Abstract. Structure computation can be carried out in the very early steps of architectural design thanks to the generalization of the use of computers. So, architects can be interested by specific computing tools dedicated to mechanical simulations in design process, especially using interactivity. Researches on these kinds of tools are developed by the ARIAM-LAREA team in the Ecole Nationale Supérieure d’Architecture de Paris La Villette, using graphic statics with a dynamic geometry software, finite element method and tensile structure software. The specificities of such tools are presented through historical examples and students projects.

Keywords: Design; simulation; dynamic geometry; graphic statics; Finite Element Method.

Introduction

With the development of the performances of personal computers, structure computation is no longer reserved to specialists and engineers but is available to every user of computers. These tools allow low cost experimentations that can occur in the early steps of architectural design.

These tools are not often used by architects but, the benefits offered by these evaluations in terms of efficiency, economy and sustainability are not negligible. When engineers use tools for advanced projects, architects need tools adapted to changing structures with increasing level of details. At the beginning of architectural design only a few decisions or options are taken, and structure computation should be adapted to this low level of definition.

That’s why it seems important to have a thought on specific tools of structural evaluation for architects.

What kind of tools using when designing?

Considering these specificities, we developed in our School of Architecture several pedagogical experiments on different kinds of computer tools in early steps of architectural design. Our goal is to experiment existing software and to develop specific tools according characteristics that appear important in a design process.

These expected characteristics are:

- Synthetic: a synthetic tool has to focus on a particular aspect of the behaviour by simplifying the structure. It permits to evaluate a solution according a particular criterion.
- Upgradeable: in a design process a tool has to
be able to adapt with the complexity of the project.

- Rapidity: in order to be interactive in a real-time process, the software has to be as fast as possible.
- Visual: interactivity is improved with a visualization of results.

Some examples of computing tools for structural design

Some tools are used in researches developed by the ARIAM-LAREA team (Ecole Nationale Supérieure d'Architecture de Paris La Villette) because of their particular adaptation to structural computation in a design process:

- Graphic statics in dynamic geometry. The dynamic geometry software used is ‘Cabri géomètre’ (http://www.cabri.com).
- Finite element method software dedicated to teaching : RDM 6 (IUT Le Mans http://iut.univ-lemans.fr/ydlogi/)
- Tensile structure software: Cadisi software (now called Formfinder available on http://www.technet-gmbh.com/) and specific developments.

Graphic statics in dynamic geometry used as a designing tool

Graphic statics in dynamic geometry

Dynamic geometry is a kind of software that allows drawing geometric figures according to constraints as parallelism, orthogonality, incidence, distance etc. These interactive constructions can be modified by moving points for instance. We use a dynamic geometry software (Cabri) in descriptive geometry and perspective lessons and classwork at the Ecole Nationale Supérieure d'Architecture de Paris La Villette (http://www.paris-lavillette.archi.fr/uel6tr) but also in optional teachings of mechanical simulations and evaluations with graphic statics method.

Graphic statics is a method of calculating structure by drawing. This method used to be the effective way to calculate structures before the invention of computers. Presently, it can advantageously be used by architects because it gives a visual interpretation of forces acting in a structure. Graphic statics used with dynamic geometry combines image, interactivity and real-time response. We exposed this approach (Ciblac et al., 2005), and carried out a collaboration in the case of historic masonry with the department of architecture of the Massachusetts Institute of Technology (Block et al., 2006; http://web.mit.edu/masonry/index.html).

Some applications of graphic statics in dynamic geometry especially used in a design process are presented through examples from Robert Maillart and the case of the equilibrium of a pole.

An historical example of mechanical simulation when designing: the Chiasso shed designed by Robert Maillart

A pedagogical application for architectural design is illustrated with an historical example of mechanical simulation during the design of a structure: the Chiasso shed designed by Robert Maillart (1872-1940) in Switzerland. This Swiss engineer contributed to the development of the use of reinforced concrete. He used it for the Chiasso shed built in 1924. He applied graphic statics to design his more remarkable realizations (Zuoz bridge, Salgina bridge) and the Chiasso shed (figure 1).

The particularly original shape of this truss is due to a precise choice of the structure behaviour where the vertical timbers are chosen to work in compression in order to transmit the weight loads of the roof, excepting the central timber working in tension as well as the lower timbers. A model of funicular can be done to describe this expected behaviour of the truss (Billington, 2003). By using graphic statics, a compatible shape is determined. Using dynamic geometry, it is possible to explore all the possible shapes and to determine the acting forces. Three geometrical configurations (figure 2) computed with a unique dynamic construction (available in ‘séance 4/ éléments de correction’ on http://www.paris-
lavillette.archi.fr/simulations-evaluations0708/) are given to illustrate the relations between shape and forces. Forces (loads, compression and tension forces in timbers) are represented by vectors. The three configurations show their evolution and the dimensions of the truss. We can notice that tensions in timber decrease when dimensions increase. In a design process, it illustrates the possibility to evaluate the dimensions and forces according to the geometry.

