

Architectural feedback in the structural optimization process

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ABSTRACT: This paper presents an interactive framework that balances visual exploration of design variations with their structural implications, in the case of the design of truss structures with aesthetic criteria. Based on the assumption that aesthetic design goals are not easily quantifiable, key elements for an interactive optimization framework are derived and implemented. Starting with an initial design, the user can visually assess interesting solutions, save them for later assessment, actively drive the optimization towards individual goals, re-initialize the optimization with a set of available solutions, or restart the design process. In addition, a criterion is introduced to measure the similarity of the shape of candidate solutions with respect to reference designs. The framework is then applied in the design of a truss tower. The effectiveness of the similarity criteria, as well as the ability of the user to drive the optimization towards specific design goals is demonstrated. The result is a framework that is conducive to the visual exploration of architectural variation coupled with structural constraints.

1. INTRODUCTION

The development of powerful CAD software has allowed contemporary architects to design geometrically complex shapes and forms that do not always correspond to the structural coherence of the building. As a consequence, the structural design of such conceptions are often carried out after the fact, by specialists who must execute the intent of the designer, which effectively disconnects the Vitruvian *firmitas* concept from the architectural design process [1]. In addition, this disconnect between design and analysis of the structure can lead to overly uniform and standardized structural designs, as well as a loss of the original concept in the translation of the design intent, or essence.

The typology of the tall building is especially susceptible to the disconnect between architectural intent and structural necessity. The structure of tall buildings necessitates rigorous adherence to structural principles, which are not always accessible to architects. However, at the same time, by virtue of their scale, tall buildings offer a prime opportunity to fuse structural logic and efficiency with architectural expression; “[w]hen the structure is disclosed on the façade in a logical manner in the spirit of an artist, structural expression contributes to the architectural look of the building, and thus the visual experience of the city” [2]. Moreover, as tall buildings are inherently material intensive to construct, savings in the structure of tall buildings can reduce their carbon footprint.

Therefore, considering the aesthetic, spatial and architectural qualities of a structural system simultaneously with the structural aspects, in the design phase, can yield a more cohesive and efficient building as a whole, than when the structure is only considered as a final step. Fazlur Khan’s structural design for the Hancock Center in Chicago was conceived in the beginning stages, in order to economically meet the height requirements. His design not only achieved new heights with greater efficiency, but also serves as a landmark for the city, in part, due to its

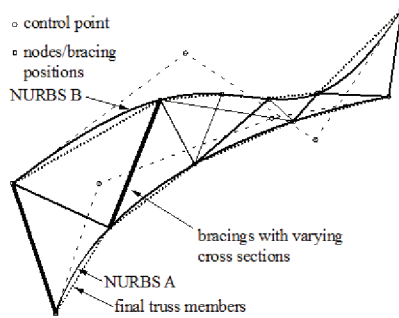


Figure 1. The general truss problem considered in this work: curved top and bottom chords connected with a variable number of bracings.

structural expression. Jean Nouvel's Tour Verre concept is another example that incorporates the structure as an architectural element. From the interior, the structure is viewed as securely embracing the space, while on the exterior, it can be seen touching the ground at various points, framing the entrance. The Willis Tower (formerly Sears Tower) in Chicago, by Bruce Graham and Fazlur Khan of SOM, and the World Trade Center Towers, by Minoru Yamasaki and engineers Leslie Robertson and John Skilling, are examples of tall buildings that, according to Guy Nordenson, "...integrate structure and form...because they were conceived at the outset as expressing the means and wonder of their structural art and achievement" [3].

In the case of curved structures, the original concept, in the design stage, may follow just two lines indicating an overall form. This initial sketch is known as a critical stage for many designers. The ideal shape may not be exactly determined, but is closely approached, as a non-verbal, non-quantifiable feeling, represented by rough sketches. At this stage, many considerations are occurring in the mind of the designer that are based on experience, intuition, personal preference, and instincts that simply do not belong to the realm of anything that can be known in the form of words or rules, long before the "choice of the curve" [4] can be made. It is this phase that must remain unhindered by rules, that a starting point of a curve can first be established, after which point it can then be improved. This way of sketching, the original form finding, can be referred to as the "thinking hand" [1].

