The design of novel roof trusses with shape annealing: assessing the ability of a computational method in aiding structural designers with varying design intent

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A study of roof truss designs conceived by architects and civil engineers as well as those generated with shape annealing, a computational design method for structural configuration, is presented. The purpose of this study is to assess the capabilities of shape annealing in (1) meeting the needs of designers with varying intent, and (2) presenting spatially intriguing, yet functional, structures that expand the range of designs considered in the conceptual design stage. An advantage of shape annealing for conceptual design is unbiased, directed exploration of the design space. The conclusion of this study is that shape annealing generates alternatives that appeal to designers with different purposes while providing insight into relations between structural form and function.

Keywords: computer-aided design, innovation, structural design, design rationale, conceptual design

In previous papers, shape annealing, a computational design technique, has been presented as a method for the configuration of optimally directed discrete structures[1,2]. This paper will assess the capabilities of shape annealing as an effective aid to structural designers through a comparison of roof truss designs proposed by six structural designers, consisting of three civil engineers and three architects, to designs generated by shape annealing. The study consists of three parts: (1) a presentation of the design rationale used by the participating designers to identify important design goals in conceptual structural design, (2) an exploration

1 Shea, K, Cagan, J and Fenves, S J 'A Shape Annealing Approach to Optimal Truss Design with Dynamic Grouping of Members' *ASME Journal of Mechanical Design* Vol 119 No 3 (1997) pp 388–394
2 Shea, K and Cagan, J 'Innovative Dome Design: Applying Geodesic Patterns with Shape Annealing' *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* Vol 11 (1997) pp 379–394

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of design models implemented in shape annealing that reflect the goals identified to computationally generate appropriate design alternatives, and (3) a comparison of the resulting shape annealing designs to those of the participating designers. Comparing shape annealing to human designers will allow us to evaluate the capabilities of shape annealing in modeling a range of practical design goals and generating structural forms that would not be conceived by human designers. The purpose in generating multiple design alternatives is to expand the number and range of designs considered by the designer in the conceptual design stage.

In order for the designs to be purposeful they must be appropriate to the design task and suit a designer's style. Since design preferences and goals change during the design of one structure and also among different structural design problems, a computational tool that can adapt to different design goals and problems is beneficial in suiting the varied requirements of structural design problems. The generality of shape annealing makes it an appropriate and effective tool for the dynamic nature of structural design by generating a variety of conceptual designs that reflect the desired design objectives and satisfy problem constraints.

The intent of this study is not to conclude that either humans or computers can design more efficient trusses but rather to compare attributes of designs conceived by both means, allowing us to explore the requirements of an effective computational tool for conceptual structural design. This design study was deliberately conducted such that individual designers were allowed to apply their own design rationale and style to the problem rather than being constrained to a specified design goal or set of goals. Taking this approach allowed designers to explore the problem in a natural way since specifying a common metric of design goals for both architects and civil engineers would be artificial. Although this approach does not allow us to make quantitative comparisons among designs, qualitative comparisons can be made about the design goals that various configurations achieve and the different ways that designs achieve the same goal. These qualitative comparisons can then be used to illustrate strengths and weaknesses of both computer-based design and the human design process allowing us to identify where shape annealing could best aid the designer.

1 Structural design

This study was performed to explore the capabilities of shape annealing as an aid to structural designers with different preferences as well as a tool for expanding their creative ability and problem insight. Design and design perception is based on a combination of insight, intuition and experience. In structural design, each designer has a different style that is founded in their knowledge of functional forms and their viewpoint of the importance of functional efficiency, economy and beauty as well as the relation among them. A civil engineer creates structural form to control physical effects, or forces, while an architect seeks to control space[3]. Following from the civil engineers' quest to control forces, they are primarily focused on functional efficiency and clarity as well as construction costs, or economy, resulting in preferences for conventional, uniform structural forms without ornamentation, which adds non-functional material. Civil engineers tend to also find beauty in structures that allude to natural forms since they are perceived to be structurally efficient. Conversely, an architect's attempt to control space results in primary design goals of artistic expression and visual impact with only a secondary goal of functional efficiency. Architects tend to have more variation in their aesthetic values since they are not always founded in functional efficiency alone allowing for greater latitude in the structural forms that are considered in the design process. In order to be effective, a computational method must support these varying preferences and design rationales used in the structural design process.

