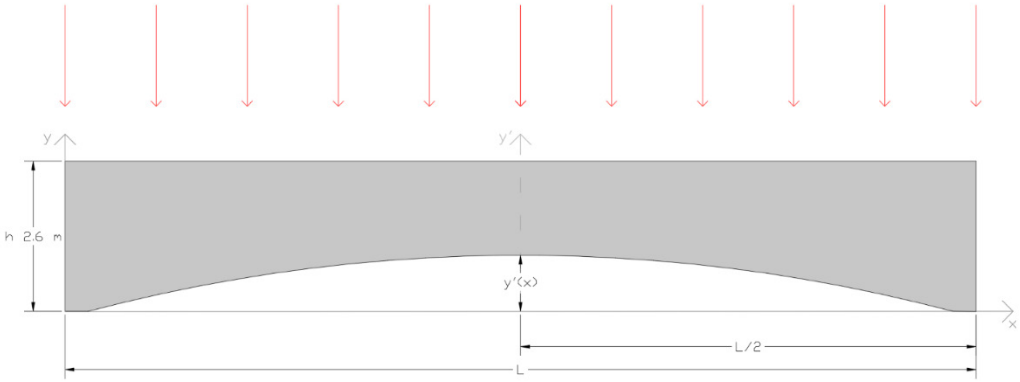

Fig. 6. Schematization of the reference beam.

So, according to Eq. (1), it is assumed that the beam height can only remain constant or reduce, but not increase.

2.1. Galapagos: Grasshopper's evolutionary genetic solver

The solver applied in the proposed study is an evolutionary genetic solver able to find the maximum or minimum given one or more objective functions. Grasshopper's working environment offers the possibility of using a genetic solver able to find the minimum or maximum of a given function. Genetic (evolutionary) algorithms are computer science techniques inspired by biology based on a metaphor, schematically illustrated in the chart [16-18]: how an individual of a population of organisms must be adapted to the environment that surrounds it to survive and reproduce, so a possible solution must be suitable to solve your problem. The problem is the environment in which a solution lives, within a population of other possible solutions; the solutions differ from each other in quality, that is, in cost or merit, which are reflected in the evaluation of the objective function, just as the individuals of a population of organisms differ or more parts of a solution; alleles are the possible configurations that a gene can take; the exchange of genetic material between two chromosomes is called crossover, while we refer to the perturbation of the coding of a solution with the term mutation. Although the computational model introduces drastic simplifications with respect to the natural world, evolutionary algorithms have proved capable of bringing out surprisingly complex and interesting structures. Each individual can be the representation, according to a suitable codification, of a particular solution to a problem [19].

2.2. Resolution of the optimization problem

The above described optimization strategy was firstly applied to the beam with span equal to 25m. In this case the solution that minimizes the middle rise is given by the full beam. In fact, the self-weight of the beam is not excessive yet (Fig. 7(a)). By successively increasing the span value, different results can be obtained. In particular, by assuming a beam span equal to 50 m and maintaining all the other geometrical and mechanical parameters constant, the solver empties the beam in order to minimize the middle rise. This is due to the circumstance that in this second case the ratio between load and stiffness, without emptying, would reach a value implying a considerable rise increase (Fig. 7 (b)). The optimization procedure was repeated many times by assuming different values of the beam span in order to find the value starting from which the beam emptying represented the optimal solution. This value resulted to be equal to 46 m (Fig. 8). That is, for the case under examination, starting from that point, vertical load and in particular self-weight becomes significant and strongly affects deformations:

$$y'(x) > 0 \equiv \ self - weight\ affects\ deformations \qquad (2)$$

The minimized middle rises obtained for each model, after the beam emptying (if occurring), are summarized in Table 1.

Table 1 Minimized middle rise for each model obtained by the optimization procedure

	L=20 m	L=25 m	L=30 m	L=35 m	L=40 m	L=45 m	L=46 m	L=50 m
optimized rise δ [m]	0.027	0.047	0.074	0.107	0.147	0.192	0.201	0.242
rise/span ratio δ/L	0.135%	0.188%	0.247%	0.306%	0.367%	0.427%	0.437%	0.484%

After emptying, the optimized rises of beams with span equal to 46 m and 50 m result to be δ_{46}=0.201 m and δ_{50}=0.242 m respectively; without emptying middle rises would be grater, that is δ_{46}=0.276 m and δ_{50}=0.371 m.

