Dynamical Structural Modeling

A Collaborative Design Exploration

Jane Burry, Peter Felicetti, Jiwu Tang, Mark Burry, Mike Xie
RMIT University, Australia
The web-address: http://www.sial.rmit.edu.au - http://www.rmit.edu.au

This paper will report on a generative performative modeling approach that engages architects and structural engineers in close dialog. We focus on knowledge shared between architects and engineers to apply the Finite Element Analysis based structural design technique Evolutionary Structural Optimization [ESO] as a way to understand or corroborate the performance factors that are significant in determining architectural form. ESO is very close conceptually to the dynamical system of matter and forces of growth itself. It has parallels both mathematical and metaphorical with natural evolution and morphogenesis so it has been poignant to apply the approach to a formal architectural case study in which the generative influence of these processes is inherent.

Keywords: *Evolutionary Structural Optimization; Finite Element Analysis; architect engineer collaboration; performance-based design; form finding.*

Background

This research is the result of a formal initiative to set up research groups in key areas collaborating across disciplines and portfolios in the University. It unites two groups working respectively in Spatial Information Architecture and Innovative Structures. The overall context is an investigation of the opportunities for closer collaborative design activity using shared tools.

One of the long term research objectives of this University-based architecture/design/structural engineering research team is to investigate the generative opportunities for the technique known as Evolutionary Structural Optimization [ESO] in architectural design cycles or iterations from conceptual design onwards. An interim step in understanding how this could be done has been to apply the technique to architectural designs that already have a degree of formal determination arrived at with or without regard to structural optimization. The choice of case studies has been predicated on the detailed level of knowledge of the examples that members of the team have already gained through scholarship and project-based design research for construction.

These project-based case studies are pure research using design data available in the public domain. However, they are undertaken in parallel to

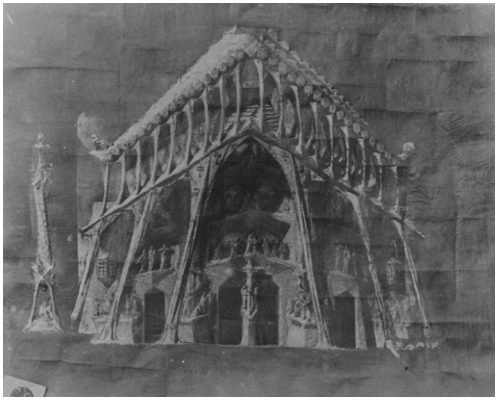


Figure 1
Part of the original surviving photograph of the Gaudí's drawing for the Passion Façade of the Sagrada Família church.

work-in-progress on applied design research projects. One of the case studies investigated to date is the Passion Façade for Antoni Gaudí's Sagrada Família church. Using a simplified abstraction of the structure derived from the photograph of Gaudí's original drawing, a series of optimizations were run, progressively revising the inputs and parameters to achieve an output more closely resembling the form of Gaudí's design, in a sense, reverse engineering the structural conditions for this FEA technique to generate one particular optimized solution. The choice of Gaudí's work clearly has a poetic and scientific significance beyond the existence of scholarship within the group. His understanding of „structural optimization" in natural form, development of innovative optimized structures using analogue modeling techniques and the reference to growth and morphogenesis within his work makes this an experimental site of particular significance.

Funicular structures

Gaudí's use of funicular structural systems to develop his architectural designs is well known. To describe the concept of funicular structural systems, it is worth quoting one paragraph from Shodek (1992):

„A cable subjected to external loads will obviously deform in a way dependent on the magnitude and location of the external forces. The form acquired is often called the funicular shape of the cable (the term funicular is derived from the Latin word for „rope"). Only tension forces will be developed in the cable. Inverting the structural form obtained will yield a new structure that is exactly analogous to the cable structure except that compression rather than tension forces are developed. Theoretically, the shape found could be constructed of simply stacked elements that are non rigidly connected (a „compression chain") and the resultant structure would be stable."