Varying intentions and preferences also play a role in design perception, which has been evident in the reactions of different designers to the designs generated by shape annealing. While regular, symmetric designs tend to please civil engineers, architects are usually unenthused. On the other hand, while a civil engineer's preference for the rhythm of conventional designs tend to make them cringe at highly asymmetric designs, the visual impact of asymmetries intrigue architects. These conflicting opinions stem from the different roles the two types of designers play in structural design. The design of a balanced structure can be achieved through an appreciation of both functional efficiency and visual appeal. Just as a conventional truss is unappealing to an architect for its lack of attention to visual impact, a novel structural form that lacks attention to physical laws is outrageous to a civil engineer. The shape annealing method will be shown to be capable of aiding both types of designers in generating structures that are derived from functional efficiency yet through the stochastic nature of the method allow aesthetic design goals to be satisfied as well.

A common structural design application for both civil engineers and architects is the design of buildings. Considering trusses for buildings, they are primarily used as structural support mechanisms designed purely for utilitarian purposes since in most cases a truss is not visible. The example in this study examines the design of an exposed roof truss, which allows the designers to explore both functional and visual components of the structural problem. A civil engineer still may decide to use a more conventional form viewing the design problem as one of function alone, but the architect

3 Billington, D P *The Tower and the Bridge: The New Art of Structural Engineering* Chpt 1: A New Tradition: Art in Engineering, Basic Books Inc, New York (1983) is given the latitude to view the problem from a visual angle while keeping the functional aspect of the problem as an aside.

To illustrate the range of structural forms that can be designed for a roof truss, a sample of trusses are shown in Figure 1. For this study, an architect submitted the design in Figure 1(a) while the more conventional design shown in Figure 1(b) was submitted by a civil engineer. Meeting the design intent of both types of designers, shape annealing was used to generate the designs shown in Figure 1(c) and (d). The details of these designs will be presented later.

In order to allow the reader to gain an understanding of how shape annealing structures are generated, a brief background of the method will be presented. Following, the specifications of the roof truss design problem will be described. Next, the solutions submitted by the designers will be shown along with their design rationale to identify significant design goals. Shape annealing will then be used for two purposes: (1) to optimize the geometry of the submitted designs, both shape and member sizing, and (2) to generate alternative topologies for a series of problem models that reflect the designers' objectives. Optimizing the fixed topologies proposed by the designers will explore the relationship between structural efficiency and form for traditional truss layouts while the generation of alternative topologies will illustrate the range of layouts appropriate to this design problem. The shape annealing designs will then be compared to the human designers' designs to evaluate the advantages and disadvantages of both, as well as the integration of the shape annealing method in the structural design process. Finally, a critique of the shape annealing designs by the participating designers will be discussed to explore the value of the generated designs and their capacity to expand the problem insight of designers.

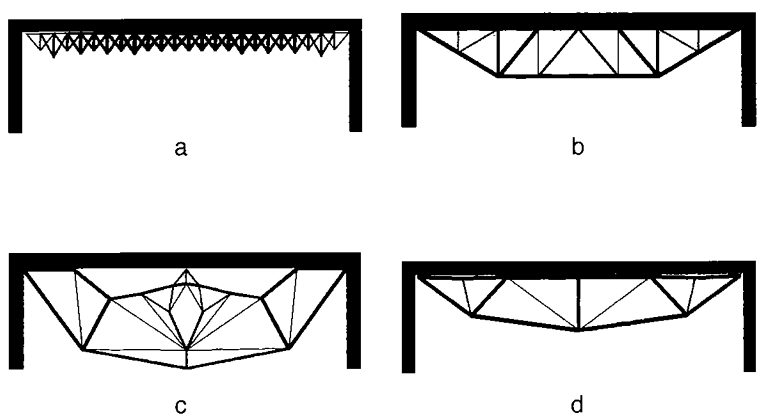

Figure 1 Illustrative comparison between human designers and shape annealing: (a) design proposed by an architect; (b) design proposed by a civil engineer; (c) novel design from shape annealing; (d) conventional design from shape annealing

