Geometry and Parametric modeling in the Conceptual Design of Bridges

Jose Romo

FHECOR Consulting Engineers, Madrid, Spain

AnnaLisa Meyboom

School of Architecture & Landscape Architecture, University of British Columbia.

Annette Bögle

HafenCity University, Hamburg, Germany

Contact: jrm@fhecor.es

Abstract

Parametric techniques are developing as an agile tool in both civil engineering and architectural design. What is especially powerful is the ability of these softwares to relate and iterate through multiple options with minimal effort. The tools that combine a parametric definition of the bridge with a 3D graphic and a FEM model gives the designer the opportunity to analyse instantaneously, the effect in the variation of the variable parameters in terms of visual appearance as well as structural behaviour simultaneously. Therefore parametric design is a valuable tool in the conceptual design phase where the geometric decisions made are the most structurally and architecturally impactful.

Keywords: Parametric Design, Conceptual Design, Bridges, Optimization.

1 Introduction

Mathematics is a field where engineers feel comfortable. During their first University courses they receive an intensive training in mathematics, therefore when they start working as young designers they have a good capability to deal with complicated mathematical and geometrical problems. Architects on the other hand learn relatively little math, especially in North America and Britain, and are much more comfortable dealing with form.

Structural analysis from its origins was based on calculus and therefore a strong competence in mathematics was required for any engineer. Nevertheless those analytical methods became much less used when the use of computers became popular in structural engineering. The consequence of that situation was a substantial reduction of the use of mathematics in the daily work of the engineers . Moreover, the introduction at the same time of CAD system entailed a limited use of complex geometry in Architecture as well as in Structural Engineering.

But nowadays there is a substantial modification of that tendency because of the development of a new generation of computer graphics for generating and representing curves and surfaces. Complex geometry can be efficiently handled by computer programs with a friendly interface for human interaction.

Also, the visual programming languages used mainly to build generative algorithms to create 3D geometry allows the parameterization of any geometrical element.

Those facts made that kind of tools a must in any contemporary architectural design, because they are an essential instrument during the iterative process inherent to every project.

One step further in the developing of the parametric design is the recent connection of those 3D graphic programs with the software for structural analysis. That connection enhances enormously the power of those tools because shape and structural behaviour could be instantaneously handled.

The formal and perceptual aspects of the conceptual design of bridges, as well as its general structural behaviour are regulated by a few parameters. Therefore could be easily programed and checked thanks to those mathematical tools.

Surprisingly those kinds of tools are not used by structural engineers, who amazingly spent a large part of their time working with parameters and looking for solutions that optimize those variables or parameters.

It is only in the field of building structures where a few civil engineers use those tools and mainly to share geometry with architects and mechanical engineers, especially when the team work with a BIM platform. In exceptional cases the structural engineers use those tools to optimize the design of the structure.

In bridge design the parametrical design are mainly used by bridge architects to modify, adjust and visualize the structural shapes of the different components of the bridge. Engineering use of those tools including parametrical structural design is very seldom used, being even unknown for the civil engineering community.

In this paper, some examples of conceptual design of bridges carried out with parametric tools will be presented. The benefits, drawbacks and today's limitation of those tools during the conceptual phase are discussed.

2 Calculus versus design: the advantages of the parametric design

During the last decades of the XX Century the extensive use of computers for structural analysis has changed the structural engineering process itself. One of the drawbacks of the extensive use of computers is that the amount of time devoted to the calculations has increased at the expense of time devoted to design itself, The incremental increase in power of the analysis software has been accompanied, in parallel, by a simultaneous growth of the number of calculations imposed by the codes: the number and complexity of the different loads and design situations has increased enormously. What in the past was impossible is now a requirement, leading to the use of complex models and analysis, as well as a colossal number of calculations and time-consuming verifications. The initial advantage of having a non-limited computing power has thus been counter-balanced by the number of structural checks and analysis to be carried out during a project.

