Data visualization for gaining insight in the structural behaviour of bow-string bridges under various load cases

Lennert LOOS*, Daniel AL SAYEGHb, Kenny VERBEECKb, Lars DE LAETc

*PhD researcher at Vrije Universiteit Brussel
Department of Architectural Engineering
Pleinlaan 2, 1050 Brussels
lennert.loos@vub.ac.be

b Master student at Vrije Universiteit Brussel

b Bollinger -Grohmann Brussels

c Professor at Vrije Universiteit Brussel

Abstract
During the first steps of the design process, architects, engineers and structural designers will come up with concepts, architectural ideas, structural considerations etc. This part of the design process is called the conceptual design process. An exploration of the design space will take place and different design alternatives are compared to each other. Based on these comparisons, the designer will proceed in the design process by selecting the best performing solutions. Currently these comparisons are mainly based on aesthetics, architectural considerations, experience… When a designer on the other hand wants to make a comparison based on structural performance and behaviour, no appropriate tools exist.

Since the amount of data that has to be considered can become relatively large within a modern computational framework, it is a good practice to make use of tools that allow for an intuitive interpretation of these vast amounts of data. In this paper, data visualisation will be used as a method to quickly and intuitively draw conclusions about the structural behaviour and performance of various design alternatives. The designer can freely explore the design space and gains additionally insight in the structural behaviours and performances. The methodology will be illustrated with a case study on bridge geometries. In addition, the computational environment that the author is developing will be discussed.

Keywords: conceptual design, structural design, informed decision-making, data-based design, data visualisation.

1. Introduction
In the design process of buildings, structures or constructions in general, the conceptual design phase is often the most decisive step. Architectural ideas, concepts and schemes are translated into a preliminary design and the overall geometry is being decided. It might be clear that this first step is of mayor importance since the geometry will not change fundamentally later in the design process (Hsu & Liu [1], Turrin [9]). Comparing is crucial in the early design phases (Woodbury & Burrow [11]) and is done very often based on architectural, geometrical, aesthetical differences while exploring different design alternatives. However, for comparing the structural behaviour and performance of various alternatives, no appropriate framework and workflow exists.

To reduce structural mass, costs and complexity a structural designer may be looking for efficient structures with a well-performing structural geometry. After all, the impact of a sound structural
design/geometry is more decisive on the final result than assigning (optimised) cross-sections in a less efficient design (Yu [12]). In this paper, strain energy will be used to quantify efficiency and thus for comparing different design alternatives in a visual manner.

2. Design alternatives in a parametric design environment

2.1. Geometric parametric design

Today’s tools for a parametric design approach allow to explore the design space freely but within a certain flow that the designer defines. One of these parametric tools is Grasshopper® (Robert McNeel & Associates [8]), a visual and intuitive programming environment running within the Rhinoceros® CAD software (Robert McNeel [7]). A parametric script in Grasshopper® can be written by placing and connecting different components on a canvas. A component typically has one or more data inputs that are processed to the output. Many designers like the way how parametric modelling is easily conducted in Grasshopper®. Grasshopper® is mainly focusing on geometrical design, however because of its open source character there exists a broad range of uses thanks to third party plugins.

The main thoughts of this ongoing research on data visualisation in structural engineering is illustrated with a case study on bridge geometries. All studied design alternatives are tied-arch bridges. The main characteristic of this bridge typology is that the reaction forces under self-weight are vertical; no horizontal thrust forces are thus taken by the supports. The arch, which is mainly loaded in compression, is held together by the main girders, acting as a tie. As a design exercise, five different bridge designs are generated based on an existing bridge geometry (Fig. 1). The geometry of the arch is altered through form-finding and the cable configuration is adapted consistently.

![Figure 1: Tied-arch bridge by Ney + Partners. This bridge is the second bridge in a series of generic arch bridges spanning the Albert Channel (Belgium). The bridge spans 118m and consists of two traffic lanes and a pedestrian zone at both sides.](image)

More precisely, the geometry of the deck, main girders and cross-girders is identical for all design alternatives, taken from the existing bridge geometry. Then, different arch geometries are obtained by a preliminary form-finding in two dimensions by means of Kangaroo (Piker [5]) a plugin for Grasshopper®. These line geometries are then optimised in an iterative way to further reduce the bending moments. Karamba (Preisinger [6]) was used to perform the structural analysis for each iteration. The parametric design environment of Grasshopper® will be briefly discussed further in this paper. As a last step in the parametric design, these 2d arch geometries are projected on two intersecting planes just as in the existing bridge geometry. This way one conceives a bridge geometry where two arches are reaching each other at the top of the bridge. This procedure is followed for four form-found arch geometries different than the existing example (Fig. 2).