2 *Shape annealing method overview*

In order to give the reader an appreciation for the origin of the shape annealing designs, a brief description of the method will be given. The shape annealing method is a design technique that combines a generative grammar with directed stochastic search using simulated annealing[4,5] to produce optimally directed designs. A shape grammar is a means of representing the relation between form and function in structural design through the specification of design transformations that define a language of structures[6]. Since the number of structures in this language is quite large, directed stochastic search is used to drive the generation of purposeful designs that satisfy a specified set of design goals and constraints. The style of the generated structures is thus a product of the structural language defined by the shape grammar and the optimization model that quantifies the tradeoffs among design goals and constraints. Since designer preferences are often unique, the optimization model and the structural language can be modified to generate structures with different purposes and spatial styles. The shape annealing method has been applied to the layout of discrete structures, both planar and three-dimensional, that reflect the design goals of efficiency, economy, utility and elegance[1,2,7].

The shape annealing algorithm works as follows: first, an initial structure is generated from a minimal connection of truss members between the applied loads and support points of the problem specification. Next, the structure is loaded and analyzed using the finite element method. The cost function is then evaluated from the specified optimization model, which can include models for structural behavior, geometric constraints, economic considerations and aesthetics. The initial design is automatically accepted. Next, a rule from the shape grammar is applied to the structure to create a new design that is then analyzed and its cost is calculated. The costs of the new design and the previous design are used in the simulated annealing algorithm to determine whether to accept the new design or revert to the previous design. A better design is always accepted while a worse design may be accepted based on a probability function[8]. A rule from the shape grammar is then applied to the accepted or previous structure to create a new design and the process continues iteratively until the annealing schedule terminates or the design has converged. The resulting design is then presented to the designer in the form of a description of topology and geometry, including both the location of joints and the sizes of members. At the designer's discretion, members in the design that have the minimum allowable cross-sectional area can be removed as long as the structure remains stable. However, a designer may choose to leave these members in the design since they add negligible mass and may provide additional visual benefits.

4 Kirkpatrick, S, Gelatt, Jr, C D and Vecchi, M P 'Optimization by Simulated Annealing' *Science* Vol 220 No 4598 (1983) pp 671–679

5 Swartz, W and Sechen, C 'New Algorithms for the Placement and Routing of Macro Cells' in: *Proceedings of the IEEE Conference on Computer-Aided Design* Santa Clara, CA, November 11–15, IEEE proceedings: Cat No. 90CH2924-9 (1990) pp 336–339

6 Stiny, G 'Introduction to Shape and Shape Grammars' *Environment and Planning B* Vol 7 (1980) pp 343–351

7 Shea, K *Essays of discrete structures: Purposeful design of grammatical structures by directed stochastic search*, Ph.D. Dissertation Carnegie Mellon University, Pittsburgh, PA (1997)

8 Metropolis, N, Rosenbluth, A, Rosenbluth, M, Teller, A, and Teller, E 'Equation of State Calculations by Fast Computing Machines' *Journal of Chemical Physics* Vol 21 (1953) pp 1087–1092

The shape grammar used in the generation of roof truss designs for this study is shown in Figure 2 where the design transformation types are divided into geometry and topology. The allowable geometric transformations include the shape transformation rule that changes the location of a single joint in a design and the size transformation rule that changes the cross-sectional area of a single member. Together these rules with the shape annealing algorithm perform shape and sizing optimization of a structure with a fixed topology. Topology exploration then occurs using the topology transformation rules that take a triangle within a design and transform it into a new configuration of triangles. A different rule is applied depending on whether the division within the triangle is associated with a free or fixed point. A free line, denoted by the label 'f', indicates an exterior line in the design. The lines in the shape grammar represent truss elements. Note that the topology rules are created in pairs, except rule 5, so that any transformation can be reversed. Rule 5 is its own reverse. Example topology rule applications are shown in Figure 3.