Nevertheless that time-consuming process is now mostly standardized and regulated, and is therefore available to all practitioners with a solid structural background. For that reason the structural analysis phase, despite its industriousness, constitutes a zone of comfort for structural engineers, in which they now operate easily.

The analysis phase starts with the generation of a mathematical model that includes the geometry and the mechanical characteristics of the structure. The modelling comprises also, the definition of the loads and the load combinations defined by the standards.

After the complexion of the model the computer structural analysis is carried out followed by the checks and verifications defined in the relevant codes.

When the results of those verifications are negative, it could be necessary to modify the model entering in a painful circle, especially when the structure is complex. It is also frequent to enter in that sort of loop when refining or optimizing a solution.

The rigidity inherent to that traditional design process could be overcome thanks to the versatility of the parametric design.

Parametric design tools give the designer the opportunity to see instantaneously the structural implications of any change in geometry.

Parametric design software allows, in standard structures, a quick, simply and effective way of refining and checking a solution.

In the case of complex structures, parametric software helps the designer to have a good understanding of the influence of a change in geometry on the structural behaviour of the bridge.

Those facts could entail a reduction in the following phases of analysis because the final verification will be carried out on a more accurate design.

That reduction of the traditional iterative process allows devoting more time for the crucial conceptual design phase.

3 Tools for parametric design

Conceptually parametric design is not new [2]. Nevertheless till lately there were no specific computers programs applied to parametric structural engineering.

As abovementioned the impulse of those tools was given by architectural practice, being the structural part a recently new achievement.

The software, necessary for the parametric design of structures combine the following parts:

– (1) Software for the generation of the geometrical model and structural analysis, for example Rhino[i]. [1]
– (2) Parametric Plug In: a 3D computer programming tool connected with (1): normally program (2) is a "plug-in" of the program (1), for example Grasshopper
– (3) Computer software for structural analysis that is served from the parameters defined in (1): Program (3) can be embedded in (1) or a standalone program. For example Karamba (embedded in Rhino) or ROBOT (stand alone).
– (4) Algorithm for optimization of variables parameters defined in (1), based on the results of the structural analysis software (3), for example 'Millipede' (a plugin for Grasshopper)

Figure 1, summarizes the parametric design software scheme which gives the designer a prompt output of the structural response of the bridge, when changes any of the predefined geometrical variables.

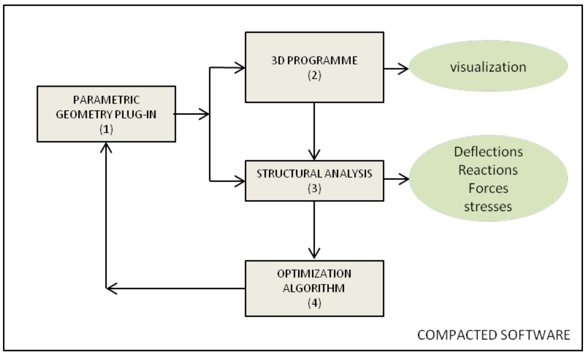

Figure 1 Software scheme for parametric design

The examples included in this paper used as basic engine program Rhinoceros© which is a commercial 3D computer graphics and computer-aided design (CAD) application software. Rhinoceros© geometry is based on NURBS mathematical model, which focuses on producing mathematically precise representation of curves and freeform surfaces in computer graphics (as opposed to polygon mesh-based applications). Grasshopper© has been used as a graphical algorithm editor integrated with Rhino's 3-D modelling tools. Grasshopper© is primarily used to build generative algorithms for creating 3D geometry.

Karamba© is a Finite Element program fully embedded in the parametric environment of Grasshopper©. This makes it easy to combine parameterized geometric models, finite element calculations and optimization algorithms like Galapagos.

