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Structural optimization of free form frame structures in early stages of design

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Abstract

In recent years the initial difficulties in the engineering and fabrication of free form building designs have been overcome, now allowing the focus to shift towards an integrated approach in which the designs are improved. The paper presents a non-exhaustive overview of methods how the structural engineering discipline could improve structural performance of free form projects in early stages of design. Through an enhanced understanding of their structural behaviour using parametric models, it is demonstrated that optimising structural form within free form designs is very well possible.

Keywords: Free form building designs, conceptual structural design, parametric structural design, form-optimisation.

1. Introduction

1.1. Background

In the past decade free form building designs have become common among architects' proposals and competition entries. When eventually built, the initial challenge was lying in the engineering and fabrication of such doubly curved and irregular geometries. Over time, experience and development of enabling tools for design, engineering and fabrication has allowed the focus to shift towards a more integrated and systematic approach.

The role of the structural engineering discipline in this trend has moved from merely performing structural analysis on a given geometry, towards the academic challenge of proposing more optimal design solutions. Such proposals interact or utilise the architect's free form proposals and thus not solely enable them, but moreover represent an improvement in the structural performance and a cost-saving as a result. This philosophy of embracing free forms and contributing to them is part of the philosophy of the structural engineering consultancy Adams Kara Taylor (AKT) (Kara and Kubo, [2]). The methods described in this paper have evolved from the practice's involvement in numerous projects featuring free forms, which in this context are defined as designs with double curved surfaces that do not originate from structurally optimal forms like shells or catenaries.

1.2. Conceptual structural design

It is commonly understood that the important design-decisions are taken in the early stages of the design process, this despite the fact that in these early stages yet little is known about the behaviour of the building in its specific context of geographic location and the types and magnitudes of external loading. A typical example of such an ill-informed design situation is an entry for a design competition for which the practice is invited to provide engineering advice. Generally a time span as short as two weeks is available for this, in which typically the design is still evolving as well. Due to the nature of the work, it is unlikely that the amount of available time will increase.

In this first possible stage where an engineer gets involved it is accepted that no all-encompassing round of design and analysis can be performed in two weeks on a project of beyond-ordinary complexity, and the focus is on gaining an understanding of the behaviour and the highlighting of potentially critical aspects instead. Further efforts will then be spent on a strategy addressing how these can be improved or steered away from as to conclude with a viable structural design that maintains the architectural design intent.

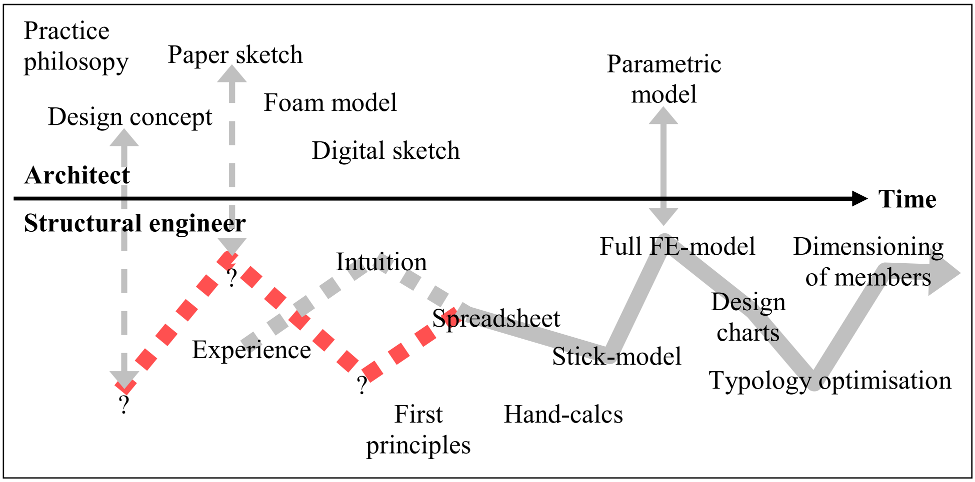


Figure 1: Models and methods for analysis and design throughout the development of a design, and the lacking of tools that matches the architect's initial activities

Of particular complexity is the preliminary consult on free form building shapes in seismic zones. A quantitative approach including early-stage analysis is necessary to overcome the unique design circumstances of the nature of the building design and the magnitude of the seismicity to be taken into account, for which no prior experience is available. Generic design strategies are to design in a material-efficient manner, particularly in the higher parts of the building, in order to reduce the mass and thus the loading in the event of an earthquake. Furthermore the design should allow for zones where energy can be dissipated. Material saving thus becomes potentially conflictuous with efficiency.