The configuration of trusses using the shape annealing method is quite different from the process generally used by a designer. Rather than relying on knowledge of standard truss configurations, shape annealing uses topology transformation rules to add and remove members based on principles

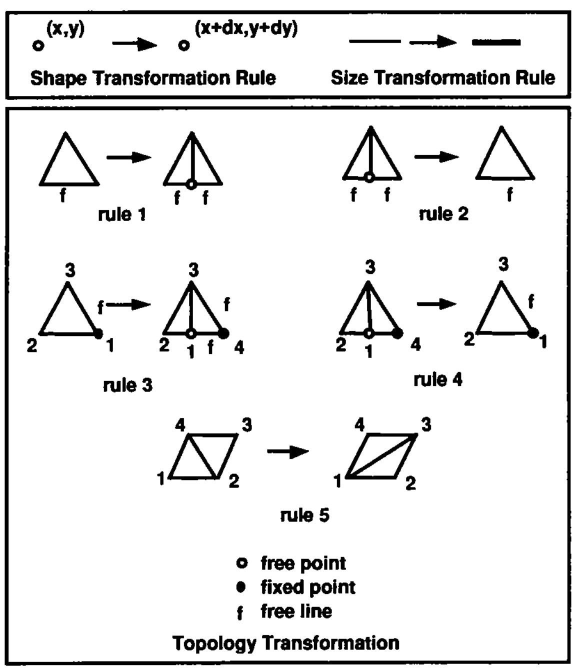

Figure 2 Planar truss shape grammar

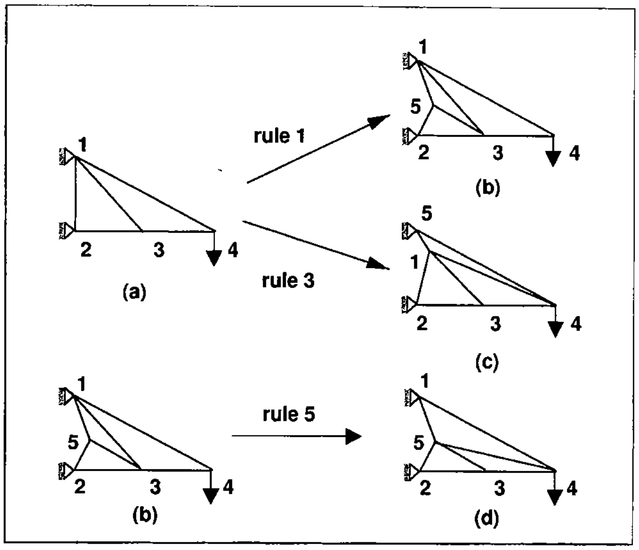

Figure 3 Example of rule applications

of simple truss design. Shape annealing is a form-driven strategy where the structural form is modified independent of behavioral implications. The function of a design then follows the form generated and in this study a design is selected in the optimization based on the functional evaluation alone. Note that an optimization process is used as the directed search method; the purpose of shape annealing is to generate alternative solutions of similar quality from a large space of designs, and for those solutions to be as good as possible rather than just feasible.

Even though in this paper the optimization is independent of the explicit structural form, the stochastic nature of the method as well as tradeoffs among design goals lead to the generation of spatially innovative structures. However, the optimization model can be extended to include aesthetic models[7].

The advantage of computer-based conceptual design with shape annealing is that the resulting design is a direct derivative of the allowable forms described by the shape grammar and the design goals formulated in the optimization model. While preconceived notions and numerous competing design issues constantly influence a designer, computational design supports unbiased exploration for optimally directed functional forms that reflect the set of modeled design goals. Optimally directed design is an approach to design optimization that directs the design generation towards the numeric range of a global optimum. In the current shape annealing implementation, the focus is on the generation of conceptual designs. Detailed design considerations such as fabrication, maintenance and durability are not included in the design evaluation and are left for the designer to assess. However, any important criteria that can be articulated can be included in the computational analysis. While shape annealing is not intended to replace the designer, the aim is an effective tool to enhance designer capabilities by presenting alternative concepts that would be difficult to conceive by hand. Additionally the generation of multiple design concepts that are optimally directed and satisfy the design goals and constraints of a given problem specification could spark creativity and lead to new insights about the design problem.