4 Parametric design applied to bridges: methodology

One of the aspects that most differentiate the parametric design of the conventional design approach is the possibility of combining the first decisions, relating to the geometry of the bridge, with its structural behaviour in a simultaneous and interactive way. Parametric design is therefore a process completely different from the traditional method of design, where decisions are made in sequential and isolated steps. The following sub - sections describes the traditional process, as well as the methodology associated to parametric design.

4.1 Traditional Design Process

Conceptual design phase is the first step in the traditional design process. During that phase the geometry and the general layout of the structure are setting out; those tasks include the preliminary dimensioning of the structural elements of the bridge, as well as an initial assessment of the integration of the bridge into the site.

That preliminary geometrical dimensioning is based on the experience of the designer as well as some basic rules of thumb and simplified calculations.

The success of the process relies then, in a good predesign, which could minimize or even avoid the number of problems encountered during the subsequent detailed design.

The predesign in this process is the most critical phase of the project, in which fundamental decisions are made. Unfortunately time dedicated to that task is only a small fraction of the total time of the project, since as noted earlier the calculation process and check is increasingly complex in the current design environment, as mentioned above.

In the conventional design process, once the geometry and mechanical properties of the structural elements have been designed, the more detailed structural analysis and design checks begin.

From that moment the geometry of the structure is "frozen". The process continues with the definition and detailed check of the different elements including thickness of plates and stiffeners in the case of steel bridges and the active and passive reinforcement in case of concrete bridges (See Figure 2)

The process is linear and if the designed is required to backtrack on any aspect, a cost overrun is incurred. This is, of course, avoided as much as possible and is only carried out when a significant deviation with respect to the provisions of the pre–design happens. Therefore the initial pre-design should be as precise as possible to avoid changes in more advanced phases of the project.

However, as every designer will recognize, this is not always possible, because the basic information for the project (topography, Geotechnics, utilities, etc.) is usually refined as more information is available through the course of the project. Also, in the case of todays increasingly complex structures, the probability of inaccurate pre-dimensioning are high, especially if there were time constraints at the front end of the project.

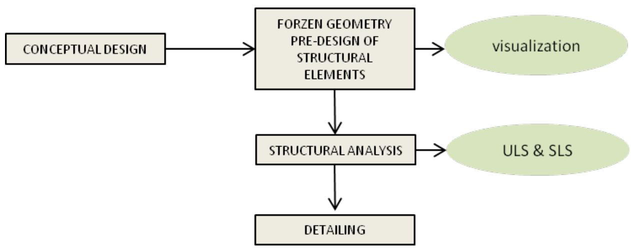

Figure 2. Traditional design flow

4.2 Parametric Design Process

Parametric design methodology is completely different from the traditional design process. In the case of parametric design, the first step is to determine by a process of abstraction [2] the parameters which define the geometry and the mechanical characteristic of the different components of the bridge.

For this paper we are reflecting on a process which was used for the bridge examples referred to later in the paper. There are, of course, other methods of designing and other parametric work flows which could be used. Parametric design is a tool and can be used in many ways. For example architects have other approaches to parametric design. The process we illustrate, however, gives readers a good idea of the advantages of the parametric integrated method under discussion.

In this process, the designer has to define three categories:

– Fixed parameters (FP): these are those parameters that are going to be considered as fixed values.
– Variable parameters (VP): these are those parameters that are going to be considered as variables inside a certain range.
– Conditioned parameters (CP): this third group includes the parameters that are mathematically related to the variable parameters. The conditioned parameters have also an established range of variation.

It is obvious that each structural type has different parameters. It is the initial task of the designer to classify those parameters in the three groups above indicated.

Within this step, it is also necessary to establish the specific values of the fixed parameters, ranges of variation of the variable parameters and relationship among conditioned parameters and variable parameters.