For form finding driven by purely structural constraints, such as minimal stresses and displacements, powerful numerical tools, such as genetic algorithms (GA) with structural optimization techniques, have been introduced. The uncritical and uninformed use of such numerical tools can, however, lead to architectural designs that seem random and unpleasant, even though the structural soundness is guaranteed; "[m]inimal materials and costs may be necessary, but they are not...sufficient... [r]ather a third ideal must control the final design; the conscious aesthetic motivation of the engineer" [7].

So far, little attention has been given to incorporate aesthetic, or more specifically, architectural criteria, directly into the optimization process. Rather, mostly quantifiable and objective criteria have been used, such as for angle uniformity, the golden ratio, and free volumes [8], [9], [10]. However, there exists far more complexity to aesthetic criteria, which are highly subjective to the architect, and, therefore, not easily quantifiable [11]. As noted by Juhani Pallasmaa, "[b]eauty is not a detached aesthetic quality; the experience of beauty arises from grasping the unquestionable causalities and interdependences of life" [1]. In addition, the architectural design process is not a well-defined problem, but a "wicked" one, with constantly changing goals and constraints. Therefore, classic engineering optimization techniques are prone to failure when applied to the architectural process.

In order to assist the merging of structural responsibility with the architectural design process, in this research, an interactive numerical framework is proposed that can support the architect in the negotiation of the form between geometric design concepts and the formal structural requirements. In doing so, *firmitas* can be reintroduced into the design process, and intuition on the structural behavior can be built up during the early stages of the design.

As an example, in this research, the general problem of shape, topology and size optimization for a truss tower is considered. The geometry of the truss is defined by a curved chord envelope, which is described by NURBS (see Fig. 1). Shape optimization considers finding the optimal position of the control points that dictate the shape. Topology optimization deals with finding the optimal number, position and connectivity of the nodes between the chords. Finally, the objective of sizing is to find the optimal cross sectional area. A particle swarm optimizer (PSO) is used for the optimization process. The topology, i.e. connectivity of the truss, is represented in a matrix C , whose rows represent the nodes on one chord, while columns represent the nodes on the second chord, and its entries c_{ij} are

$c_{ij} = 0$ if nodes i and j are not connected, and

$c_{ij} = 1$ if nodes i and j are connected

The c_{ij} values are, therefore, binary, which effectively is treated by rounding towards 0 or 1.

The paper is organized as follows. The next section details the background for the tools used in this work. Then, Section 3 describes the proposed algorithm. Section 4 shows the interactive design of a truss tower. Finally, Section 5 concludes the paper and discusses future research directions.

2. BACKGROUND

2.1. Particle Swarm Optimization (PSO)

The particle swarm optimization (PSO) method is implemented as the optimizer tool. As opposed to GA, which is based on the natural selection process, PSO mimics the behavior of flocks or “swarms” searching for food or escaping a predator [18]. The advantages of PSO compared to the GA include a simpler setup, an often faster convergence rate, and computational efficiency, while still providing the same quality solutions [6]. See [19] for an extensive review on successful applications of the PSO method.

The general working of the algorithm is as follows. At each iteration k , a candidate solution (particle) in the swarm is described by a position $x(k)$ encoding a candidate solution, and a velocity $v(k)$ encoding the direction and magnitude of motion in the search space. The position of the particle for iteration $k+1$ is updated as [18]:

$$x(k+1) = x(k) + v(k+1) \quad (1)$$

and the velocity of the next iteration is found from

$$v(k+1) = w*v(k) + r_1*c_1(\text{PBest}-x(k)) + r_2*c_2(\text{GBest}-x(k)) \quad (2)$$

where PBest is the best position that the particle has encountered so far, and GBest is the overall best position that the swarm has encountered. The inertia weight w , and the cognitive and social factor, c_1 , c_2 , are settings of the PSO algorithm, scaling the influence of the respective terms, and r_1 and r_2 are uniformly distributed random variables in the range (0,1). Selecting PSO parameters that yield good performance has, therefore, been the subject of much research [12], [13], [14].