Identifying critical aspects of a proposed design is hindered by the vast size of the design space that typically characterises free form buildings. The absence of experience, intuition and standard cases that designs can be extrapolated from needs to be compensated by project-specific early stage information. While structural modelling would normally provide this information, the indeterminacy and speed of change of the architect's proposal excludes any major effort in a large complex model that risks becoming abortive quickly, instead favouring more simple but quicker models instead (Figure 1).

1.3. Increasing the structural efficiency of forms through the potential of form-action

This paper proposes three fast and simple methods appropriate to the early stages of design of frame-like structures in free form (parts of) buildings where the structural form intends to follow or in the extreme case to equal the architectural form. While all four types of structural action (form-, surface-, vector- and section-action) as defined by Engel [1] could be employed to affect the structural performance, the optimisations presented here are achieved through activating an increased portion of form-action. Form-active structures transfer loads through change of form and are highly material-efficient. When employed in isolation the design space is mostly limited to the boundary conditions, but it offers big potential when combined with other structural actions, notably the most versatile acting in bending (section-action).

2. Method 1: Manual generation of discrete curved frames

For a project with a large number of different frames cantilevering with a bulge we wanted to know the impact of the frames' shapes on their structural performance. The project is the Heydar Aliyev Merkezi Cultural Centre in Baku (Azerbaijan) designed by Zaha Hadid Architects (Figure 2). Parallel frames, eventually to be realised as trusses, form the primary structure and follow the curvature of the building envelope.

The bulging cantilevering frames are all similar in nature, but different in span, curvature and tangent at their lower end. The form-exploration covers the portion of the frames that are supported on the ground on one end and on a core on the high end, but when rotated 90 degrees it also covers the highest portion of the building. As the building is in a seismic zone, the frames are subjected to both vertical and horizontal loading. To understand the effect of the shapes on the performance under these typical loading conditions, we manually drew two series of instances (Figure 3) out of a continuous space with an infinite number of possible frame-shapes. The first series features various inclinations of the lower end depending on the cantilever of the frame, the frames of the second series feature cantilevers similar to first series but all have a vertical tangent at their lower end. The frames in both series have a constant cross section and are loaded first by a vertical uniformly distributed load and then by a horizontal UDL. The resulting horizontal and vertical deflections (Ux, Uy), axial force (N) and bending moment (M) will be compared against those of a familiar orthogonal frame between the same start- and endpoint.