For instance in a standard viaduct (Figure 3) one possible selection of parameters was selected as follows:

- Fixed parameters (FP):
    – Deck width: defined by functional requirements.
    – Total length of the viaduct: fixed (see figure 3).
    – Geometry of the piers: as the valley is rather flat, all the piers have the same cross sections and it was considered to be independent of the span length, since that variable has a limited range.
- Variable parameters (VP):
    – Span length of the typical span: in this case this was the main variable defined in the project and therefore was the parameter considered variable. In this particular case a maximum and minimum span length (70 to 50 m) was also established.
- Conditioned parameters (CP):
    – Deck's depth: in this case a fixed relationship between and deck´s depth and span length was established: 1/22
    – Lateral span length: the dimension of the lateral spans depends on the number and value of the typical span length as well as the total length of the structure. The range of values for the lateral span/ typical span length was established in 0.55 to 0.85.

As previously mentioned, the designer has to select which parameters are going to be fixed, variable and conditioned. The output of the process will be highly dependent on that selection; hence the experience of the designer has a predominant role in the quality of the result.

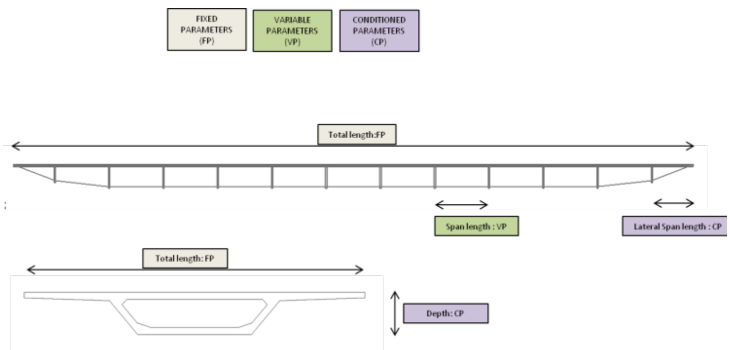

Figure 3. Parameter's categories

The construction of the geometric and mechanical analytical model required the definition of the mathematical equations that characterized the geometry of the structure, in which the various parameters defined are configured as inputs of the system. This characterization of the mathematical relationships that defines the system is not based on geometric constructions made previously with CAD, but on analytical equations specified by the designer. The specification of the relationship between the parts of the structure is the essence of the parametric design model. Good analytical thinking, along with an understanding of mathematics is essential to the proper set up of the parametric model.

Besides analytical and numerical skills, it is crucial to have good understanding and experience in structural engineering in order to establish and limit the number and range of the variables to be considered. That expertise and knowledge is also vital when defining the relationships among conditioned and variable parameters.

To complete the process, the designer could even define the design targets. These targets could help the designer in the decision making process, especially when the structural solution is broadly defined and the designer wants to make an optimization or adjustment of the solution.

As it is an automatic tool the design objectives have to be analytically established, and normally are part of the output of the structural analysis. For example, a possible design target could be the maximum deflection of the structure. The process will start by automatically studying which combination of the variable parameters achieves the minimum deflection of the structure.

Obviously it is difficult to select only one factor as target. But in some cases a precise selection of an objective will help the designer to get rid of the less adequate solutions.

Again, here the possibilities are very broad, and the designer will be with your experience which determines which target variables seek to control.

In general it will be necessary to define more than one quantifiable target. In any case the result of the optimization process should be confronted against the general requirements and the context.

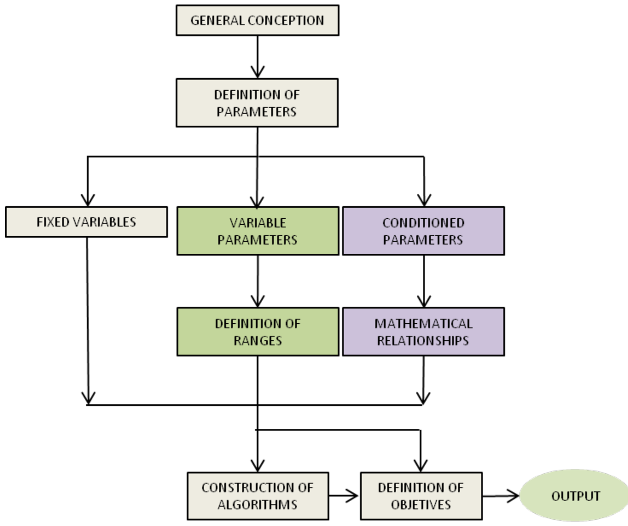

Figure 4. Parametric Design flow

Obviously, as the result of the parametric analysis depends on the classification of the parameters and its relationship as well as on the selection of the design targets, it is crucial a good understanding to achieve a sound solution.