The goal of the optimization process is to minimize the objective value, typically the weight or volume of the structure for a given set of constraints. These constraints are added as a penalty to the objective function and are defined as normalized nonnegative values. Thus, the optimization problem is formulated as follows.

$$\text{minimize } f_{\text{obj}}(x) = \sum_i x_i L_i \rho_i + f_{\text{penalty}} \quad (3)$$

where x_i is a design variable reflecting the cross sectional area of element i , L_i is the length of that element and ρ_i the material density. The form of the penalty function in (3) is similar to [15]

$$f_{\text{penalty}} = f_{\text{Min}} \cdot \sum_i \max(g_i, 0) \quad (4)$$

where f_{Min} is the minimum objective value over all feasible solutions in the previous iteration, and g_i indicates a constraint function, which has to be formulated such that $g_i < 0$ if the constraint is fulfilled. Typical structural constraints are maximally allowed displacements and stresses, buckling constraints and natural frequencies. In addition, heuristic constraints, such as limits on the length of the members, or truss stability can also be imposed.

A heuristic constraint is defined to reflect the similarity of a design to reference designs: The approach is to compare the position and orientation of the NURBS at the bracing positions on the candidate solution to those on the reference design, as this is a necessary criterion for similarity. The position variables are (x,y) coordinates; for the orientation, the derivative of the NURBS is evaluated, resulting in (x',y') coordinates. These coordinates are gathered in vectors

$$xB = (x_1, x_2, \dots, x_N), \quad yB = (y_1, y_2, \dots, y_N) \quad (5)$$

$$x'B = (x'_1, x'_2, \dots, x'_N), \quad y'B = (y'_1, y'_2, \dots, y'_N) \quad (6)$$

for the candidate solution, and

$$xB_{\text{ref}} = (x_{1,\text{ref}}, x_{2,\text{ref}}, \dots, x_{N,\text{ref}}), \quad yB_{\text{ref}} = (y_{1,\text{ref}}, y_{2,\text{ref}}, \dots, y_{N,\text{ref}}) \quad (7)$$

$$x'B_{\text{ref}} = (x'_{1,\text{ref}}, x'_{2,\text{ref}}, \dots, x'_{N,\text{ref}}), \quad y'B_{\text{ref}} = (y'_{1,\text{ref}}, y'_{2,\text{ref}}, \dots, y'_{N,\text{ref}}) \quad (8)$$

for the reference shape. Then, the similarity measure is computed as

$$g_i = 0.5 (|xB - xB_{\text{ref}}| / |xB_{\text{ref}}| + |yB - yB_{\text{ref}}| / |yB_{\text{ref}}|) + \\ + 0.5 (|x'B - x'B_{\text{ref}}| / |x'B_{\text{ref}}| + |y'B - y'B_{\text{ref}}| / |y'B_{\text{ref}}|) - \text{LIM} \leq 0 \quad (9)$$

where LIM is a user-defined constant, representing how much room for exploration the algorithm has on the similarity. If any of the heuristic checks fails, a large penalty value is assigned, and the structure is not analyzed further. Otherwise, structural analysis is performed using ANSYS, a well-known engineering simulation software.

2.2. User Interaction Framework

Typical interactive evolutionary computation is performed by asking the user to assess the fitness of candidate solutions, for example, by ranking them [16]. However, this approach requires that the problem and its variables be well-defined at the onset of the optimization, which is not the case for the architectural design process. Few rules could be predictive enough to account for all possible design complexities, meaning they cannot be coded in advance. Moreover, architects must be able to create their own design without excessive digital interference, if the design is to maintain a unique character that is satisfying both to the creator and to those it was designed to serve.

Therefore, the aim of interactive optimization for architectural design should not be to simply generate solutions, which are then assessed by the architect. Rather, its objective is to use the available computational power in order to support the exploration of feasible design variations. For this, Candy and Edmonds identified three key features [22]. First, the user must be able to update the design rules, i.e. the constraints, easily during the process. Second, the user must be given support for the evaluation of the results, e.g. allow the user to ask “why or why not about the results”. Finally, the user should have the ability to compare results stemming from different constraint sets.