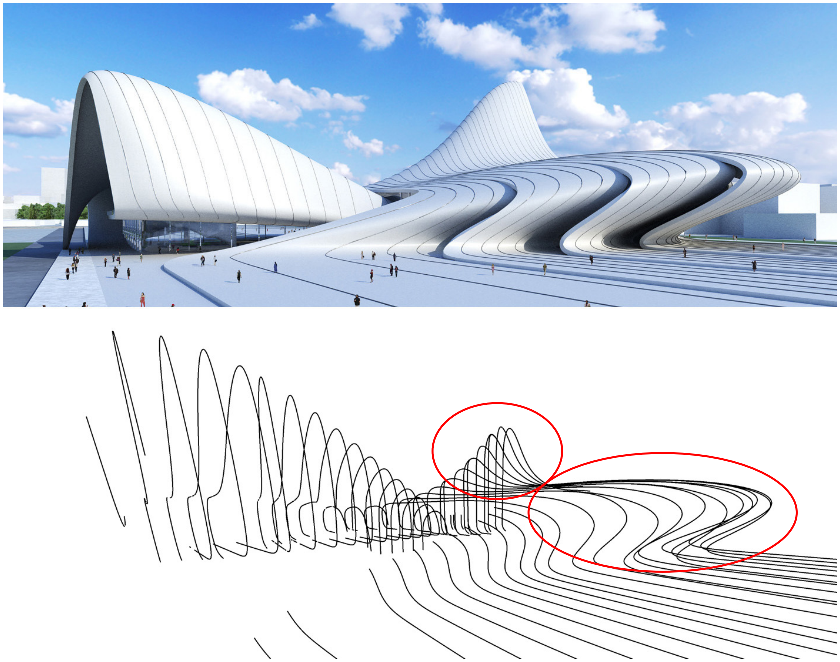


Figure 2: The Heydar Aliyev Merkezi-project designed by Zaha Hadid Architects and zones (encircled) that feature cantilevering curved frames

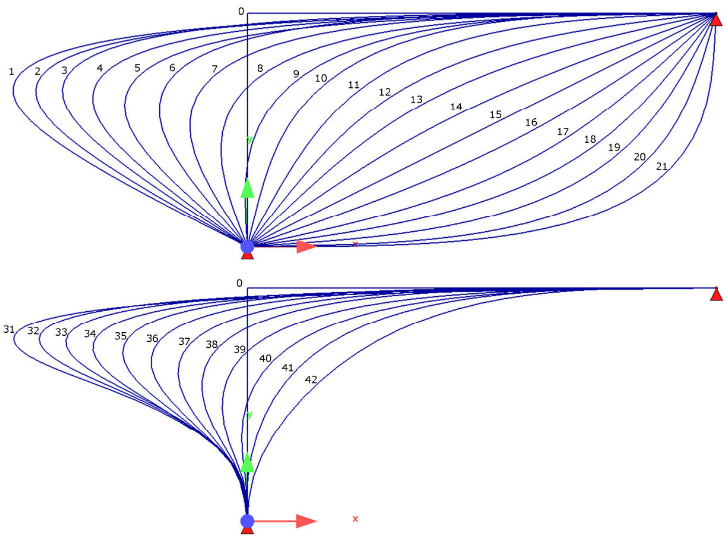
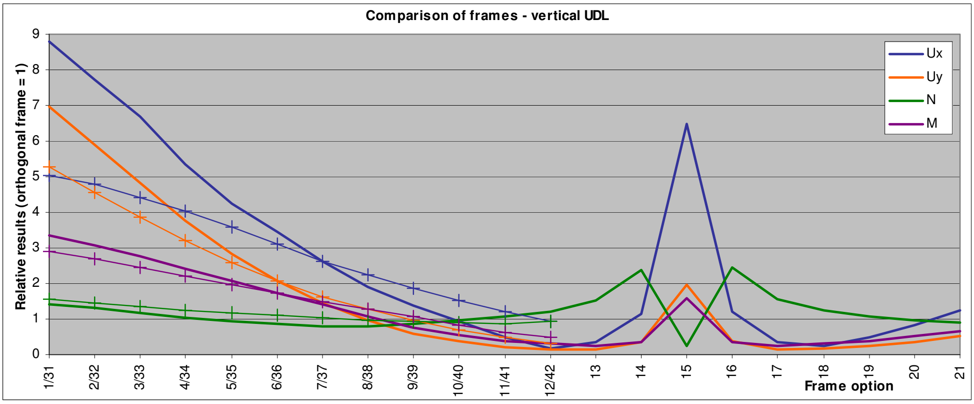


Figure 3: Two series of manually drawn curves and the orthogonal reference frame (0) whose performance is to be compared

The analysis results (Figure 4) of vertical loading show that Ux, Uy and M, and to a lesser extent N, are all decreasing as expected when the cantilever decreases. Despite being curved, frames of both series close to the orthogonal reference frame feature a performance similar to the orthogonal frame. Around the shape of curve 14 the frame develops a maximum N as it approaches the form of a compressive arch, but then drops suddenly at curve 15, which is the straight beam between the supports. This signifies a change in the predominant structural action where the form-action is locally absent and the structural behaviour is fully governed by section-action. In the case of horizontal loads the differences in performance of the frames of series 1 are fairly small as they do not exceed the results of the orthogonal frame by more than 50%, while those of series 2 show an up to 7 times higher value of Uy. Summarising, this study on discrete curves provides insight in the impact of the change of the frame's shape, showing that the explored shapes are more sensitive to vertical loads than to horizontal loading.



