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***COVER:*** *Figure 9(a) from paper by Block and Ochsendorf*

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# MORPHOGENESIS AND STRUCTURAL OPTIMIZATION OF SHELL STRUCTURES WITH THE AID OF A GENETIC ALGORITHM

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## ABSTRACT

*The paper presents a method to generate and structurally optimize the shape of free form shells by means of a genetic algorithm. The shape of the shell is described with the aid of a NURBS representation and the algorithm modifies and improves it on the basis of the structural behaviour. A FEM analysis is performed for each individual and at each generation of the evolutionary process, in order to evaluate the structural behaviour in terms of maximum vertical displacement under a distributed load condition. The method is applied to a recent example of free-form architecture and the results are discussed referring in particular to the role of the architect as 'decision maker' in the evolutionary process. From this point of view the necessity to fit different requirements (structural, functional, aesthetic) involving the work of many professionals, can then be interpreted as a problem of multiobjective optimization.*

***Keywords:*** *free form design, genetic algorithms, computational morphogenesis, optimization*

## 1. INTRODUCTION

The genetic algorithms, and more generally the evolutionary computational techniques, can be applied with success to a wide range of structural and architectural problems. The structural optimization of complex structures, as membranes, shells [3], grid shells [13], has been historically an important research field since the work of Gaudì and the experiences on physical models. The use of evolutionary algorithms in this problems is relatively recent [1][2] and it goes in parallel with their use in other structural applications, specifically in topological optimization of trusses [8][14]. The recently developed technique of Evolutionary Structural Optimization (ESO) [4][15] seems to approach the design problem with particular attention to architectural and aesthetic aspects. In other disciplines the use of genetic algorithms is diffuse since thirty years, starting from the studies in biology, on the adaptation in natural and artificial systems, until the research on the genetic programming [9]. John Frazer is the pioneer that in '70s brought this kind of research inside the architectural design, thus evolved in the personalization of the software and in parameterization [6].

The evolutionary approach to architecture is a powerful strategy to handle complex problems, involving different requirements to be fit, from the structural and economic aspects to the constructional, functional and aesthetic ones. The traditional multidisciplinary approach, in which different professionals are involved in design, each one solving just a specific problem, is put in discussion by the recent developments of computational technology; many architects feel that their role in the design team is changing and the interest for the Non-Standard Architecture as well as the attention for the interactions between architecture, engineering, mathematics and computation is the clue of these new trends in architectural design.

In this contest the application of a genetic algorithm to the morphogenesis of the structural and architectural shape for free form concrete shells can help to better understand the role of the architect and of the engineer in the design process. There is an intrinsic difference between the form-finding strategies usually adopted, for instance, in the design of tensile structures or of grid shells, and a morphogenetic process of structural optimization. In the first case the solution is well defined, even if unknown. It can be represented by a minimal surface or it can correspond to an equilibrium configuration of the structure under a specified load condition. Into a morphogenetic design process, on the other hand, the final sub-optimal solution is not univocally determined by a mechanical (or physical) property, but is the one which better fit a set of design requirements.

## 2. THE EVOLUTIONARY ALGORITHM

The morphogenetic application presented in this paper is based on the interaction of three computational technologies: the geometric modeller, the FEM solver and the genetic algorithm.

First, the shape of the structure has to be defined from the geometric point of view. Different descriptions are possible: if the shape is relatively regular it can be described with the aid of an explicit function of two parametric variables and it can be modified by changing the values of the constant parameters involved in the description. If the shape is complex the surface can be described as a NURBS surface, i.e. a rational polynomial continuous function, defined by a set of control points. Secondly the structure must be analyzed and the structural behaviour studied. The surface needs to be discretized into a structural mesh and a linear or non linear structural FEM analysis has to be performed, in order to evaluate the mechanical behaviour in terms of displacements, strain energy, buckling load, dynamic response, etc. Finally, the genetic algorithm (GA) is used to perform the evolutionary optimization of the shape. A set of interacting solutions simultaneously approaches the optimal or sub-optimal configuration through an iterative process.

Each of the three computational tools has is own internal representation of the solution: a matrix of control points for the NURBS; a discrete finite element mesh with constraints and loads in the FEM solver; a binary genetic code in the evolutionary algorithm. Hence an important part of the procedure is devoted to translate the information from one representation to the others.

### 2.1 The geometric representation of solution

A free-form surface can be represented as a two dimensional NURBS with a suitable degree of approximation [10]. In this case the surface is completely defined by a net of control points, a vector of weights and the polynomial degrees in the parametrical directions. With respect to the Bezier curves, the presence of a weight associated to each control point allows to locally modify the surface by changing the control point coordinate, without modify the rest of the surface. This property is important when the position of some points is fixed, as in the case of constrained points, or when one or more edges of the surface . The positions of the free control points can be assumed as design variables in the morphogenetic optimization.