5 Selection of parameters: worked example

Parametric design software is especially useful when a non-classic solution is studied.

An example of that kind of application is the study of a symmetric multi-span cable-stayed bridge [3] illustrated in the figure 5.

In that case the total length of the bridge was fixed, as well as the conceptual idea of the bridge: a four span cable stayed bridge.

Here the main goal was to select the more adequate span dispositions to minimize the problems inherent to the lack of back stays in the central pylon.

To carry out the study the selected parameters were:

- Fixed parameters (FP):
  - Total length of the bridge
  - Deck cross section: as the span lengths were inside a limited range, it was assumed that the cross section of the deck will not depends on the final span arrangement.

- Cross section of towers: as in the deck it was not expected significance changes of the towers geometry when the span length changes into a limited range.
- Distance between cables anchorage at deck.
- Distance between cable anchorages at pylons.
- Minimum angle of the axis of the stays with the horizontal (see figure 5).

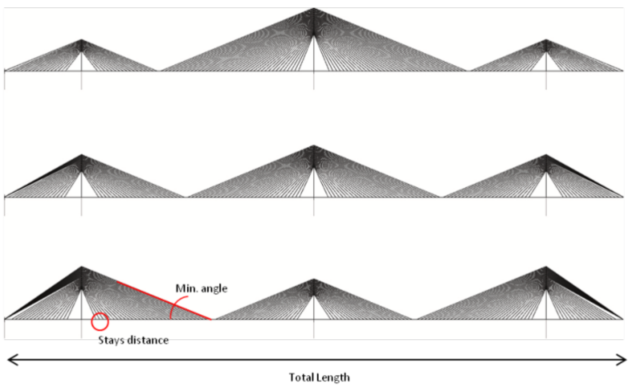

Figure 5. Fixed parameters for a 4 span's cable stayed bridge

- Variable parameter (VP):
    - Length of the main spans: that was the only parameter considered as variable, because the behaviour of the bridge is mainly affected by the dimension on the main span. As it is usual a limited range of that variable was established (figure 6)

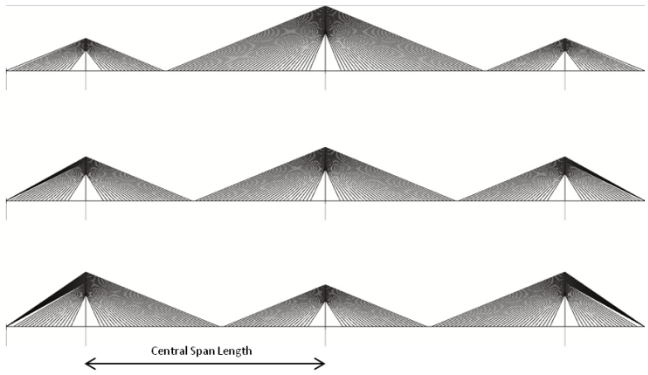

Figure 6. Variable parameters for a 4 span's C.S.B.

The rest of parameters were defined as conditioned and could be calculated depending of the values of the fixed and variable parameters.