Therefore, it is proposed that an interactive optimization process for structural design has, but is not limited to, the following components:

1. use the initial design(s) of the architect
2. set constraints and ranges for design variables
3. visually assess solutions

4. drive optimization towards architect's design goals
5. keep track of all solutions for later assessment
6. support the iterative design process by easily allowing to update constraints and design objectives

Table 1. Data for truss tower design

Item	Value	Item	Value
Young's Modulus	210 GPa	Width at bottom, W_{bottom}	100m
Density	8000 kg/m ³	Width at top, W_{top}	20m
Maximal allowed stress σ_{all}	250 MPa	Maximal allowed displacement	$H/500 = 0.6\text{m}$
Wind loading at Top, F_{Wind}	10kN	Maximal bracing length	120m
Height, H	300m		

To incorporate these components, the following user interaction framework is proposed.

1. At the beginning of the process, the designer can draw the chords of the truss by means of a NURBS curve. The user could also import a design from another program, from which the NURBS structure is detected. This initial design is used as a reference for the similarity measure (9).

2. The designer can specify a) the amount of shape similarity (9) below which candidate solutions are penalized, b) the degree of influence of the visual assessment ("high", "medium", "low"), and c) the number of segments into which the NURBS is to be divided to create the truss.

3.—5. As new candidate solutions become available at subsequent iterations of the optimization, they are shown to the designer together with their weight, so that a comparison can be made. In addition, the current optimum, as well as the initial design, is shown. The user can then select preferred designs. A selected design is marked and saved for possible later assessment. In addition, in subsequent iterations, the similarity measure is evaluated for every saved design, and the best result is kept for the objective term. This allows the designer to update the design constraint dynamically during the optimization process, should the algorithm reveal an interesting solution. Finally, to effectively drive the optimization towards the ideas of the user, the weight of the structure is artificially reduced, and the objective function (3) updated as

$$f_{\text{obj}}(x) = (1 - \alpha) (\sum_i x_i L_i \rho_i + f_{\text{penalty}}) \quad (10)$$

where α quantifies the influence of the visual assessment, and its value is 5%, 15% and 25% for low, medium and high influence, respectively, as specified by the user in the previous step.

6. The user is given three choices to continue after the design selections: First, to proceed with the generation of the next candidate solutions; second, to restart using a selection of candidate solutions as initial designs (reseeding); or third, the designer can go back to the initial design of the NURBS and start over (restarting). This ensures an iterative design process.

The implementation of the algorithm is done in MATLAB using the PSO and NURBS toolboxes [20], [21], and has been validated with the design of a 10-bar truss structure [18].

3. APPLICATION: DESIGN OF A TRUSS TOWER

The user interaction framework is applied in the abstract design of a planar truss tower. Formal, i.e. non-optimized, requirements are a bottom width of 100m, top width of 20m, a height of 300m, a horizontal bracing at 2/3 of the height to mimic a platform, and the use of steel as the material. The tower is pinned at the bottom, and subject to gravity, as well as horizontal wind forces, which are applied at the bracing positions proportionally to their height. For each

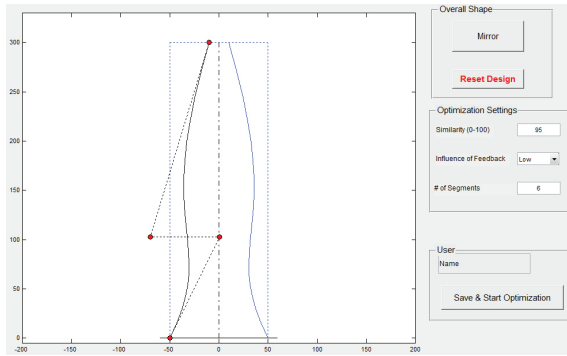


Figure 2. Screenshot of the initial interface where the user can design the profile of the tower, and define settings for the optimization