### 2.2 The coding

The evolutionary algorithm works on a coded representation of the surface. The coordinate z of the NURBS control points are stored into a two dimensional matrix. If this matrix is coded in a one-dimension binary chromosome, containing all the genetic information about the individual, the classical crossover operation can introduce a kind of asymmetry in the process, related with the way the matrix is reshaped into a vector. If the vector is obtained reordering the matrix by rows and columns, for instance, the single or multiple crossover cuts will divide the matrix in submatrices in a specific direction. This problem can be solved by reshaping the matrix in other ways, as taking the elements randomly, in order to avoid any asymmetry, but the best approach is to adopt a two dimensional binary representation of the chromosome and defining a suitable two dimensional crossover operator [11].

### 2.3 The domain

The choice of an appropriate domain for the design variables is a fundamental task. The whole design process is strongly influenced by the definition of the range of variability of each variable. When a very small range is adopted, the final solution is relatively close to the starting ones, and the algorithm improves the mechanical behaviour without altering significantly the global shape. In this case the initial shape, from which the initial population is randomly generated, can be drawn by the architect on the basis of the aesthetic and architectural requirements. The process of optimization modifies this first tentative solution in order to improve its structural performance.

If a wider range is assumed for the design variables, the evolution of shapes acts as a true morphogenetic process. The initial population is composed of random generated individuals and the evolution selects the one (or the ones) with the best fitness value. Unsuitable or incorrect shapes are frequently generated, depending on the definition of the fitness function: if only the structural behaviour is taken in account, for instance, the result can be not interesting from the aesthetic point of view or economically unsustainable. Nevertheless the morphogenesis always produces solutions with high fitness values, due to the robustness of the genetic algorithm, and the architect obtains an interesting set of new structural shapes, capable to fit the structural requirements. The designer controls and rules the morphogenetic process acting on the constrains, on the domain and on the fitness function, so that the evolutionary shape generation can be regarded as a true, even if not conventional, design process.

## 3. APPLICATIONS AND RESULTS

The design method described above has been applied to a real case study. In 2004 the construction of the new Kakamigahara crematorium in Gifu, Japan, has been completed (Figure 1). The Toyo Ito architectural concept has been constructively and structurally developed in collaboration with Mutsuro Sasaki. The shape of the reinforced concrete roof shell is free-form in plan, with a set of supporting columns randomly positioned at the ground level. The shape has been optimized from the structural point of view by means of a sensitivity analysis, in which the total strain energy is the function to be minimized. After the sensitivity coefficient of each structural node have been determined, the optimal configuration has been calculated iteratively [12]. Due to its characteristics this structure is a very good case study for the application of a genetic algorithm based process of optimization and morphogenesis. The presence of many local solution and the strong interaction between the work of the architect and of the engineer require a robust and versatile tool of analysis, in which the evolutionary progress of the solution is controlled and guided by the architect decisions. In this paper, the position and the height of pillars, as well as the plan projection of the roof boundary, are assumed as the fixed input data for the generation of the optimal shape. The thickness of the concrete shell has been assumed of 15 cm and the dead load due to self weight is the only load condition applied during the FEM analyses.