These five geometries are used as a case study to investigate the use of data visualisations in structural engineering. As shown above a broad range of different design alternatives can quickly be generated
with a parametric design approach, leading to complex 3-dimensional geometrical and structural models to use in the further workflow of the design.

Figure 2: Five different bridge geometries with the same deck configuration, but different arch and cable geometries

2.2. Efficiency in architectural design: an ambiguous architectural exploration

Structural efficiency shows the intelligence of a structural design, it reduces the structural mass and therefore also the cost. An obvious way of obtaining such intelligently designed structures is by using form-finding and optimisation procedures. However, these tools are often very typology oriented and return only a single equilibrium and/or optimal solution. As a consequence, an important shortcoming of these design methods cannot be overlooked: the lack of exploration. The mathematical character of these procedures are in large contrast with the main goal of the conceptual design phase. With the help of current design tools, the designer finds himself in an ambiguous situation. On the one hand is the designer looking for an architectural construction that has aesthetical qualities and that is able to not only fulfil the functional needs, but in addition has an architectural meaning. Exploration is a keyword in this early part of the design process. On the other hand, the structural designer wants to create an efficient structure and to design a clear structural logic. However, with the current design tools there exist no appropriate way to deal with this design ambiguity.

3. Informed decision-making

If a designer has made several design alternatives that are appealing to him/her, in example the presented bridge alternatives, he/she probably want to look for the structural behaviour and performance of these alternatives in order to make an informed decision. One way to look for the best performing design alternative of the above discussed geometries is to perform for each design a full analysis and design procedure according to the Eurocodes. If one in the end assigns optimal cross-sections, one can easily find the design alternative with the least structural mass and thus performing better from a structural point of view.

Doing a full structural analysis, followed by dimensioning and detailing each design alternative is however elaborate and time consuming. In addition, it blocks the creative workflow in which the designer finds himself/herself during the first stages of the design since the exploration should make place for a thorough structural Eurocode analysis. A designer is interested in the structural performance of these structures in a qualitative and relative way. Doing so, he/she is able to take into account both structural and architectural design parameters. This research investigates data visualisation as a way to offer an informed decision-making method during the early stages of the creative design process.

Parametric modelling and the available computation power allow to quickly analyse a whole series of design alternatives. This data can be used to inform the designer about the different designs. The author suggests data visualisation as a way to intuitively gain insight in these large data sets and the associated design alternatives. This way a guidance-based design exploration is provided.
4. Case study

The five tied-arch bridge geometries illustrated in Fig 2 and 3 were compared and evaluated on their structural efficiency and behaviour. This investigation allows to further gain insights in data visualisation for the structural conceptual design phase.

![Figure 3: Front view of the five different arch geometries.](image)

4.1. Structural efficiency assessment

Strain energy (Formula 1, 2) is used in this study to quantify structural efficiency. An efficient structure is in general the one with the more direct internal force path, a more uniform distribution of internal forces and smaller internal forces. These three interrelated concepts will lead to stiffer and thus more efficient structures. These concepts can indeed be found in Michell trusses and the structural layouts generated by evolutionary structural optimisation algorithms (Ji [2]).

Very often, the efficiency of a structure is reduced in practice to the maximal values of its internal forces. However, the strain energy (a part of the structure) in the efficiency assessment gives a better idea about the total distribution of internal forces as the forces are integrated over the entire length of the members. The following two equations describe the strain energy of a structure when integrated over all members’ lengths. $U_n$ is the strain energy due to axial stresses (axial force and bending moments), $U_v$ is the strain energy because of shear stresses (shear forces and torsion). The latter (Formula 2) will not be considered because of its limited impact on the design process in an early phase.

\[
U_n = \frac{1}{2} \int \frac{N^2}{EA} dx + \frac{1}{2} \int \frac{M^2}{EI_x} dx + \frac{1}{2} \int \frac{M^2}{EI_y} dx
\]

\[
U_v = \frac{1}{2} \int \frac{V^2}{GA_y} dx + \frac{1}{2} \int \frac{V^2}{GA_x} dx + \frac{1}{2} \int \frac{T^2}{GJ} dx
\]

These formulas clearly show that the value is dependent on the internal forces as well as the member lengths on which they are acting. If a design alternative produces for example the highest extreme bending moment, it doesn’t necessarily mean that the overall appearance of bending moments in the structure is also the highest compared to other design alternatives. In addition, strain energy relates the internal actions to the inertia of the structure’s actions. This gives the designer an insight in the stiffness of the structural elements ($A$, $I_y$, $I_z$, as geometrical properties of the cross-sections) and the structure as a whole.