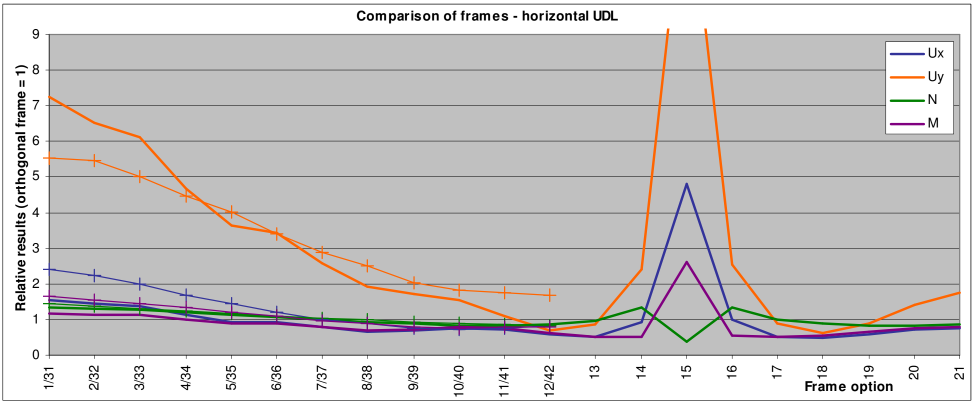


Figure 4: Comparison of vertical and horizontal deflections, M and N of discrete curves. The curves of the second series (31 to 42) are marked with a '+'

While the figure of the curves suggests a transient continuity of structural forms, these are the result of manual input. Such a visual continuity however cannot easily be related to the variation of a single parameter, which hinders the exploration of the full design space through a computational parameter study or optimisation.

3. Method 2: Parameter study of a frame using a polynomial interpolation

To overcome the limitation of the previous method of not being continuously explorable and requiring extensive manual inputs, the current method is using a polynomial interpolation of degree 2 (equation 1, Figure 5a) to define a curve going through 3 points giving the required free form resemblance:

$$\begin{aligned} x &= x_0 + t(-3x_0 + 4x_1 - x_2) + 2t^2(x_0 - 2x_1 + x_2) \\ y &= y_0 + t(-3y_0 + 4y_1 - y_2) + 2t^2(y_0 - 2y_1 + y_2) \end{aligned} \tag{1}$$

The coordinates of the second point (x_2,y_2) will be varied while keeping the start- and endpoint (x_1,y_1 and x_3,y_3) at the same position as in the previous method. While the position of this second point gives an indication of where the curve goes, it does not go through the tip of bulge, which would arguably serve the parametric exploration better as it would then have a direct relationship to the cantilever which is, intuitively, a critical parameter.

The curves are generated through loops for the incremental value of *t* (from 0 to 1) and the x- and y-coordinate of intermediate control point, using the scripting facility in the Sofistik-finite element software (Sofistik [4]). All beams have the same and uniform cross section and although all in the same model, the frames are structurally independent. Three generic load cases represent typical horizontal and vertical loading, as well as a generic trapezoidal load ranging from +1 at one end to -1 at the other end that represents a non-uniformly distributed load like wind (Figure 5b, c and d).

