Enhanced decision making in the structural design process by means of a dashboard approach

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Abstract

This paper proposes a novel approach for comparing different structural geometries based on data visualisation and illustrates this with bowstring bridges as case study. The aim of the approach is to have a quick and overall insight in different design proposals at the beginning of the design process. The approach will use a dashboard that is a combination of charts. This dashboard will enable the (structural) designer to have all information on the structural behaviour of a series of design proposals at hand and to make informed design decisions based on the compact dashboard.

Keywords: Structural Design, Performance Aided Design, Structural Informed Design, Bow-string Bridges, Data Visualisation, Design Decision-making, Dashboard Approach

1 Introduction

Quite often the design of a structure is based on a shape imposed by the designer. It is clear that optimizing structural geometries is a field in itself, but the question in the early design phase is to estimate the impact of different structural topologies and boundary conditions on the overall behaviour of the structure.

A possible way to compare different structural geometries is to model a geometry, conduct a finite element analysis with all load cases and run the code checks to dimension and verify the structure. After the dimensioning, the model will have a clear output: the weight of the structure. Based on this parameter, one is able to compare different design alternatives. However, this approach might become very time consuming when wanting to compare a whole series of topological alternatives. An experienced structural designer will start to point compare structures: maximal normal forces, maximal bending moments, maximal deformations, etc. Yet this gives punctual information about peak performance, while neglecting the view on the overall performance and behaviour [10].

In this paper, a novel approach is presented using two-dimensional models and lightweight FE-calculations followed by a dashboard of graphs. This dashboard represents the overall behaviour and performance of structural design alternatives and enables the structural designer to compare different design alternatives in a nuanced way, rather than looking for the strict optimal solution and ignoring the architectural needs. The approach will be illustrated on the basis of a case study of bowstring bridges. The tool is aimed to offer the experienced engineer a synthetic view of the whole, whilst not reducing the behaviour of bowstring bridges to a single number. This tool is part of ongoing research and has as main focus to illustrate a methodology for comparing structures in an early structural design phase. Previous research on this topic, but focussing on gridshells, is presented in [10].

2 Integrated methods for structural design considerations

2.1 Traditional sequential approach

A succession of different sequential phases exists in the traditional design process. The overall geometry (shape, topology) is first conceived (often by an architect). During this phase architectural and functional criteria such as aesthetics and boundary conditions are taken into account. The structural behaviour and efficiency is often only considered in a second phase, in which the geometry is subjected to finite element calculations and in which the results are analysed (Figure 1). If the results are not satisfying, the design is changed iteratively. If design modifications are made in the geometric modelling tools, those changes need to be remodelled as well in the engineering tools, an approach which is time consuming and can lead to errors.

According to Clune et al. [2], the reason for this sequential approach is the specificity of the software applied by the architects and engineers. Architects use geometrical modelling tools that stimulate the exploration of the design space and creativity, mostly without considering structural efficiency, whereas engineers conduct finite element calculations on a predefined shape. In addition, the results generated with a finite element analysis software can in general only be checked case per case, making it hard for the structural designer to compare design alternatives. Also, only maximum values are often taken into account with this approach, leaving into the shadow the global structural behaviour.

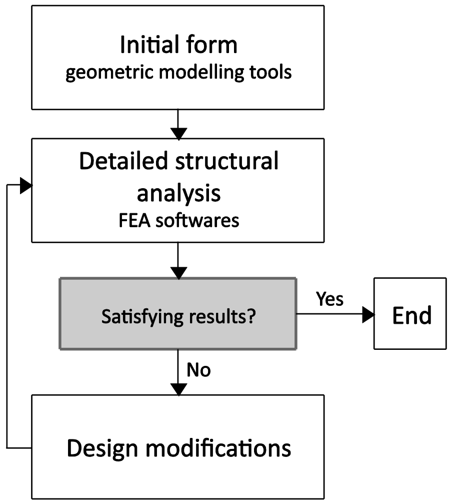

Figure 1. Flowchart of a 'traditional' sequential design process

2.2 Structural design tools and their focus

Geometrical properties, such as shape and topology, are an important factor for a structure's performance [5]. Hence structural considerations should preferably be introduced in the first stages of the design process.