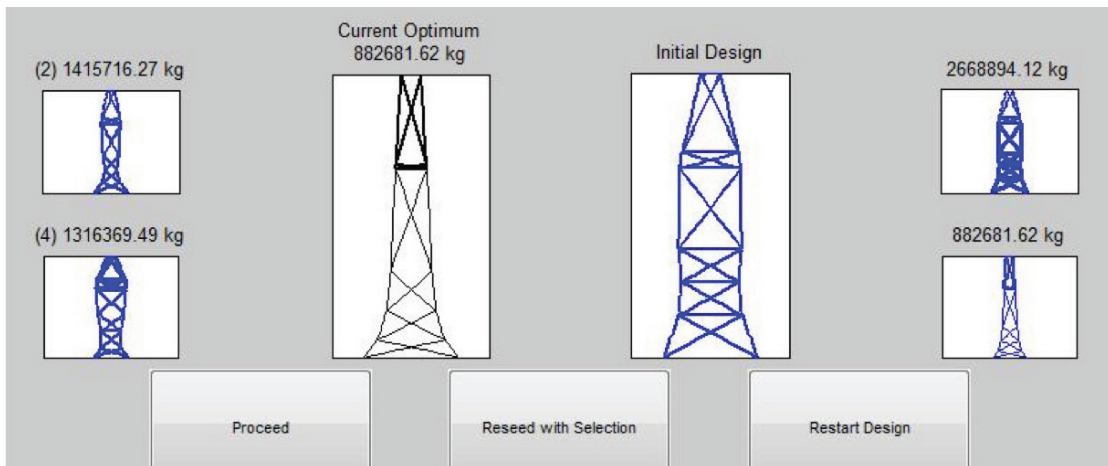


Figure 3. The user interface after a few iterations, showing candidate solutions on the left that the user can select, and previously selected solutions on the right.

member, S4 x 7.7 profile (I-beam) is used, i.e. sizing optimization is not performed. Buckling and member length constraints are considered as well. The initial number of segments on the profile is set to six. For this, three bracing positions are considered between the ground and the platform and one between the platform and the top. Thus, there are seven possible bracing positions. Table 1 summarizes the settings of the problem.

Figure 2 shows the initial interface, where the user can design the profile of the tower by means of a NURBS curve. Also, the user parameters on the optimization (influence of visual assessment and similarity) can be set. When this process is completed, the optimization process is initiated. A total of 10 particles are used.

Figure 3 shows the interface after a few iterations. On the left, the current candidate solutions are shown, from which the user can choose by clicking on the image. Only solutions that have passed the structural constraints of stress and displacement are shown. In the middle, the current optimum and the initial design are shown as comparison. Finally, on the right, all the designs selected so far are visible. In addition, the weight of each design is displayed above it, and the thickness of the lines in the plot is scaled according to the cross sectional areas. The buttons for proceeding, reseeding, and restarting are shown at the bottom.

Three design case studies are performed mimicking different types of architect-engineer collaboration. For all these cases, a cubic NURBS is used, i.e. the order of the NURBS is not varied, and the initial design with the reference bracing is shown in Figure 4a). Typically, the solutions converged after 50-100 iterations. In the first case, shown in Figure 4b), no designer interaction or shape similarity is applied, and, thus, the tower is purely optimized for weight without aesthetic considerations.

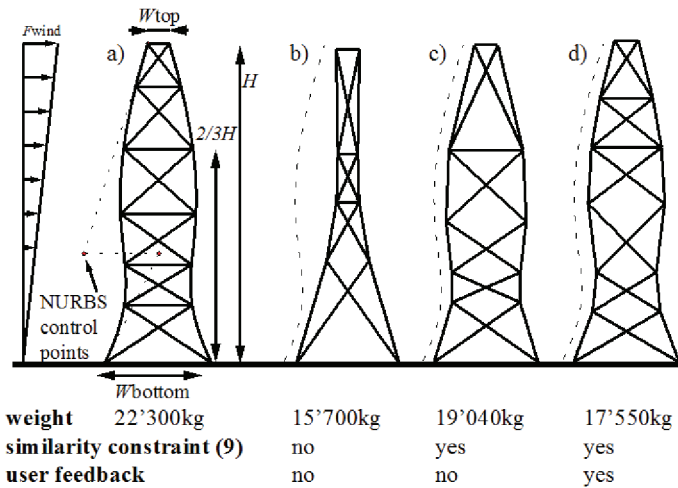


Figure 4. Results for interactive optimization of a truss tower. a) initial design, b) optimal solution without interaction or similarity goals, c) optimal solution considering the initial design, d) optimal solution with strong user interaction