Evolutionary Structural Optimization

Generally engineers rely on a trial and error process for establishing a structure once a design has been created by an architect, or an architect establishes a design without a resolved structural concept. Gaudí considered the structural system as an integral part of the architectural design but the structural design process is generally a reactive process of calculations based on a predetermined conceptual geometry. Even contemporary digital Finite Element Analysis is a static process, where the designer determines the deflections, stresses and forces on a structure and then uses this information to determine the appropriate member sizes (i.e. beams, columns, slabs etc.) based on the original building geometry. Generally the areas/members that are most highly stressed are used to determine the buildings elements sizes, and therefore there can be significant over design and redundancy in the building. It is not necessarily the most efficient design and use of resources. This can be described as a passive approach to the results of the structure.

Within the last decade a dynamic approach to the use of the Finite Element Analysis has been developed through the use of structural optimisation. This technique seeks the most efficient use of material by altering the shape and topology and geometry of the building and its various elements. Therefore there is a direct and rational connection between form and material. The method of Evolutionary Structural Optimization (ESO), developed approximately 100 years after Gaudí's first experiments with hanging models, is a contemporary digital procedure that can produce novel forms of funicular structures. Mike Xie, Peter Felicetti and Jiwu Tang modified the original ESO method pioneered by Xie and Steven in the early1990s (see for example Xie and Steven 1997). The original ESO method consisted of removing redundant material at each iteration using von Mises stress criterion. Instead of von Mises criteria structures in the modified method can be evolved such that all remaining elements are in compression (as examples shown in this paper), or optimizing such that all remaining elements are in tension.

In this automated procedure each iteration consists of a finite element analysis (to determine stresses) and then removing inefficient/inappropriate elements. For example, in order to design compression only structures, elements with the highest level of tensile stresses will be removed at the end of each finite element analysis. The cycle (iteration) of finite element analysis and element removal is repeated many times until a desired geometry is produced. Typically, the number of iterations ranges from 10 to 100.

Case study

The ESO method creates the geometries based on a first principle mechanistic design process, rather than seeking to input the actual geometry of Gaudí's buildings into a finite element model and analyzing forces/stresses etc. The case study focused on the inclination and general form of, firstly, the (as yet unbuilt) columns in the inclined colonnade in the upper section of the Passion Façade and subsequent further study will extend this to the (built) lower columns supporting the porch with the crucifixion scene and colonnade above. The loads applied are gravity only.

Description of process

The following is a series of trials undertaken to reverse engineer the final structural form of the Passion Facade represented by the photograph in Figure 1. Careful consideration needs to be given to the mathematical model (Finite Element Initial model) to ensure that appropriate boundary conditions, restraints, loads and design/non design regions are accurately modelled. The series of examples below are results of various trials in adjusting these conditions.

The critical conditions that were found to influence the analysis/optimization process were;

1. Non design region. The strategy in the initial model was to create a non design region along the centre line of the six main supporting columns, and also at the centre line of each of the upper level columns to the colonnade (Figure.2). It was envisioned that this would be necessary so that particular columns would not be removed by the ESO process. However it was found that creating non design regions for the columns was restrictive to the outcome. The non design regions attracted load away from directions of natural force flows and load paths, and therefore resulted in these areas being lightly stressed and removed in the ESO process. Later models turned off the non design region in the columns, giving these regions the opportunity to evolve also, thereby not hindering the natural path of evolution.
2. The base support condition. Initially base fixity was applied to each node of the finite elements at the base over the complete 4m x 4m initial design domain. Later models reduced the support zone to 1m x 1m.
3. Slots in the upper level colonnade.
4. Stiffness of the large gable lintel over the upper level colonnade (the large non design region), and the thin gable lintel to the underside of the upper level colonnade (the thin non design region.)

In Figure 2 note that the dark regions indicate areas that are „non design“ regions, i.e. areas that although subject to stress analysis are not modified by the Evolutionary Structural Optimization process. The grey regions indicate „design“ regions, i.e. areas that can be modified by the Evolutionary Structural Optimization process. Base support fixity is indicated by the series of triangles at the base of each column. The facade is subjected to vertical gravity loads only. It is supported by a wall, the supporting points being represented by the triangular elements to the right of the Section A-A. As this was not the aspect of interest, it was not necessary to include the supporting wall in the structural finite element model.

A: Design Analysis Model 1; non design core to each column

This initial model included a core region to each of the columns that was a non design domain, that is, the cores could not be removed by the structural optimization process.