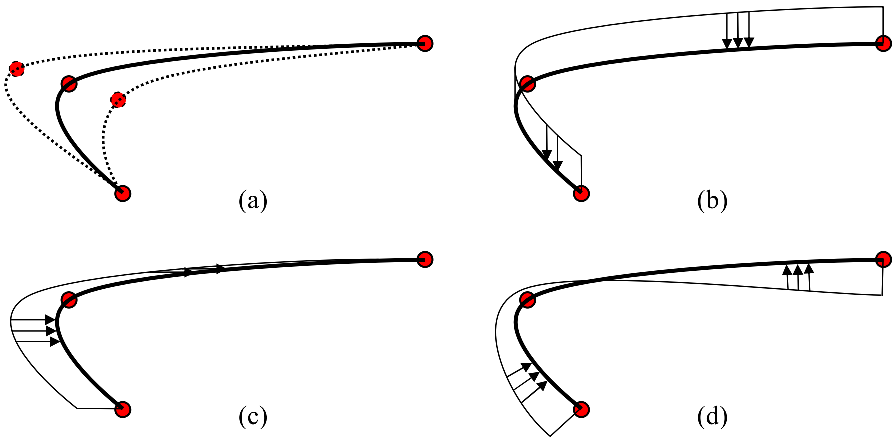


Figure 5: Generation of geometry from three points (a) and generic load cases for distributed vertical (b), horizontal (c) and trapezoidal perpendicular loads (d)

The resulting maximum bending moment per frame are displayed per load case as a 2-dimensional representation of instances at the position of the variable point (Figure 6). This allows overlaying with the generated curves (as shown in Figure 6a), which would not be possible with a representation in a continuous three-dimensional graph. The area of each circle represents the performance of that curve relative to the curve with the lowest bending moment. This optimal position of the variable point is obtained from an optimisation per load case using Sofistik's optimising-module Optima (Siffling [3]). The target function is to search for the position of the variable point that yields lowest overall bending moment in that curve. This optimal position is given by the star and theoretically should be at the position of the smallest circle.

For the case of vertical loading the variable point creates a compression arch for iterations starting above the straight member, while it resulted in a catenary for iterations starting below the straight member. Combining the results from the parameter study with the single result from the optimisation verifies the optimisation and in this case highlights that for the cases with vertical and perpendicular loading the optimisation gave an optimal result, while for the case with horizontal loading it didn't. This has no impact on the comparison of performances of curves however.

For all load cases similar graphs were made for the relative axial force per curve. As in Method 1, the variation of the absolute maximum bending moment is more significant compared to that of the axial force. Hence the bending moment is used as performance indicator. Reduction of the bending moment also reduces deflections, which is often another important criterion in frame structures.

For vertical loads, as in Method 1, the conclusion can be drawn that the bending is only depending on the cantilever and not on the vertical position of the tip. For horizontal loads however, the vertical position of the tip is highly significant and happens to be close to the vertical position of the tip in Method 1. The impact of the tip's position would not normally be established intuitively in a quantitative manner. Other than the cantilever being the most unfavourable zone, the rib shapes do not appear to be sensitive to the trapezoidal perpendicular load as the performance of most is similar. While presented as a loading type generically defining wind, the loading is too much simplified to accurately mimic wind load as the rib shapes towards the right end of the spectrum do not result in a trapezoidal load.