In Figure 4c), the similarity constraint is set to LIM=100%, but still no user feedback is applied. This corresponds to the situation of an architect presenting a design to the engineer, and giving him the possibility to alter it within a limited range, e.g. only the cross-bracings, not the shape. It can be seen that the algorithm uses the bracing positions to create the curvature of the initial shape. This effectively demonstrates the use of the similarity measure (9).

Finally, Figure 4d) shows the case for strong user interaction. For this, again LIM=100% is set. In addition, equation (10) is used to update the objective function with $\alpha=25\%$ for the shapes that the user chooses. Clearly, the user's choices led the algorithm to converge onto a third solution, which has slightly less curvature than the initial shape. This demonstrates that the user was able to drive the optimization towards his goals, changing the constraint dynamically during the process. In addition, it can be seen that the weights for each tower are quite close to each other, confirming the possibility for effective structural optimization that does not sacrifice aesthetic considerations.

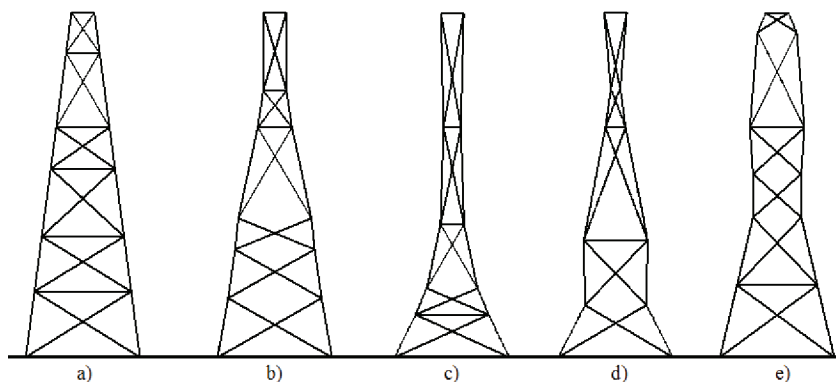


Figure 5. Examples of designs using the proposed interactive framework. a) Initial generic profile. b)- e) Results of four different users interacting with the software.

Finally, the capability of the framework to generate design variations is demonstrated. Four different members of the author's institute were asked to create a design from the same generic initial profile shown in Fig. 5a). The shape similarity constraint was set to LIM=100%, and

activated after the second iteration to avoid that the generic shape is used as a reference shape. In addition, only the latest selected profile was used as a reference shape. As can be observed in Fig.5b)-e) very different designs are obtained for each user, which resulted from the interaction of the designer with the software.

4. CONCLUSIONS AND OUTLOOK

A design framework has been proposed that allows for an interactive negotiation between form and structural requirements. The parts of the design problem which can be formalized, such as structural soundness, are carried out by numerical analysis. To deal with the “wicked” characteristic of the architectural process, possible variations of the design are presented to the user for visual assessment.

In addition, the key elements for a successful interactive design have been identified and implemented in a prototype system. The proposed framework has been applied in the design of a truss tower, successfully demonstrating the potential of interactive optimization using NURBS curves. The use of NURBS provides a flexible design tool, which easily extends to more challenging free-form geometry problems. In addition, it allows a natural way of drawing forms without the need for verbalizing or formalizing the underlying ideas of the designer.[1]

Future directions of this research include the integration with standard architectural design software, e.g. Autodesk 3DS Max or Rhinoceros (TM) as well as including additional variables in the optimization, such as program, energy performance, etc. The objective is to apply the proposed framework in the design of structural systems of tall buildings.

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