Computational structural design tools tend to enable a better integration of structural performances during the early conceptual design phase. Various structural design tools exist, all with their specific focus, complexity, user interactivity and required technical background. Each of the existing structural design tools has its own goal and is very suited for a specific use: think of interactive graphic statics, real-time numerical structural analysis, form-finding tools and definitions, …

However, we are looking for an approach whereby various designed proposals can be calculated quickly in a familiar FEA software, after which the load bearing behaviour of all cases can be compared with each other rapidly and easily in one general interactive overview. Most importantly, the comparison of structures should be possible without the need to calculate the total weight of the structure. First comes understanding the structure, afterwards dimensioning that structure.

2.3 Interactive data visualisation

Data is currently generated at very high volumes and the generation rate is still speeding up. The exploration and analysis of these vast volumes of data is increasingly difficult. However, information visualisation and visual data mining often helps to deal with a lot of information. The advantage of visual data exploration is that the user does the most important part: he is directly involved in the data mining and interpretation process [4]. As Joyce states in his paper [3], data visualisation is the link between graphic design and quantitative information. Besides that, the discipline of data visualisation searches for the cognitive understanding and interpretation of graphical figures by people [3].

Nowadays data visualisation is used a lot in all different kind of fields. Main reason is the availability of relative easy-to-use tools. Think of the well-known chart-makers implemented in MS Office. However also more complex visualisations can be found in a whole range of topics; think for instance of the popular publications *"Information is Beautiful"* and *"Knowledge is Beautiful"* by *Mc Candless* [6][7]. New tools are making the way for more user-interactive dynamic visualisations on the web. Several newspapers (i.e. New York Times) picked up the potential of this new information medium and show increasingly interactive visualisations on their websites. The new web standards implemented on modern web browsers and the relative ease of scripting these visualisations are making interactive data visualisations more accessible [3]. In this paper the JavaScript library "D3" [1] is used.

Before elaborating on the developed approach, we first present the case studies that will serve to illustrate the approach.

3 Case study: bowstring bridges

3.1 Geometries

As mentioned before, bowstring bridges will be used as subject to discuss the general thoughts of the dashboard approach. Various bridge geometries have been generated (Figure 3) in the interactive design environment of *Grasshopper3D*, a plugin for *Rhino3D*, CAD software developed by *Robert McNeel & Associates*. Not all of the design proposals are form-found. The very preliminary and approximate form-finding of some models has been performed by means of the Grasshopper plugin *Kangaroo*. This serves the opportunity to generate quickly a variety of geometric models that can easily be implemented in the further workflow of the comparison tool.

The span of all bowstring geometries is 85 meters and the ratio span/height equals 5 for all designs. The calculation models are considered in two dimensions and also the structural analysis is conducted in 2D. The bowstring bridges consist of a continuous arch, a continuous deck and connecting cables. The arch and deck-ends are connected with hinges. The bridge itself is simply supported at both ends of the deck. The connections between the cables and the bridge deck divide the deck in 19 equal parts for all models.

3.2 Structural analysis

A general typical section for the arch, the deck and the cables is applied equally in all structural models, after which the structural models are linearly calculated in the finite element software *SCIA Engineer (Nemetschek)* under a reference load. This reference load consists of 18 identical equally distributed point loads at on the deck (Figure 2) for each bowstring model. This reference load is a fixed assumptive self-weight for all cases.