3 Problem statement

The design problem used in this study is based on the open truss system found in the aquatics area of the University Center at Carnegie Mellon University. The following specifications present the information given to the designers. The problem posed entails designing a truss system to support the roof using the simplified model shown in Figure 4. The placement of the structure in the building is such that the structural system is exposed and visible from both inside the room and through windows in a dining area that overlook the room (Figure 5). The current design uses eight identical, standard inverted Warren trusses to support the roof (Figure 6). In this study, the designers were asked to either submit one design to be used for all eight trusses or different designs that could be interspersed. In both cases it was assumed that lateral cross bracing between trusses would be provided. The designers were also asked to keep the proposed structure below the roofline to eliminate the effect a new design could have on the form of the exterior roof. An assumption was made that the applied load is uniformly distributed across the length of the truss and is attached at the points where the roof and the truss meet. The walls at the two ends of the truss are assumed to be load bearing. The applied load was calculated

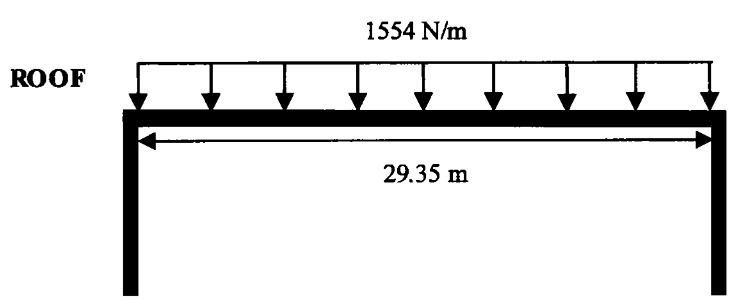

Figure 4 Roof truss problem

Figure 5 University center aquatics area

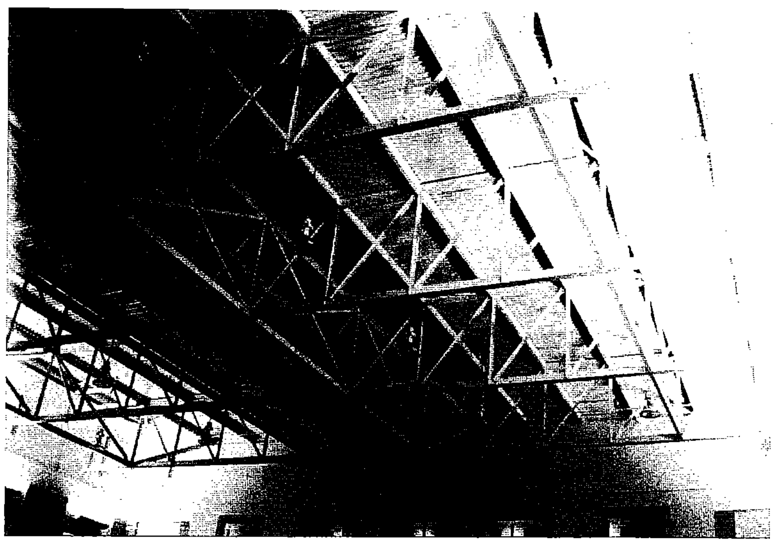

Figure 6 Current roof truss system

from a combination of the prescribed dead load (weight of the roof) and live load (snow and rain) given by the structural designer of the current truss system. The material used for the truss was structural steel ASTM-A36 with Young's modulus, E, 206 700 MPa, mass density, ρ, 7850 kg/m^2, and allowable stress in both tension and compression, σ_a, 111.6 MPa ($.45_{\sigma y}$).

4 Designs proposed by human designers

This section will present the roof truss designs submitted by the group of six participating designers, of which three are architects and three are civil engineers. The participants were given the problem statement described in section 3 and asked to submit a design along with their assumptions and criteria used when formulating their solution. The designers were not told to design a truss for minimum mass but were left to interpret the problem statement and impose their own design goals and personal style, although it was mentioned that eight trusses would be needed. The designers were also told that the submitted design could be shape and size optimized if so desired. While no designer wanted their design shape optimized since this could drastically change the appearance, all of the architects wanted their design sized indicating their role as creators of form and not function. Conversely, the engineers submitted their designs sized and did not request size optimization perhaps since they wanted to keep the particular shape member they had chosen or wanted a uniform size member to be used. While shape annealing is capable of generating designs with a limited number of distinct sizes[1] this option was not considered in this study.

The designs submitted are summarized in Table 1 along with a description of each designer's rationale for selecting the proposed structural form. All six designs that were submitted are based on familiar truss styles: three are variations of Warren trusses, two are variations of Pratt trusses while one design is a tensegrity (tensional-integrity) truss. The design rationale listed identifies important design goals in the conceptual phase of structural design for the participating designers and fall into four categories: efficiency, economy (which includes fabrication and building costs), elegance, and durability. Comparing the designs submitted by civil engineers to those submitted by architects, while the civil engineers submitted traditional, utilitarian designs, the architects submitted designs motivated by the visual impact of the structure from either the inside or the outside of the building. The architects' original drawings are shown in Figures 7–9 to best illustrate the visual nature of their designs.