***Figure 1.*** *Kakamigahara crematorium, Gifu, Japan, designed by Toyo Ito together with Mutsuro Sasaki.*

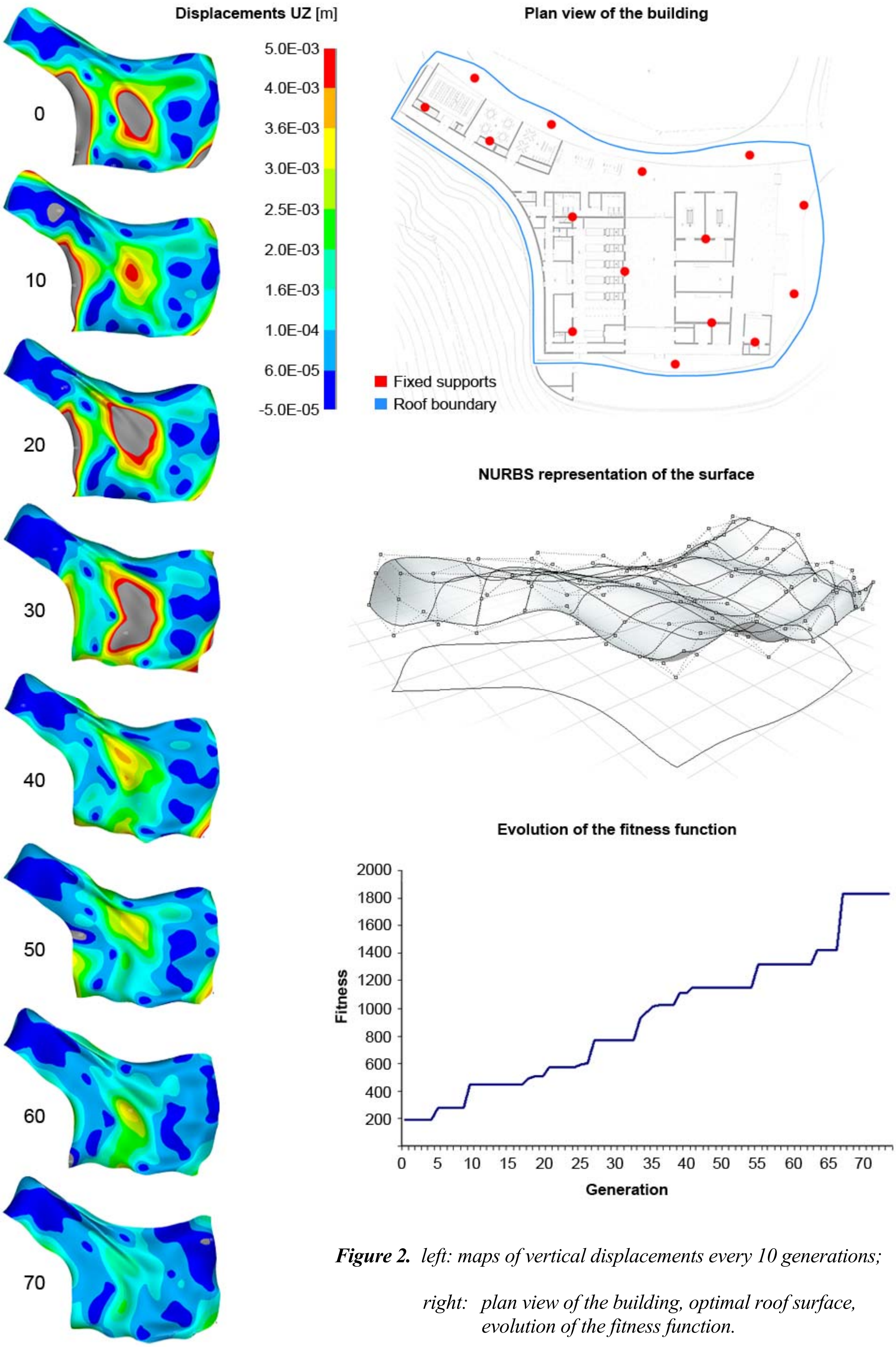


***Figure 2.*** *left: maps of vertical displacements every 10 generations;*

*right: plan view of the building, optimal roof surface, evolution of the fitness function.*

The shape of the shell is described by means of a 3th degree NURBS surface with a net of 10 x 10 control points. The vertical positions of control points are assumed as the design variables in the morphogenesis process. The position of a subset of control points is fixed, because they represent the column-slab joints. Because the control points do not lie on the NURBS surface, fixing the control points does not guarantee the surface to pass through the constraint points when it is deformed. Two methods can be applied to solve this problem: first the surface can be defined by means of a net of interpolating points, instead of control points, so that the surface can be constrained to pass through a set of fixed points; secondly the constrains can be handled introducing a penalty in the fitness function [11] and then reducing the surviving probability of solutions that do not fit the constraints. The goal of the optimization process is to obtain a stiff structure, hence the fitness function is the inverse of the maximum vertical displacement of the structure. An analogous result can be obtained calculating the fitness function from some integral parameter of the structure, as the total strain energy, instead of the maximum displacements that represent a local behaviour.

The use of a local mechanical parameter, on the other hand, allows understanding what are the parts of the structure where the algorithm is working, i.e. the parts which behaviour needs to be improved. In Figure 3, left, the vertical displacements are mapped on the roof surface at different stages of the evolutionary process. The maps show that at the first stages of the evolution both the edge and the centre of the structure have large displacements and that the algorithm reduces them alternatively. It is well known that free edges are the weakest parts of curves shells [3] and the algorithm spends a large part of the evolution in stiffening them. The procedure can be improved using the Schema Theory [7], that is used to find, inside the genetic code of the best individuals of a population, common parts that support their fitness value. In order to improve the global performance of the shape, without lose these best parts in the reproduction and mutation phases, a genetic operation called "encapsulation" can be adopted, In this way, a shape with a low displacement value on the centre and a worst behavior on the free edges can evolve preserving the parts of its genetic code that geometrically describe its centre.

## 4. THE MULTIOBJECTIVE OPTIMIZATION

As a future development of the research, the morphogenetic process can be enhanced adopting the multiobjective optimization technique, in which the fitness assignment is interpreted as a multicriteria decision process [5].