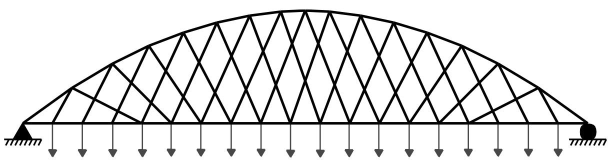

Figure 2. The used structural system for each design alternative

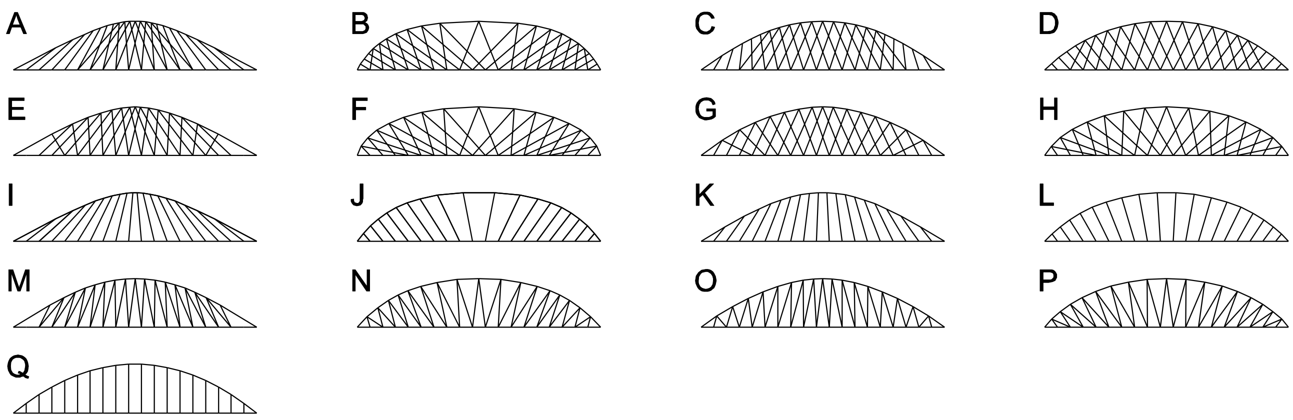

Figure 3. The considered bowstring configurations and their respective model name.

4 Dashboard approach

The structural numerical outcome of these quick FE calculations is post-processed to gather the information of all models in a dashboard overview (Figure 5). When considering a whole series of structural models and possibly wanting to add more models, it is important to make this process as generic and automatic as possible.

The interactive dashboard allows the designer to hide and show different structural models and their represented structural information in order to have all essential parameters for comparison and interpretation at one single place. Moreover, this way of nuanced comparisons facilitates the choice of proposals that both satisfy the architectural and structural criteria, rather than looking for the strict optimal solution whilst ignoring architectural needs. In what follows, the used dashboard and its components will be discussed and illustrated with an example.

4.1 MN-chart

The MN-chart displays the axial force and bending moment in all structural elements of the numerical model; each dot represents one structural element. The horizontal axis represents the bending moments while the axial forces are located on the vertical axis. This representation gives a first understanding of the overall behaviour of the structures, each in its own colour. An illustration of the principle is given in Figure 4. We clearly observe three different main structural types of a bowstring bridge: arch, deck and cables (Fig. 4). The cables are taking relative small tensile axial forces only, the arch is mainly in compression and the deck is in tension while exhibiting relative large bending forces. The area of the dots is a function of the proportion M/N. This is an important parameter if we are looking for structures with the smallest bending moment, compared to their axial force. It can be clearly observed that cable members are loaded more efficient (axial, rather than by bending) than the deck elements. By having this chart, the structural designer immediately gets a view on the different design proposals and the consequences of their geometries on the structural behaviour.

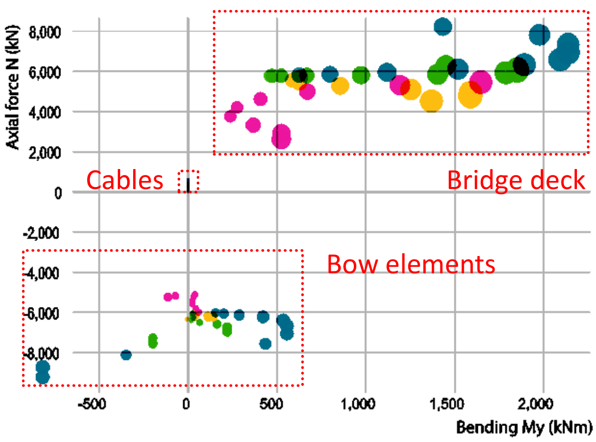

Figure 4. MN-chart including 4 bridge models represented in *blue*, *pink*, *green* and *yellow*. The MN-chart turns out to be useful for a general interpretation of different design proposals.