**Graphic statics in 3D: equilibrium of a pole with three stays**

Graphic statics can be used in 3D thanks to the use of descriptive geometry. The problem of the
equilibrium of four forces gives an example that can be illustrated by the determination of the position of three stays to ensure the equilibrium of a pole.

The dynamic application allows determining in 3D the forces in a pole and 3 stays for variable positions in order to check if a geometrical configuration is acceptable, in a tensile structure for instance.

The determination of the equilibrium of a force applied at the node of three stays (force in the direction of the stays) can be done graphically by the double projection in descriptive geometry (figure 3, left) of the forces polygon. The three forces in the stays are deducted considering that the addition of the forces of two couples of forces have the same

Figure 3
Two configurations of four forces equilibrium in 3D, represented in dynamic geometry in descriptive geometry.

Figure 4.
Primary shape of a bridge limited by the deck and an arch (up) and new shape defined by removing the low stress areas.
direction.

In the case of the design of a pole, the given force in the pole has to be in compression and the dynamic figure allows to check if the forces in the stays are in tension according to the choice of their place and to evaluate their intensity. Such an example is given in figure 3, on the right. This dynamic figure is used in our optional teaching on tensile structure. This example gives to the students an example of problem supposed to be unsolvable by them. But the use of two distinct knowledge, descriptive geometry and statics, gives an unexpected success to an apparently too complex problem.

Use of finite element method in design

Using software of mechanics by finite elements, it is possible to impose geometrical constraints and to change the structure according to the results in order to optimize a shape or to model it to satisfy a function.

An iterative process using elasticity computation could be used to remove material in the less stressed areas of a structure, according to a defined stress level. The following step consists in evaluating the new stress field and to define the areas to remove, and so on. This process optimizes the weight but cannot find a shape idea!

An illustration of this process is inspired by a bridge built by Maillart in Tavanasa (Switzerland). A former experience of Maillart on a bridge, showed some cracks near the abutments, between the deck and the arch. His solution consisted in removing this area to change the arching system to a three hinges...
system, more adapted to reinforced concrete. Let’s consider the primary shape of the bridge by a block limited by the deck and an arch (figure 4, up). The computation of stresses shows the less stressed areas near the abutments. After removing these areas, a new stress field is computed (figure 4, down).

Another possible use of finite elements methods software is experimented with students to evaluate a personal structure and to propose changes in a design process.

**Design of tensile structures**

Form and structure are deeply connected in tensile structures. Some software help architects to design tensile structures. It gives another example of an architectural form partially imposed by mechanics.

Tensile structures are appreciated for their lightness and elegance, but the necessity of a pure tensile behaviour requires a high level of precision in their design. The researches on minimal surfaces, experimented by Robert Le Ricolais with soap films and systematized by Frei Otto since 1970, offered a wide panel of tensile shapes.

The mean curvature is equal to zero for each point of a minimal surface, and is constant for a pneumatic surface. An application to the computation of a cable network for a pneumatic structure leads to solve the inverse problem of determining the shape of a uniformly stretched structure (all cables in pure tension). Some illustrations, given (figure 5) from computations (Maille et al., 1978), show the shapes of pneumatics leant against closed contours. For a contour based on two circles, the initial mesh (5a) changes in the case of a pneumatic loading (5b) and for vertical loading (5c).

For a square contour, the initial mesh (5d) is given symmetrical but with arbitrary breaks of lines on axes. The solution for a pneumatic loading changes the shape to form continuous lines (5e). For a far higher pressure, a huge deformation occurs (5f).

In our teachings on light structures, we use Cadisi software. It allows determining the shape of tensile structures according to contours (border lines) defined by fixed lines (anchorage, hoop) or boundary cables. A pole can be place on each area. Our students of second year of ‘licence’ (bachelor’s degree) in architecture have to design a tensile structure by this way and to evaluate the rigid structure with ‘finite element method software’ (RDM). An example of such a project is given (figure 6) with a rendering image.

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![Image of a tensile structure modeled with Cadisi and rendering image.](image)

**Figure 6**

Example of a student work: tensile structure modeled with Cadisi and rendering image.
Conclusion

These experimentations show some possibilities offered by structure calculations in design process as well if the behaviour of a structure is imposed to determine a compatible shape, or if a shape is mechanically analysed early in the design process. In both cases, structure software needs an accurate model to process whereas a designer could be interested in giving only indications of forms or structural solutions. The creation of a computable model from a sketch could be a goal for specific software for architects. The importance of interactivity and rapidity in a design process appears to be a more specific aspect than a perfect accuracy or the respect of codes for instance that have to be checked later.

Structure computation can easily be used by architects if they have a minimum background in sciences and techniques and if the tools they use are adapted to their needs. The development of such tools could be extended to other technical fields (acoustics, thermal, lighting) with the same kinds of problematic. The development and use of such tools could be stimulated by teaching and research in schools of architecture as well as with the involvement of innovative architects.

References