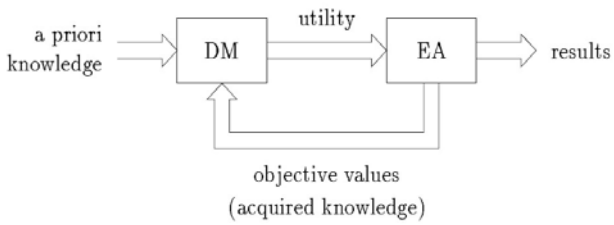


***Figure 3.*** *A general multiobjective evolutionary optimizer (from Fonseca and Fleming 1995).*

Different architectural requirements, as structural behaviour, cost, aesthetics and functionality, are very often in conflict with each other, so that the fitness of individuals needs to be calculated combining different objectives. The final configuration will be an acceptable solution rather than an optimal solution, but all the objectives included in the fitness will be partially reached. The designer acts as the Decision Maker (DM) in the Evolutionary Algorithm (EA) optimization process. In this frame, the concept of morphogenetic algorithm should lose its role of 'black box' and could be more correctly considered as a design tool with which designers actively interact.

## 5. CONCLUSIONS

A method for shape generation (morphogenesis) and structural optimization of a reinforced concrete roof shell, based on the application of a genetic algorithm, is presented in the paper. The use of a NURBS representation of the roof allows to modify the shape by changing the position of control points or interpolating points, so that the coordinates of this points can be assumed as design variables. The structural optimization, based on reducing the maximum vertical displacement of the structure under the self weight, improves the structural behaviour of about ten times in 75 generation, modifying selectively the parts of the structure showing the worse behaviour.

The application of a complex interactive and iterative computational tool to the architectural and structural design is a starting point for a more general, theoretical discussion on the role played by new digital technologies, specifically in the world of free form architecture. When the designer is directly involved in the development and in the use of the digital tools, he can keep the full control on the evolution of the project, focusing on the objectives and on the constraints of design.

## REFERENCES

[1] ***Banichuk, N.V., Serra, M., Sinitsyn A.***, Shape optimization of quasi-brittle axisymmetric shells by genetic algorithm, *Computers and Structures*, Vol. 84, No.29-30, 2006, pp. 1925-1933.

[2] ***Baverel, O., Nooshin, H., Kuroiwa, Y. Parke, G.A.R.***, Nexorades, *International Journal of Space Structures*, Vol. 15, No.2, 2000, pp.155-159.

[3] ***Blezinger, K., Wüchner, R., Daoud, F., Camprubí, N.***, Computational methods for form finding and optimization of shells and membranes, *Comput. Methods Appl. Mech. Engrg.*, Vol. 194, 2005, pp. 3438-3452.

[4] ***Cui, C., Ohmori, H., Sasaki, M.***, Computational Morphogenesis of 3D Structures by Extended ESO Method, *Journal of the International Association for Shell and Spatial Structures,* Vol. 44, No. 141, 2003, pp. 51-61.

[5] ***Fonseca, C. M., Fleming, P. J.,*** Multiobjective Optimization and Multiple Constraint Handling with Evolutionary Algorithms-Part I: A Unified Formulation, *IEEE Transactions on Systems, Man, and Cybernetics, Part A: Systems and Humans*, 1998.

[6] ***Frazer, J.,*** *An Evolutionary Architecture*, Architectural Association Publications, 1995.

[7] ***Holland, J. H.***, *Adaptation in Natural and Artificial Systems*, The MIT Press, 1992 (1975).

[8] ***Iuspa, L., Scaramuzzino, F., Petrenga, P.***, Optimal design of an aircraft engine mount via bit-masking oriented genetic algorithms, *Advances in Engineering Software*, Vol. 34, 2003, No. 11-12 pp. 707-720.

[9] ***Koza, J. R.***, *Genetic Programming: On the programming of computers by means of natural selection*, The MIT Press, 1992.

[10] ***Piegl, L., Tiller, W.***, *The NURBS book: 2nd edition*, Springer, 1997.

[11] ***Renner, G., Ekárt, A.***, Genetic Algorithms in Computer Aided Design, *Computer Aided Design*, Vol. 35, No. 8, 2003, pp.709-726.

[12] ***Sasaki, M.***, *Flux Structure*, TOTO, 2005.

[13] ***Sassone, M.***, Geometry and Structure Generation in Grid Shell Design, *International Workshop on Computational Morphogenesis*, October 10-12, 2006, Nagoya, Japan.

[14] ***Togan, V., Daloglu A.***, Optimization of 3d trusses with adaptive approach in genetic algorithms, *Engineering Structures*, Vol. 28, No. 7, 2006, pp. 1019-1027.

[15] ***Yang, X.Y., Xie, Y.M., Steven, G.P.***, Evolutionary methods for topology optimisation of continuous structures with design dependent loads, *Computers and Structures*, Vol. 83, No. 12-13, 2005, pp. 956-963.