- Conditioned Parameters (CP):
    - The lateral span length
    - Height of the towers
    - Minimum and maximum deck length without being support by cables in the proximity of its support in the towers (L_1, L_2, L_3, L_4): Figure 7

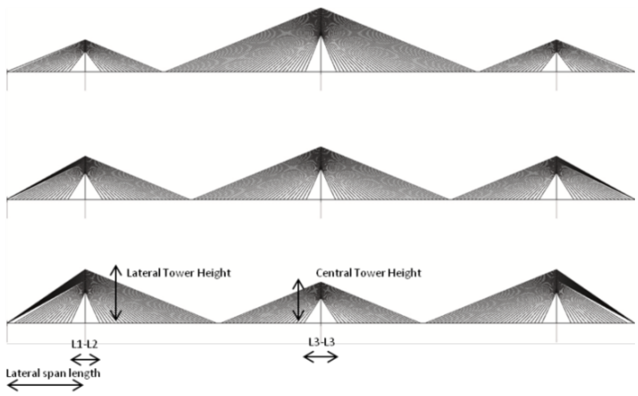

Figure 7. Conditioned parameters for a 4 span's C.S.B.

Among the big number of possible objectives, two main targets were studied: first the maximum displacement due to non-symmetrical live load, and secondly the bending moment in the central tower foundation due to the same load case.

Both variables were considered critical, as the efficiency of that type of bridge is highly conditioned by its behaviour against asymmetrical loads [3]

6 Visual design quality

One key benefit of using parametric software is the possibility of visualizing the bridge design in real time. This allows the designer to observe a wide variety of options in a very short period of time.

Parametric design also allows the definition and simple change of relations between variables parameters and conditioned parameters to observe their impact on the appearance of the bridge. This type of design can be shown in the following examples.

The Kinsol Trestle (in British Columbia) bridge was a new bridge structure carefully placed over a historic railway trestle bridge to take the loads from the deteriorating historic structure. Several design options and arrangements were considered. What is shown here was the cable supported truss structure option (See Figure 8 and 9).

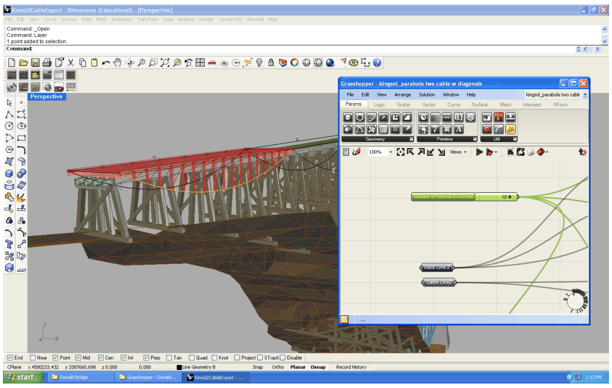

Figure 8. Parametric model for the structure for Kinsol Trestle showing close spacing of verticals in truss

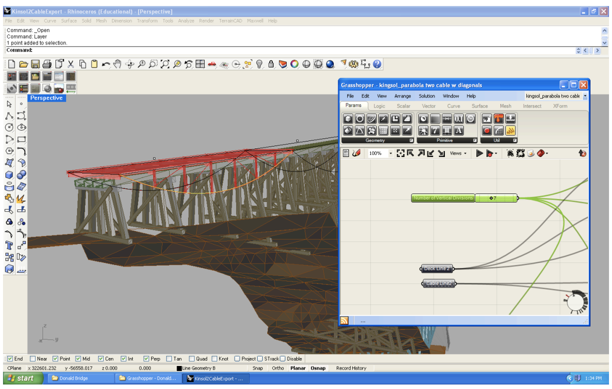

Figure 9. Parametric model for the structure for Kinsol Trestle showing larger spacing of verticals in truss

The project was scripted in Rhino with the Grasshopper plug-in, primarily because it was accessible and easy to use. Each span of the bridge is generated with a line - that of the side of the deck (Image 3). From there, the parabolic shape of the cables, verticals, diagonals, floor beams and decking is generated. The shape of the structure is parabolic, with a slider which directs spacing of the bents. Depth of the parabola is determined as a function of span, maintaining relatively consistent stresses and sizes of elements. Sliders were used to set vertical spacing, allowing easy visualization of different configurations of the spacing (Image 4) and how it interacted with the existing structure, a key architectural consideration of the project. Other sliders were used to vary such things as cable sizes, vertical sizes, deck thickness and top chord size.