Since efficiency always plays a role in structural design rationale, either as a primary or secondary goal, all but one of the submitted designs were optimized for efficiency as an illustrative measure in using shape annealing to indicate the level of structural efficiency of a proposed layout. One design, the design submitted by Architect 2, could not be optimized since it consists of multiple materials and the design rationale would be considerably altered if a uniform material were imposed. The optimization model used for functional efficiency minimized mass, or material cost, subject to behavioral constraints on stress and Euler buckling. Additionally, a

Table 1 Summary of submitted designs

Designer	*Truss Style*	*Design Rationale*
Civil Engineer 1	Warren	• assumed horizontal top chord • considered depth variation or bowed string truss unattractive • found the rhythm of a Warren truss attractive • preferred 60° inclination angles • preferred square tubes for attractiveness and durability • preferred uniform tubes that only vary the inside dimension • considered fabrication of joints
Civil Engineer 2	Pratt	• designed for behavior and efficiency
Civil Engineer 3	Warren with verticals	• used a rule of thumb that the length of upper chords should be 6–12 feet • considered practical depths to be 1/8–1/12 span • chose 45° diagonals to keep joints aligned • desired an even number of panels • reduced the number of connections by removing the bottom verticals • noted that the fabrication of joints effects the choice of member sizes
Architect 1	tensegrity	• derived from Buckminster Fuller's tensegrity (tensional-integrity) patent • noted fabrication considerations
Architect 2	Pratt	• changed problem specification from an interior roof truss for a flat roof to an exterior roof truss • used a rule of thumb for the depth ≈ 1/ 24 span but increased for ease of detailing • used a combination of steel and glass for even light distribution • considered weather protection since the truss is now on the exterior of the building
Architect 3	Warren	• chose an arched design to allow for a shallower depth in the center to improve the site line from the windows that overlook the pool

geometric obstacle was placed below the designs at approximately one-sixth the span, chosen by relaxing the heuristic suggested by Civil Engineer 3, to constrain the depth of the truss. Two design variable cases were considered: (1) varying member size only, and (2) varying member size and the planar location of joints not attached to the roof. The results of the optimization are shown in Figure 10. The design submitted by Architect 1 was modified to include a top structural member, rather than a non-structural membrane as specified in order to make the design stable. This alteration results in a transformation of the truss type from a tensegrity truss to a Fink truss but maintains the design intent of horizontal compression members and crossing tension members.

The shape optimization for efficiency of the submitted designs reveals two observations: (1) all submitted trusses become a bowed string shape