In previous research by the authors, the use of reference cross-sections has been studied [3][4][10]. This means that plausible cross-sections are chosen as an initial guess, and equally applied for the different design alternatives. For the tied-arch bridge alternatives, cross-sections are chosen for the main girders, cross girders, arch elements and cables. These cross-sections, were then assigned for all models. The choice of using reference cross-sections was made because it enables to make a preliminary comparison of the structural efficiency of all alternatives without the need to do a full Eurocode check of all design alternatives. Of course, cross-sections for sure have an influence on the behaviour of structures, but the differences are considered small when it comes to making comparisons in a qualitative and relative way.
In addition, it is generally known that the structural layout or overall geometry of a structure is of great importance for the efficiency of structures (Yu [12]). If two structures with the same initial cross sections are subjected to a set of external loads, the one having less strain energy is considered the more efficient.

4.2. Performance graphs

All load cases as described by the Eurocode are applied on the five models: self-weight of the steel elements, the super imposed dead load of the concrete and finishing layers, wind loads in different directions and multiple traffic loads. According to the code all load combinations are made with the appropriate combination factors.

Different types of graphs are being generated in order to get an insight in the structural efficiencies of the five tied-arch bridge geometries. First of all, a graph is plotted (Graph 1) with the global strain energies, divided in axial strain energy and bending strain energy. This means that the total strain energy by normal forces is calculated for each structure, as well as the total strain energy by bending forces (both $M_x$ and $M_y$), while the reference cross-sections are assigned. For the internal forces, the envelope of all load combinations is considered. This plot already gives a very global insight in the relative efficiency of the bridge geometries under all load combinations. The same graphs can be created for the different parts of the bridge (arch, main girders, cross girders, cables), in order to get a further insight in the performance of the different bridges.

Graph 1: The global deformation energy (split into the axial and bending contributions) for the five different bridge geometries under the ultimate envelope of internal forces.

From Graph 1 one can conclude that model A has the least stored strain energy under the envelope of load combinations and is thus more efficient. Model A is followed by models B, E, C and D. As a further observation it is worth to mention that the structure’s strain energy consists more of axial strain energy than bending strain energy under the ultimate envelope of internal forces: which can be expected in a form-found tied-arch bridge.

To get a basic insight in the structural behaviour of the different bridge designs, the strain energies are examined for different parts of the structures separately: main girders, arch and cables. The strain energies of the cross-girders are more or less the same for the different design alternatives, since their layout is identical for each design as well as the loads acting on it.
4.3. Reference cross-section validation

Beside gaining insight in the performance of these different structures and the constituent parts, a validation of the use of reference cross-sections was done. Practically this means that the use of reference cross-sections is only valid if the same performance ranking is obtained as if it would be obtained by a full Eurocode calculation. Small differences in strain energy can be observed in the graphs (2, 3) underneath. Despite these small differences, the same relative ranking of the bridge geometries is obtained and the use of reasonable reference cross-sections is validated. The ultimate envelope of internal forces under all load combinations was used for calculating the strain energy. Graph 2 shows the ranking of both the Eurocode structures and the ranking when using reference cross-sections. This ranking is based on the strain energies of the whole bridges that are under comparison. In order to have a full understanding of the use of reference cross-sections, the same kind of graphs was made for the different parts of the bridge (arch, main girders, cross-girders, cables). For all of these graphs the same ranking was obtained for both the Eurocode cross-sections and the reference cross-sections. In Graph 3 the strain energies of the arches are plotted.

![Graph 2: The global strain energies (axial and bending) of the five different tied-arch bridge geometries when using a reference cross-section compared to the Eurocode cross-sections.](image)

![Graph 3: Strain energies (axial and bending) of the arch of the five different tied-arch bridge geometries. Comparison of reference cross-section and Eurocode cross-sections.](image)

4.4. Behaviour graphs

Having an insight in the relative structural efficiencies, a new graph type is being developed to visualise the behaviour of the structures under different load combinations. For each structure the strain energy is being calculated multiple times for all load combinations prescribed by the Eurocodes. Again the energy is split up in the axial part and the bending part, resulting in multiple points for a single bridge model representing its behaviour under all load combinations.

In the illustrative graph underneath (Graph 4), the aim of this kind of graphs becomes clear: the different dots can be interpreted as a region in which the structure behaves. By indicating the load combination of the self-weight, the designer gets immediately an indication of the way in which the different bridge geometries react on the design loads.