A key advantage to scripting the design was the ability to generate each span independently and quickly, even dealing without effort with the complicated geometry of the existing structure, which is on a curve and superelevated (tilted to provide centrifugal force helping keep the train on the track in the curve). The span arrangement proposed for the new bridge was such that only a few of the existing bents be rehabilitated, the others were not required to be structurally sound, allowing their existing condition to be maintained and not retrofitted, both a cost and historical conservation advantage.

The ability to script the mathematical shape of the catenary form of the structure modified the design process, which otherwise would have been a different geometry, likely not a catenary structure and whose modelling would have been cumbersome, inaccurate and difficult to modify. Even the simple ability to modify the subdivision of the structure gives a change in design process, enabling quick visualization of multiple options.

The second project follows a similar methodology - it was a cable stay bridge proposal for the Donald

Bridge in northern British Columbia. Consideration of the tower made an interesting question for what kind of a shape the structural forces themselves might generate if they were questioned. As well as axial loads, the tower is also required to resist lateral loads, applied at the cable attachment to the tower, which result from unsymmetrical loading of the structure.

In this case the backstay cables were required to splay over the road to avoid interference with traffic. The main cables fan slightly as the bridge is on a circular curve. Again the ability to generate the structure based on two lines enables an easy modification and visualization of cable angles and number of cables (Figure 10 and 11). This scripting of a mathematical derivation provides a methodology which both expresses structural forces and results in a form which is well structurally suited to its purpose.

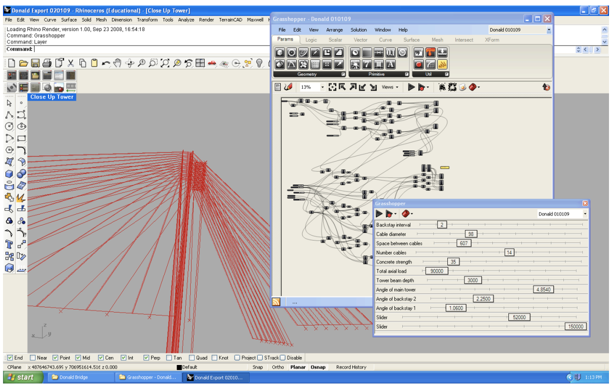

Figure 10. Parametric model for the Donald Bridge tower showing a very close spacing of cables

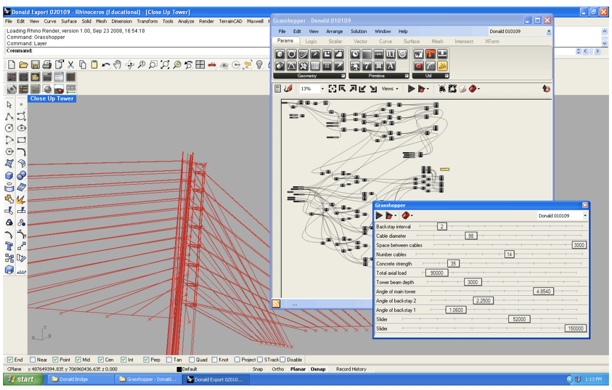

Figure 11. Parametric model for the Donald Bridge tower showing a larger spacing of cables

Tower plane thicknesses are automatically generated by an equation which requires an axial load for the tower to be entered and a material strength of concrete: from these variables, the thickness of the tower plane is adjusted. Other structural criteria could have been programmed, such as diameter of the cables as resulting from a simple force equation from the unit length of deck area, however these are smaller details not required for a preliminary stage proposal. Material use is minimized in this design by the placement of material only where it is required by the force flow. The separation of the three planes of the tower as it reaches the top is pulled together only by struts to provide tension ties only where it is required. Scripting enables easy adjustment of the spacing and frequency of the backstays and struts relative to main cables and easy adjustment of the cable anchorage locations and roadway alignment. Since this bridge was generated for a design/build proposal, it was required to be easy to construct and materially efficient and the ability to program the material to be where it was required gave a highly efficient and visually expressive tower structure.