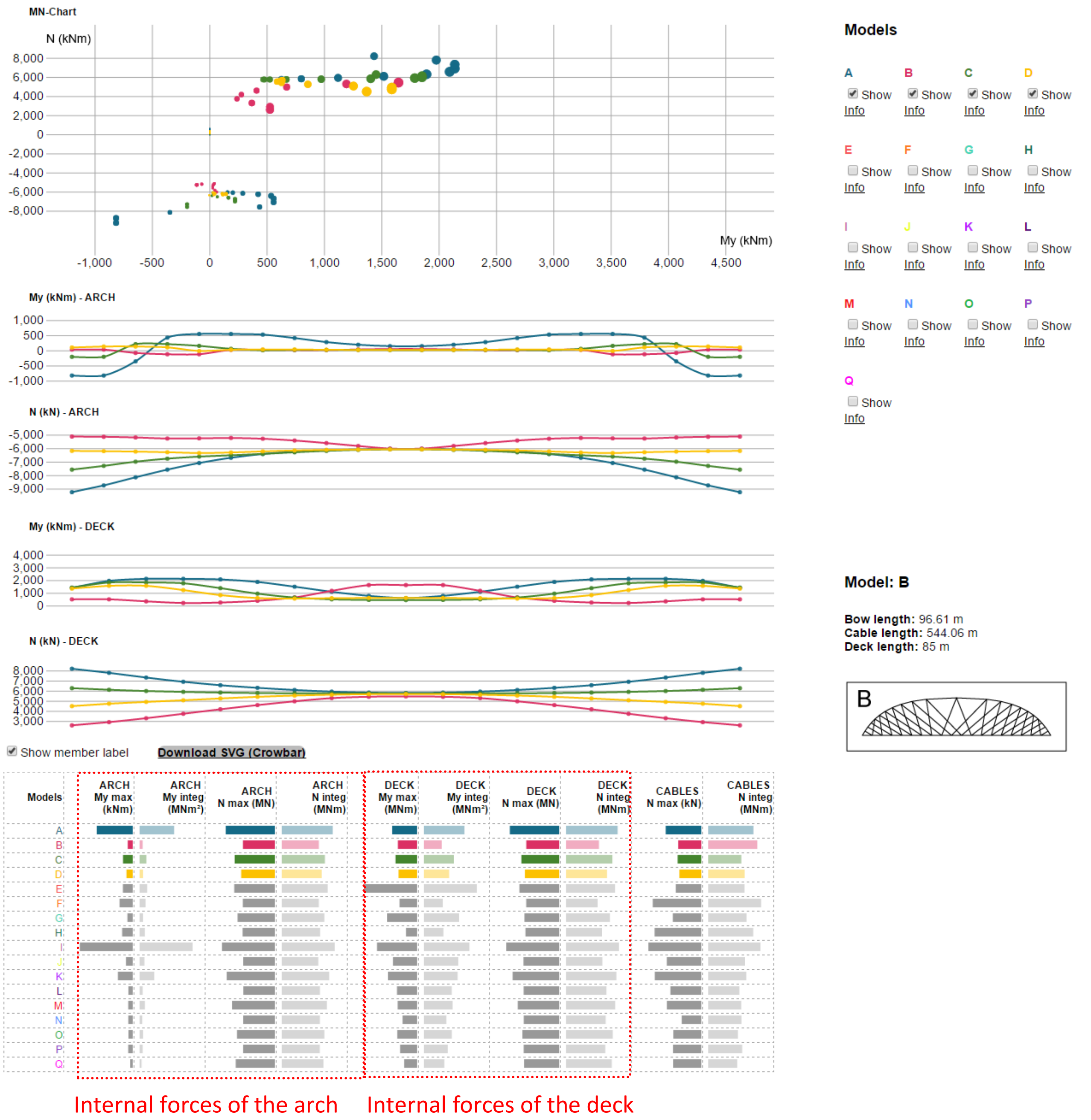

Figure 5. Complete dashboard containing the MN-chart, 4 line charts and the bar charts. Models A, B, C and D are visualised.