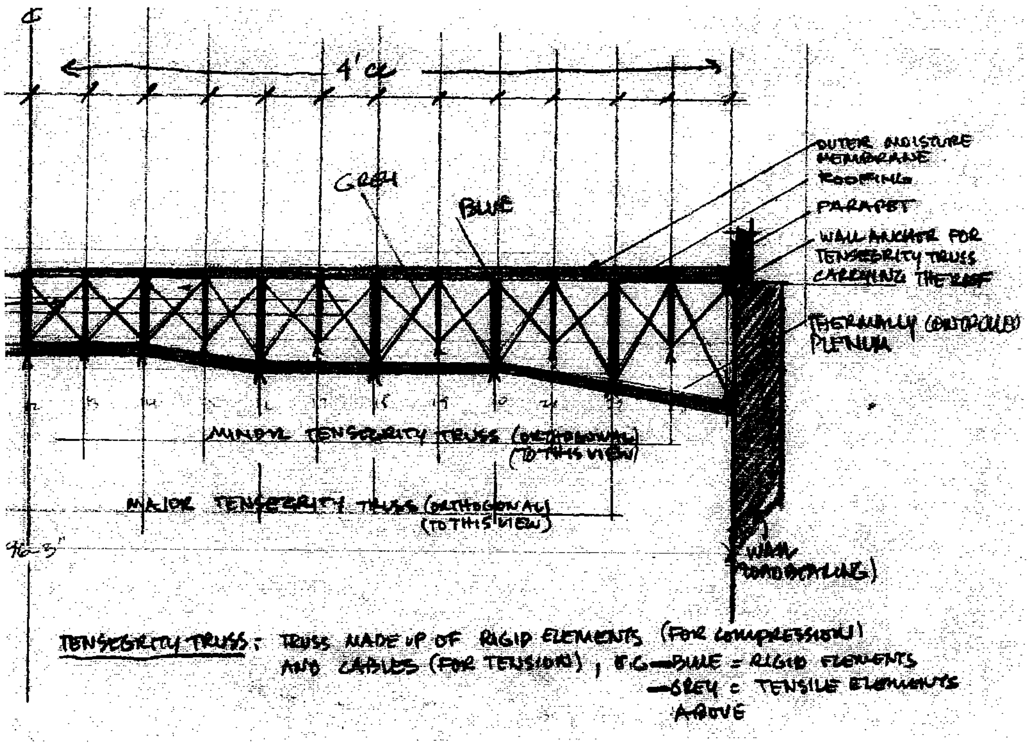

Figure 7 Architect 1

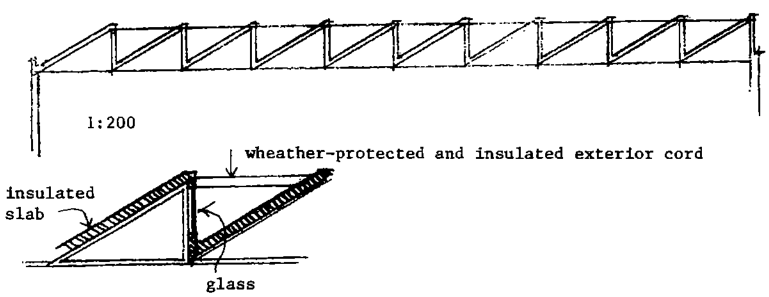

Figure 8 Architect 2

(Warren or Fink) and (2) a Warren truss is more efficient than a Pratt for the specified loading. The one Pratt truss submitted by Civil Engineer 2, was the best size optimized design of the ones submitted, but converts to a Warren truss when shape optimized. Thus, if a horizontal lower chord is desired a Pratt truss is an efficient choice, but given the latitude for depth variation, a Warren truss is more efficient. Shape optimization was also useful in indicating that, for efficiency purposes, too many members were used in the design by Civil Engineer 1. Due to the large number of elements in the design submitted by Architect 1, shape annealing found a

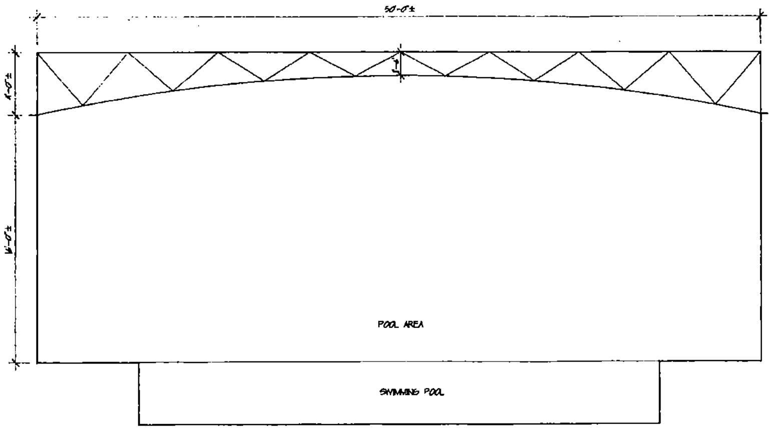

Figure 9 Architect 3

size optimized design that is lighter than the shape optimized design. In this case, shape optimization could be performed again with a larger number of iterations but is not shown here as it would be an unfair comparison to other designs. Integrated into the design process, similar explorations of the relation between structural efficiency and form could provide feedback to the designer concerning assumptions about efficiency of conventional topologies for the problem at hand. While shape annealing can be used for shape and sizing optimization the advantage of the method that will be illustrated is the generation of alternatives to standard layouts that reflect the design goals of the participating designers.