Using this parametric process, visual assessment and decision-making is much easier. It is also possible to easily incorporate not only fundamental structural elements but also the accessory elements such as handrails, safety barriers, lighting, etc. which have an important impact on the appearance of the bridge. The immediate incorporation of context, allows thus to have a very clear idea of how the different elements influence the final aspect of the structure.

Parametric design, therefore, could solve quickly one of the most complex aspects of the process of selection of alternatives: the visual assessment of the various proposals and their interaction with the environment.

7 Parametric design and innovation

The use of parametric design in the conceptual design phase can be a double-edged tool. On the one hand its use allows devoting more time to the initial design phase, since to be held together the geometric definition and the first structural analysis, and subsequent iterations in the final stages of testing and dimensioning are reduced. On the other hand parametric design could be used as a tool for optimization of the well-known orthodox solutions.

The design of unorthodox or even hybrid solutions, require a time of conception and preliminary analysis that often are not available during design competition or tenders. Such solutions often are aborted because there is little time for develop a sound structural proposal in a short period of time. In those kind of situation parametric design could help the designer to quickly assess their ideas both from the geometric and structural perspectives. Therefore parametric design could be an essential tool in a high pressure environment that demands innovation but where there is no time for an in-depth analysis. Parametric design tools could bring a good understanding of the structural behaviour of complex structures (figure 12)

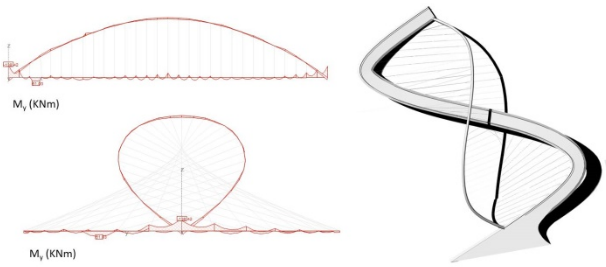

Figure 12. Salford footbridge. J. Romo (FHECOR)

8 Parametric design limitations, present and future

Parametric design is nowadays a very useful tool for the conceptual design of structures in general, and for bridges in particular.

During the earliest phase of the project the designer can have an instantaneous output in terms of the visualization of a parameterized concept, as well as, valuable essential information about the expected structural behaviour for each combination of the main selected parameters.

The possibility of setting out specific targets increases the utility of those tools especially when optimization of a solution is desired.

Nevertheless the available computer parametric compacted software performs only linear analysis and the sectional verification are only in terms of stresses. Currently the plasticity of the material cannot be taken into account .therefore the cross section checks in ULS have to be carried out using a simplified method. Also, in the case of important dynamic loads, for instance in highly seismic areas ,the analysis has to be carried out in a very simplified manner.

To address these constraints, one possible alternative it is to export-import the data generated by the 3D program to a standard FEM program iteratively This loses the benefit of the instantaneous interaction achieved with the integrated parametric software. Likely, in future, the FEM programs will develop to include features which will facilitate these more complex analyses.

9 Conclusions

Parametric techniques are not new in civil engineering design but the new integrated software that combines a parametric definition of the bridge with a 3D graphic and a FEM modeller gives the designer the opportunity to instantaneously analyse and visually assess the appearance and structural behaviour of the design options. Therefore the geometry of the bridge can be easily altered and the design iterations can be conducted in a friendly environment, without the rigidity inherent to the traditional design techniques where a change of the geometry of the structure entails unexpected extra work.

Parametric design techniques can be highly effective in the conceptual phase of the project, where decisions are crucial, giving to the designer more freedom and a solid understanding of the structural and aesthetic behaviour of the design variations.

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