Note that in Figure.4 the non design core regions to columns are clearly in the view after 20 iterations. Note also how the non design column cores at the lower level are supporting the thin non design gable lintel and thus creating a redundant arch between the centre two columns, which is becoming thinner with progressive iterations. The upper level non design column cores are not co-linear with the direction of evolution of the upper level colonnade. The

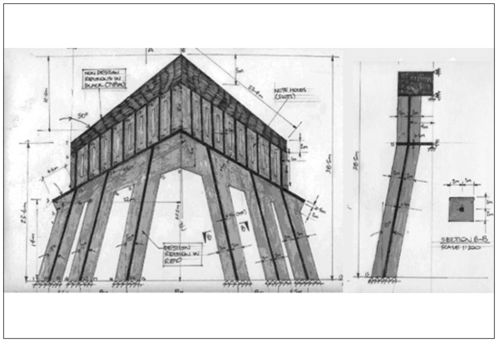


Figure 2
Front elevation and Section A-A sketches of idealized Passion Facade.

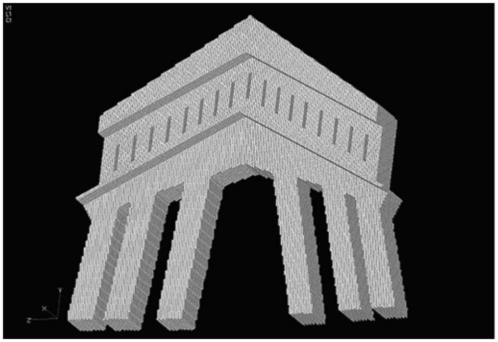


Figure 3
The initial Finite Element model based on the sketch drawings above.

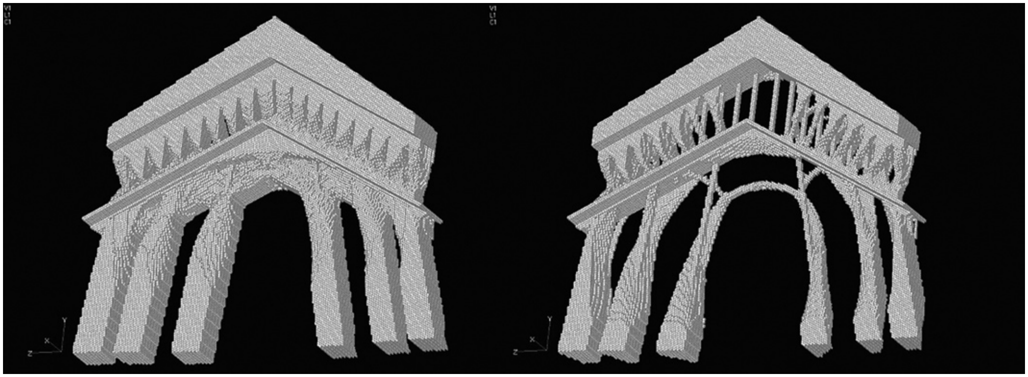


Figure 4
Evolution after 10 iterations and after 20 iterations.

series of colonnade arches directly under the ridge of the upper gable lintel have disappeared, redundant due to being lightly stressed.

As it was revealed that the non design core regions of the columns were influencing the direction of evolution, it was decided that this constraint was unnecessary and that the structure should be given more freedom.

B: Design Model 2: non design core to columns turned off

The non design cores of the columns were turned off in this model. That is, they were free to evolve with the rest of the structure. However the thick gable and the lower thin gable under the colonnade were retained as non design elements.

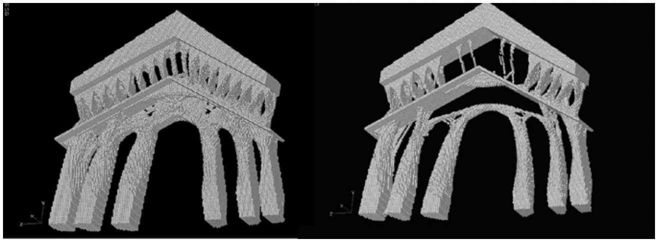
In Figure.5, whilst the non design column cores are no longer influencing the structural evolution, the rigid upper thick and lower thin gables are resulting in the loads being transferred to the outer columns resulting in a redundant arch. Again the non design domains were having a significant effect on the direction of evolution. Also with respect to modeling the real masonry structure, treating the gables as a continuous rigid elements is not correct. The masonry elements are, in reality, a series of interconnected blocks that can move with a degree of independence.