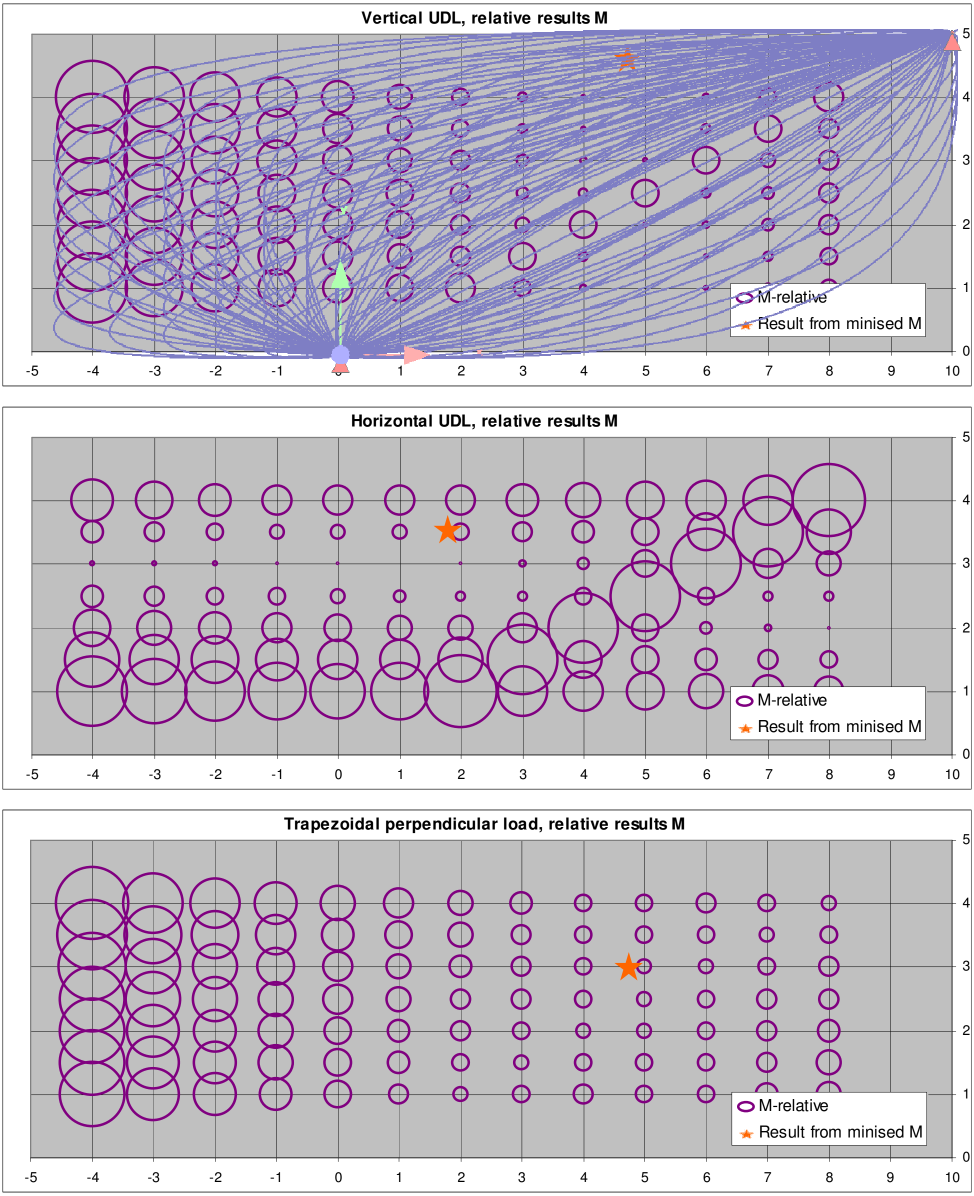
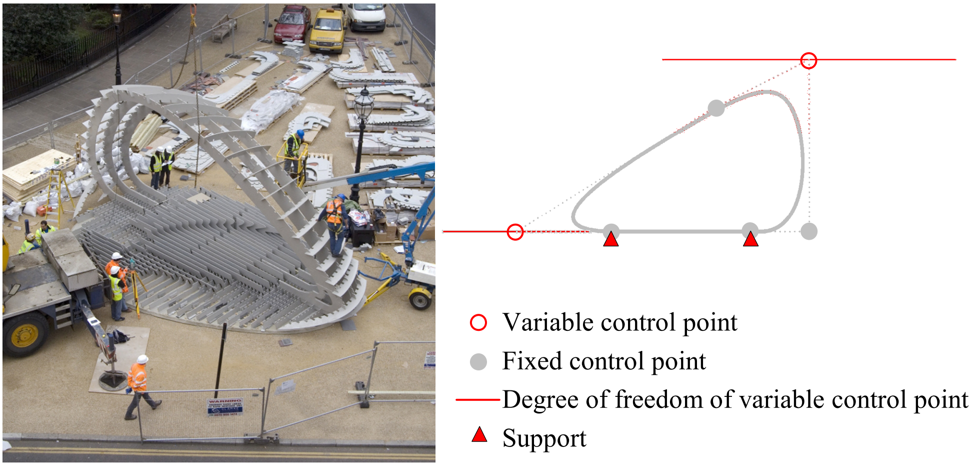