If a structure has a ‘shorter’ region in this graph, that is additionally concentrated very near to the self-weight indicator, it is behaving in a more efficient way compared to the other design alternatives. This kind of graph can be easily integrated in the calculational workflow of designers and offers an intuitive way for comparing structural behaviours quickly.
Graph 4: This graph visualises the behaviour of the different tied-arch bridge geometries. It becomes very clear that model A performs the best under all load combinations. Models B, D and E have a similar structural behaviour.

4. Tool

4.1 Introductory note
From various practical cases studied by the author in the past, the use of data visualisation in addition to advanced computational modelling has already shown its potential [3][4][10]. Nevertheless, the effort for translating the structural models into data visualisations is relative large if this procedure is done manually. To facilitate research and to further explore this topic, the author is developing a tool that automates the data visualisation process. This development is part of ongoing work. However, it will help to assess the value of informed-decision making by means of data visualisation for structural design matters. The developed plugin can be tested quickly for new typologies and design problems. This testing on the other hand gives rise to insight in missing visualisation methods for general or specific design problems, typologies and in the meantime triggers the further development of the tool.

4.1 Digital environment
The tool for generating visual data charts is packed as a plugin for Grasshopper®, written as a custom Grasshopper® assembly. It makes use of Karamba (Fig. 4), developed by Preisinger [6]. Karamba enables to run finite element calculations of structural models within the parametric environment of Grasshopper®. Any changes that are made in the structural model, are immediately altered in the finite element model. This plugin gives easily feedback on the structural system and allows an interactive exploration of the parametric design space.
The analysed Karamba FE models are taken as an input for generating the visual charts immediately in Grasshopper® by means of the developed plugin. Karamba is chosen as structural analysis software because it seamlessly integrates within the Grasshopper® environment. By using Karamba, there is no need to use other software in addition to the Rhinoceros® and Grasshopper® framework for generating interactive visual data charts. The visual chart components of the custom Grasshopper® addon are discussed on an abstract level in the following section.

4.2 Components

To create visual data charts in Grasshopper® three main component types are developed. The first component is the “Model Component”, giving a name and colour to the structural model. With this component a dataset is made containing the Karamba FE model and its results, together with other data to facilitate the generation of the charts based on the structural model later on. Fig. 5 shows the input and output of the Model Component.

The output of the Model Component, “dModel” is then be used as input for the various “Chart Builders” (Fig. 6). Every dModel that is connected to a Chart Builder will be included in the visualisation. This means that the each structural model that is included in the graph, is represented in its own colour. Of course different types of charts exist, all with their own advantages, use, representation... For that reason each Chart Builder component plots its own visualisation. As illustrated with the case study above it can become handy to focus on a specific group of elements only. If we take for example the case study of the tied-arch bridges, the designer might only be interested in the structural behaviour of the arch without including all other elements of the structure appearing in its chart. Karamba allows to assign identifiers to structural elements in order to group different elements for the further flow of the parametric design and finite element calculation. In the visual chart builder component, the identifiers of Karamba can be used to show only the results of a selection of elements in the data visualisation. This way, a bunch of structural models can be compared based on only a part of the structure.
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Figure 6: The assembly of different dModels to Charbuilders. The height of the graph can be adjusted and by using id’s, only a part of the structure can be plotted.

In addition to the Chart Builders, some “Layout components” are developed that allow to align or group the graphs in a way that makes sense for the designer (Fig. 7). The Layout Components are then added to the “Page Builder” that generates an interactive sheet consisting of multiple graphs.

Figure 7: The final step in the Grasshopper®-script is to assemble these different charts to a Page Builder.

These sheets are constructed as webpages based on modern web technologies, making use of php, html5 and javascript. Since web browsers are available on every pc and mobile device, the author took the advantage of using this medium in order to generate interactive webpages.

These webpages are built by the Grasshopper® components and make use of a predefined framework. This framework consists of javascript libraries, css files and php files to ensure a smooth and brief definition of the visualisation webpage itself. When this webpage is opened in a browser, it will detect if a newer version of the page exists. If this is the case, the page will refresh automatically and show the current version. Practically, this means that if any change has been made in the Grasshopper® model, the graphs and the page layout are instantaneously updated.

5. Future work

The further development of the custom Grasshopper® addon is crucial in order to fully understand the added value of an informed decision-making process during the design, based on data visualisations. Developing such a tool will help to explore this research topic thoroughly since it will give rise to investigate the drawbacks and shortcomings. When more Chart Components are available, the informed exploration of the design space will for sure be facilitated. This in turn will allow to subject more case studies of different typologies to this informed way of designing.

References