4.2 Bar charts

Additionally to the MN-graph, a bar chart with information on the distribution and maxima of internal forces is given. A bar chart can be found at the bottom of Figure 5. For all main elements of the bowstring bridge (arch, deck and cables), the maximum internal forces are listed for each design proposal. In addition, the integrals of the internal forces over the element lengths of the arch, deck and cables are included per model as well. These integrated forces give a better insight in the needed structural mass compared to considering maximal forces only. All values are also graphically represented by coloured bar charts that can be sorted by value, aiming for a more readable and intuitive way of comparing. In a glance, the designer can make some intuitive observations and categories based on the performance of the structures.

4.3 Line-graphs

For a more detailed view of the distribution of the internal forces in the entire structure, the dashboard includes a collection of line-graphs, representing the normal forces and bending moments along the structure's length. Because the arch of bowstring bridges typically exhibit large axial compression forces while the deck is in tension, the dashboard contains separate graphs for both the deck and arch elements, resulting in 4 line-graphs (Figure 5). Since the bow lengths of the various models differ slightly, one can choose to normalise the total length of the arch, or to use the actual scaled lengths on the horizontal axis.

5 Case study

To illustrate the new approach, the four models B (*blue*), G (*pink*), L (*green*) and M (*yellow*) will be discussed and compared by using the dashboard (Figure 3).

A reasonable way of comparing these bowstring models would be to look for the model with the smallest maximal bending moment in the arch. However, we selected four different design alternatives that have a similar maximal bending moment in the arch. Nevertheless, the MN-chart in Figure 6 shows that the various models differ in structural behaviour. Looking at the bar charts in Figure 7, it becomes even clearer that focussing on maximum values alone does not provide a complete view of the structural efficiency since the 'non-peak' values would be ignored.

Model M, as an example, has a lower maximal bending moment in its arch than models B and G (see first column figure 7). However the integral of bending forces along the complete arch is higher than the other three alternatives. This will have an influence on the required structural material. The same occurs with the bending moments of the deck. As can be seen in the MN chart and the bar chart, models B, L and M have similar maximal bending moments in the bridge deck. Yet, model B has a smaller integral (distribution) of bending moments along its deck.

These are considerations that are important to have a more overall but nuanced view for intelligent decision-making during the preliminary design phase. In addition, the MN chart allows the designer to cluster elements for preliminary dimensioning. The bending moments in the deck of model G know a large spread (which indicates more different sections to be applied), where the bending moments in the deck of model M are very similar.

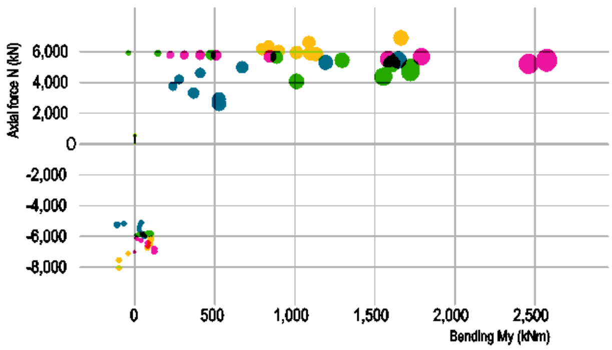

Figure 6. MN-Chart of models B (blue), G (pink), L (green) and M (yellow)

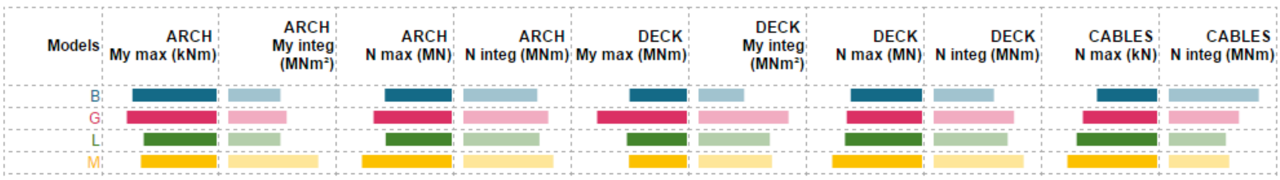

Figure 7. Bar charts representing the maximal internal forces and integrals of internal forces for each model.