Figure 6: Relative absolute maximum bending moments for typical vertical, horizontal and trapezoidal distributed loads against a calculated optimum for a minimized M

4. Method 3: Restrained form-optimisation of a nurbs-frame using control points as variables

Assessing a curve using Method 2 required the existence of and familiarity with its mathematical description. A more general approach is the use of a nurbs-curve that is generated by the modelling software itself, based on the control points defined by the designer. Going through the first and last control point, the remaining control points act as magnet to the curve. This way curves can be described by only a small number of inputs that could be turned into variables and used to optimize the curve's shape towards a performance target. This is demonstrated on the case of the DRL10-pavilion for the Architectural Association in London, designed by Alan Dempsey and Alvin Huang (Figure 7a). The design comprises a large number of planar frames of different yet similar shapes, all being structural.



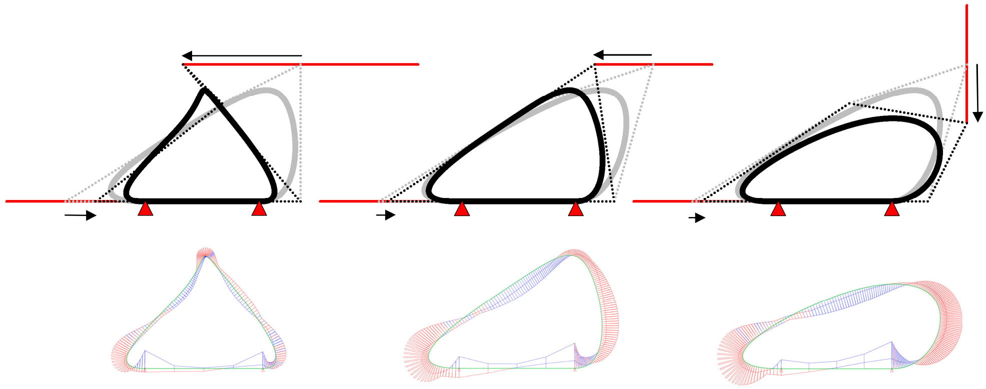
(a) (b)

Figure 7: The DRL10-pavilion under construction (a) and the adopted parametric description of its frames (b)

As a post-realisation research it was suggested to investigate if an optimal frame-shape exists that would meet the architectural intent. To do this a frame was generically defined using two control points at its supports, a further two to set the required re-entrant corners at the base, one fixed control point at top of frame to ensure minimal enclosed space, and a final control point to achieve the typical asymmetry of the design (Figure 7b). Although this method did produce a satisfying setup, as the control points act as magnets only, the frame-shape is not actually going through any of the intermediate control points. It is therefore a rather indirect method if one wishes to set boundary conditions to for example the minimal height or fix the area that the frame should enclose.

The applied loads were self weight and two typical wind-load cases with loads perpendicular to the building envelope: one uniform, the other trapezoidal ranging from -1 to +1. The Optima-module was used to run the optimisation, its target function being to minimise the critical bending across all load cases.

The first optimisation with large degrees of freedom led to a little imaginative symmetric shape enclosing a minimum amount of space (Figure 8a) that was far from meeting the architect's ambitions that included asymmetry, inclination and cantilevers. When manipulating the degrees of freedom of the variables the tendency to iterate towards a symmetric form was blocked off, and architecturally acceptable shapes were found (Figure 8b, c). As all iterations ended at a limit-value of a degree of freedom, it became clear that the resulting shapes were not overall optima. However the optimisation was meaningful as it balanced positive bending moment with an equal moment of opposite sign.



(a) (b) (c)

Figure 8: Form-optimisation minimising bending moments based on different degrees (shown in red) of freedom resulting in the smallest possible symmetric (a), narrow (b) and shallow (c) frame

In an attempt to enforce re-entrant corners and eccentricity, a minimum difference of the x-coordinate of the control points that set the re-entrant corners was imposed. Figure 9 shows that in that case eccentricity on the right side is minimized as far as the boundary conditions allowed it to, but it also increases the cantilever to the left in order to balance the right side.