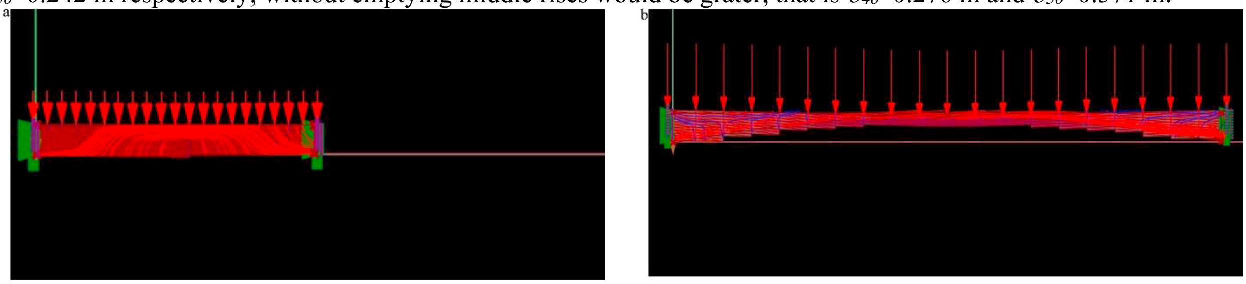

Fig. 7. (a) Test n.1: Application of the geometric constraints and Galapagos solver on a variable section beam with span equal to 25 m; (b)Test n.2: Application of geometric constraints and Galapagos solver on a beam with variable section with span equal to 50 m; both images show the isostatic lines - blue and red – respectively relating to the main tensile and compressive stresses.

The proposed methodology can be particularly useful for practical applications, when large spans have to be covered. In this case beam self-weight can become excessive, significantly affecting deformations and amplifying seismic action, so requiring suitable design strategies able to reduce volume. The one herein proposed consists in emptying the beam by imposing the minimization of the middle rise.

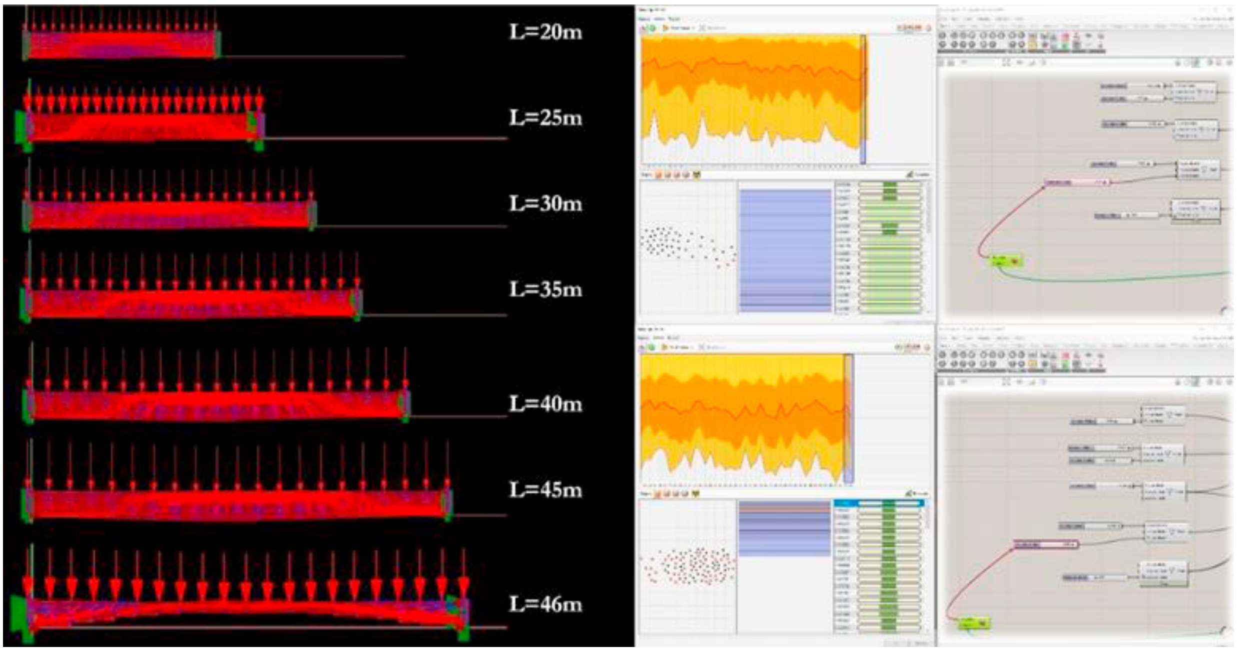

Fig. 8. Application of Galapagos solver to different span beams.

3. Conclusions

In this study a practical tool was proposed for the optimal design of large span beams, combining both architectural and structural aspects. The optimization procedure was implemented by Grasshopper® software, an algorithm-aided design tool. It consisted in searching for the optimal shape of a variable section beam by minimizing the middle rise and by imposing specific architectural/geometrical constraints. It was shown how, when vertical load becomes significant so as to strongly affect deformations, the beam emptying represents the optimal solution. A practical solution can so be provided when it is necessary to reduce beam self-weight, in the case of large spans to be covered.

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