5 *Designs generated with shape annealing*

We have seen how designers have approached the design of an exposed roof truss and will now explore the capabilities of shape annealing in generating novel solutions to the same design problem. A novel or innovative structure in this paper is defined as a structure that is not a conventional truss layout (Warren, Pratt, Baltimore, etc.). Using design criteria detected in the design rationale of the human designers, six different problem models of the design problem were formulated. Shape annealing was then used to generate design alternatives for each of the six problem models to form a range of design styles that reflect the designer preferences and also adhere to the functional constraints of the problem. The material specifications and constraints given in section 3 were used along with a specification for a round tube member with a ratio of diameter to thickness equal to 10 for all problem models with continuous sizing.

All structures generated took into account structural efficiency, that is the minimum mass required to meet stress and buckling constraints. Additional design considerations included in some designs were economy, imposed preferred the asymmetric designs for their uniqueness and expressiveness. One architect favored the extremes of the designs and singled out the design in Figure 11a for its uniqueness and the design in Figure 13b for its minimalist expression. It was also noted that the designs without a horizontal top chord could be used to create interesting roof contours. In contrast to the engineers, the architects were not adverse to using the deeper trusses in Figures 11, 15 and 16 and were captured by the effect that would be created when looking through the structure from the upper windows. While the evaluation of structures for visual goals is very subjective some commonalties were found. The symmetric innovative designs, especially the design in Figure 14b for its simplicity but unconventional form, intrigued most designers (engineers and architects).

It was noted by many designers that there are considerations (fabrication, maintenance, durability) that go into a practical design, some of which were noted in the design rationale portion of Table 1, that were not modeled explicitly in the shape annealing method. Some of these considerations can be incorporated in the problem model, such as the spacing between load points, or in the optimization model, such as minimizing the number of connections in the structure. For this particular problem, roof truss design, the cost of connections is not as great a factor as in larger scale designs such as bridges, and thus connection cost was not considered. Since the purpose of the current shape annealing implementation is to provide conceptual design alternatives and not perform detailed designs, many of these considerations are left for the designer to evaluate when assessing the set of generated designs. While we did not include design issues of manufacturing and construction, any important criteria that can be articulated can be included in the optimization model.

This study has presented a simple structural design problem that would generally be considered routine and explored alternative solutions. An extension to the problem is the design of eight different trusses, all with the same function but different spatial form, to support the roof. This variation of the design problem turns a utilitarian structure into a structure that adds interest to the surrounding space. Although it was mentioned to the designers that eight trusses would be needed to support the roof, no designer submitted more than one design. Shape annealing can easily generate a range of similar quality solutions, while for a designer, conceiving multiple structures that serve the same purpose can involve much expense. Once the problem is modeled, the only costs of generating alternative solutions with shape annealing are computation time and further assessment by the designer. Thus, it is conceivable that eight different trusses could be used to support the roof and perhaps provide for maximum visual impact.

7 *Conclusions*

Structural design is moving towards the design of intricate configurations that are only conceivable with the aid of computers and integrated manufacturing techniques. The intent of shape annealing is not a structural design tool that replaces the designer but rather one that aids the designer by providing new possibilities for structural forms that may enhance their creativity and insight. This study has presented designs conceived by structural designers, without the use of computers, and the design goals that were used in their conception. These design goals were then modeled in shape annealing and used to generate both conventional and novel, functionally efficient structures. The generation of both types of structures makes it possible to satisfy both the architect's preference for visual impact and the engineer's preference for functional efficiency and clarity. The results of this study illustrate that shape annealing is capable of generating multiple, spatially innovative solutions to a standard truss design problem that efficiently achieve the design goals of conventional truss styles. The resulting essay of structural forms provides design alternatives for the designer to investigate further to create a detailed design that takes into account considerations such as fabrication, maintenance and durability.

The advantage of computer-based conceptual design is that a design is not restricted to intuition based on knowledge of standard forms, but rather can be generated as an innovative form based on the evaluation of imposed design goals. The disadvantage is that design goals are often difficult to model computationally. While human designers through their intuition, experience and knowledge can very quickly come up with satisfactory solutions, it is this knowledge that often hinders them from moving freely within the space of design alternatives. Thus, the combination of computational methods for the design of novel yet functional forms and human designers to assess these forms in the context of more extensive design goals can make an effective design team for creating innovative, feasible structures.

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