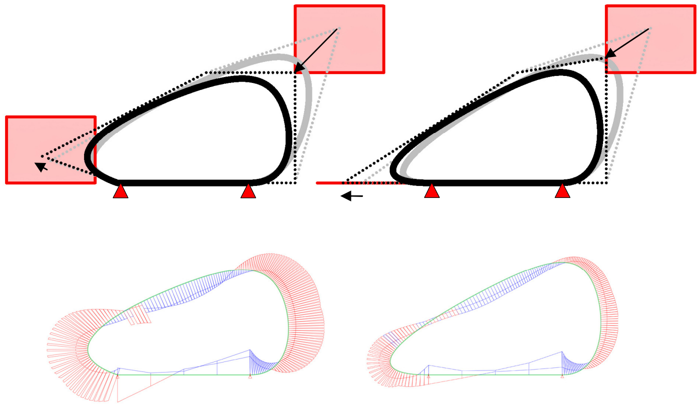


Figure 9: Two optimized frames based on different degrees of freedom with their resulting envelope of bending moments

5. Discussion

In early stages of structural design, the initial need is for a qualitative understanding of the structure's behaviour, followed by a quantification of relative improvements that are possible. It is accepted that free form designs are unlikely to be the most structurally optimal, yet the examples of the three presented methods show that minor changes could result in significant savings, for instance by reducing peak bending moments. Ideally such directions for improvement should be identified in the conceptual design stage. The three presented methods do this through heavily simplified parametric representations of structures where the structural form is the variable. The models are then used to explore a large number of design-instances (Method 1 and 2) and/or to find an optimum instance within the design space (Method 2 and 3).

Foreseeing the structural implications of a proposed change in the design is highly desirable in the early stages of design. This is achievable through a structural model based on geometrical parameters that is able to quickly generate and evaluate numerous instances of the generic design – provided that the proposed change is covered by the model and its assumptions and simplifications remain valid. For example the simplification of loading as uniformly or trapezoidal distributed loads becomes inappropriate for shape-dependent loadings like wind. The parametric model could also be used for a speculative exploration of the impact of parameters in order to actively steer the design development in a beneficial direction, yet the impact of variations to multiple parameters cannot be readily displayed through graphs and thus alternative means of representation need to be found to give insight to the designer.

Where a parametric exploration features numerous variables of unknown interaction, an automated optimisation could provide information on a set of values combining into a well-performing design instance, yet without the understanding or insight supporting it. For any optimisation to be meaningfully performed a clearly defined target function accompanied by constraints is indispensable, and it would in such a case be possible that the optimisation yields in new, surprising results that would not have been identified through conventional methods.

An optimisation could also be used to determine an initial combination of design values and explore the design-potentials around it. The case used to demonstrate Method 2 for instance indicated a favourable height of the cantilevering tip. Examples also revealed the possibility that optimisations could yield in inaccurate results or local rather than global optima. Also, parameter studies have highlighted regions of parameter-values where a particularly advantageous structural behaviour can only be achieved through specific conditions of geometry and loading. A sole optimisation will not highlight the sensitivity of the optimum to parameter-changes.

As soon as the design process has reached a more stable phase, which is probably only after the initial (e.g. competition-) phase, the earlier simplifications should be verified through a more extensive model incorporating the interaction between parts that were previously considered in isolation. As the design parameters will then be clear, the efforts to build a parametric model are more likely to be justifiable.

6. Conclusions

The paper presented a non-exhaustive overview of methods using discrete and continuous models used in the early stages of structural consultation on free form building designs. While simple in nature, it is demonstrated that parametric explorations at an early stage enhance the understanding of structural behaviour and enable manual or computational optimisation of structural form. The structural rationale that is thus activated in free forms contributes to the state of the art in design of shell and spatial structures.

Acknowledgement

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