C: Design Model 3: non design core to columns turned off and gable soft material

In the next model the material properties to the two gable elements were changed. The gables were now made a soft material which, in being more flexible than the surrounding material, would thus not attract the load, and would have a minimum influence on the direction of evolution. They were still retained as non design elements so as not to be removed due to being lightly stressed and therefore redundant. As can be seen from Figure 6 above, the results produced by the criteria adopted in this third model produced a result with respect to the modelling of the colonnade and the 6 lower columns that was much more akin to the original image. A structurally efficient solution would have the columns to the upper colonnade sloping progressively inwards to the centre of the facade.

Conclusions

At the outset, the focus in this case study was on abstracting the geometrical model from photographs and giving as much skeletal geometric information as possible as a starting point for the optimization. Through the stages of the process this „starting point“ information was progressively reduced, rather than increased, and, as the constraints were removed, the formal outcome of the optimization progressed closer to Gaudí's formal representation of the façade. This demonstrated that, not only is it vital to understand and appropriately model the constraint system and material properties (rather than try to impose a general geometrical solution), but to gain true value from ESO as a contributing generative architectural design tool, it is critical not to over-constrain the starting model. This makes



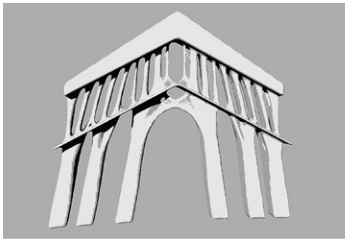


Figure 5
Evolution after 10 iterations and after 20 iterations.

Figure 6
The final facade model after implementation of soft material criteria to the upper and lower gables.

perfect intuitive sense in considering the behaviour of analogous funicular models such as Gaudí's hanging model for the Colonia Güell church but presents a challenge in digital optimization practice where all constraints are explicitly expressed rather than implicit in the construction of the model.

This particular exercise will be a useful milestone for „calibrating“ ESO applications in future projects. It also suggests that constructing simplified physical analogue models in which the material properties can be changed could be a useful parallel line of enquiry in building tacit knowledge of defining appropriate constraint systems.

Gaudí's work applied structural optimization, through form finding funicular modeling of gravity loading. The opportunity that ESO offers through finite element analysis is complex architectural form finding under not only vertical gravity loading but applied lateral loading also. We could ask the question: „what form would the optimized model assume with applied wind or earthquake loading?“

This series of exercises has built an understanding shared across two disciplines of the opportunities and future research directions. Clearly we need to build on our understanding of how flexible early design intention models might be represented to give appropriate reign to the optimization process.

References

Book:

D'Arcy Wentworth Thompson, On Growth and Form, Dover Edition 1992, first published Cambridge University Press, 1942

Mark, R. Light, Wind and Structure. The Mystery of the Master Builders, The MIT Press, 1994.

Martinell, C. Gaudí, Su Vida, Su Teoria, Su Obra, Col.legi Oficial d'Arquitectes de Catalunya I Balears, 1967. English translation, 1975, Editorial Blume, Barcelona

Mattheck, C. Design in Nature: Learning from Trees. Springer-Verlag, Berlin, 1997

Schodek, D. Structures, 2nd edition, Prentice Hall, New York, 1992.

Xie,Y.M. & Steven, G.P. Evolutionary Structural Optimization, Springer-Verlag, Berlin, 1997

Chapter or other contribution to a book:

Burry, M., C., Gaudí, Teratology and Kinship, Architectural Design issue on 'Hypersurfaces', Academy Editions, London April 1998

Paper in a Journal:

Bendsoe, M.P. & Kikuchi, N., Generating optimal topologies in structural design using a homogenization method, Comput. Methods Appl. Mech. Engrg. 71, 1988, p.197-224

Fuchs, M. N.,& Moses, E. Optimal structural topologies with transmissible loads. Struct. Multidisc.Optim.,19, 2000, p.263-273.

Rozvany, G.I.N. & Querin, O. M. Combining 'ESO' with rigorous optimality criteria. Proc. Of OptiCON 2000 Conf.,Newport Beach, California, Oct. 26-27, 2000.