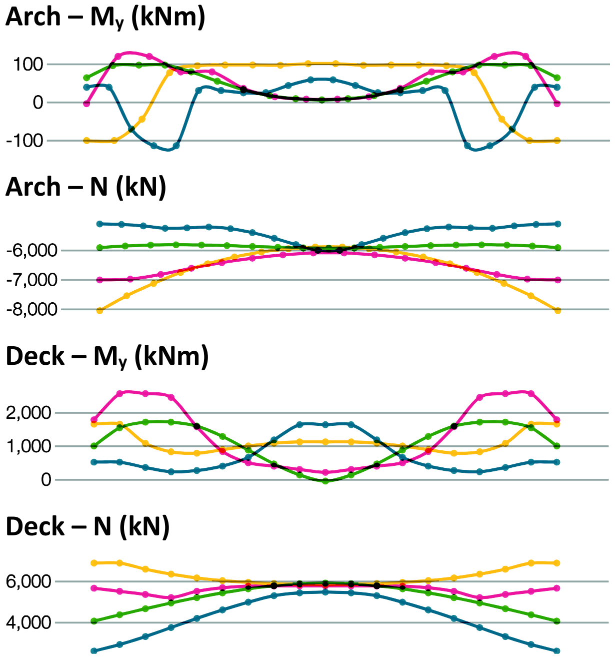

Figure 8: Line charts with the continuing of the internal forces

When looking at the line graphs in Figure 8, one immediately gets an insight in the distribution and peaks of internal forces in the decks or the arches. It becomes clear that the selected design proposals have different types of bending moment diagrams in their arches. The question now is to compare these alternatives, based on the line charts of the bridge deck and the arch. Model B (blue) has the smallest bending integrals for both its arch and deck. The designer may however prefer a more fluent bending diagram such as model L (green) or model M (yellow) whereby the bending moments do not change a lot over the design (for reasons of dimensioning).

This discussion shows the more nuanced and interactive way of comparing structural geometries in the first conceptual design phase. For reasons of clarity, only four models have been lighted out. Of course this interactive dashboard approach lends itself to incorporate many structural geometries that can be switched 'on' or 'off' in the visualisation of the tool.

6 Conclusions

In an early structural design stage, it is important to quickly and easily assess the structural behaviour of various design alternatives. When considering bowstring bridges, various geometries can be imagined. In order to make informed design decisions, these geometries should be analysed before proposing a viable design solution.

In the traditional engineering process, different structures will be compared after all load cases have been taken into account and the dimensioning of all elements has taken place according to the current Codes. This process is time consuming and complex, whereby the user needs to make comparisons based on a lot of various screens and extreme values.

To avoid this, we proposed a quick and easy approach whereby the comparison of the structural behaviour of a large amount of design proposals is facilitated. The difference in structural behaviour is reflected by the use of one single reference load case. After the structural calculation the generated data is plotted in a dashboard of graphs, like an overall MN-graph, bar and line charts. The bar charts not only illustrate the maximum occurring internal forces and bending moments, but also the integral of the internal forces and bending moments. The line chart represents the forces and moments along the structure's length. These graphs prove to be interesting for bowstring bridges. It takes some effort to create the appropriate dashboard. However, future research will search for the right representation methods and will indicate which graphs are useful for comparing other structural typologies.

This dashboard allows comparing roughly at a glance the structural behaviour of the various proposals. By combining the dashboard including an automated graphical plot of all the occurring forces and a table containing key numerical values, the structural designer has all the tools at hand to quickly assess design alternatives.

With this approach, the structural designer can assess more quickly the different design proposals based on a more complete understanding of the structure. The goal is to replace a *'computed therefore it is'* approach for a knowledgeable approach in the structural design thinking..

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