SHAPE CONTROL IN RESPONSIVE ARCHITECTURAL STRUCTURES – CURRENT REASONS & CHALLENGES

Tristan d'Estrée Sterk
The School Of Interactive Arts & Technology, Simon Fraser University, Canada
tsterk@sfu.ca

Abstract

Shape control within architectural structures is a natural extension to the practice of engineering and architectural design. The knowledge needed for this builds upon two well understood foundations: 1) the long existing knowledge that building performance and function are intimately connected to the shape of built spaces; and 2) the relatively new idea that embedded computational systems may be employed to control devices in useful and beautiful ways. When combined each type of knowledge can be used to further architecture and engineering at both theoretical and methodological levels. Structural shape control is of major interest within architecture because it is the primary ingredient needed to produce building envelopes that change shape. Structural shape control also currently represents a major technological and methodological stumbling block for architects, posing many challenges that have theoretical and practical origins. Theoretically, responsive architectural structures demand a re-evaluation of existing notions of space making. Practically these systems demand a re-evaluation of construction and design methodologies across both engineering and architectural practice.

Introduction

One cannot understand the relevance of shape control within architectural structures without coming to grips with the theoretical and practical position that designers find themselves in today. Shape control within architecture is significant because it provides a series of new technologies and methods that architects can apply to realize current theoretical positions – positions that have until now struggled to find any built resolution.

Theories represent the highest type of knowledge used within architecture. They provide specific knowledge that is distinct from the knowledge captured within methodologies or styles. Theories are used to build meaningful relationships between building forms and existing visions of the world. The values that underlie a significant portion of architectural design today have been undeniably shaped by general system theory. In the 1950's, system theory fundamentally changed the understanding that architects had of the world. The change was significant because it led architects to question concepts of space, structure, and time. Concepts of 'rationality' were also challenged.

General system theory demanded that the profession of architecture recast the assumptions that it had previously made about space and the relative influences people had over it. New more sophisticated models of our relationship to space were produced which, in turn, lead architects to question the way they designed for people. Though a gradual shift away from simple models of space, time, and rationality, new values and design goals resulted. It is from within these developments that feedback became a tool for use within architecture. As a mechanism, architects discovered that feedback could be incorporated directly into buildings via the use of responsive systems and that these systems would enable spaces and people to enter into a dynamic relationship. With this shift the tradition of modernism within architecture was slowly eroded, until in the mid 1960's, responsive systems became a favorite topic of the discipline. Unfortunately this movement was short lived. It came to an end in the mid 1970's as architects struggled to build the computational and structural systems needed to implement their new architectures. By the 1980's the idea for using responsive systems within buildings had completely transferred from architecture into the domain of engineering.

Engineering precedents for the use of adaptive structural systems are varied and include now commonly known systems such as mass dampeners, piezoelectric structures, actuated tensegrity systems and deployable structural systems. References for the use of actuated tensegrity systems can be found within aeronautical, marine, space, and civil applications. Namesake works for other types of adaptive structures also exist with Chuck Hoberman's spheres providing one example. These precedents form an important part of the practical knowledge currently available for the development of shape control within architecture. It is worth quickly mentioning that this practical wisdom is encapsulated within methodological knowledge. Methodologies provide designers with ways to attack design problems and realize solutions against higher-level goals. Within architecture, methodologies typically constitute inside-out or outside-in approaches to design. Within engineering, methodologies constitute approaches for calculating how a particular element will perform within a larger system. Because shape controllable structures and building envelope systems are currently unsupported by architectural design methodologies, engineering methods provide an important starting point for the development of new types of architectural knowledge.

The Role Shape Change in Architecture

The role of architecture and our relation to it was most elegantly described by Charles Eastman forty years ago when he wrote "The ethic of modern design is to take human activities as given, without constraints, and to create and environment which maximally supports them"(Eastman, 1972). Today, environmental concerns play a more important role within design so this focus has shifted slightly. The role of architecture at present can be more accurately described as to support human endeavors while using the minimum number of resources throughout the life of a building. This includes minimizing the resources used within construction and lifecycle processes. Responsive architectures help achieve this goal by finding best-fit formal solutions to both user activities and environmental changes. They also may help reduce building mass and embedded energy costs.

Architects have always known that the shape of a building is directly related to the way it performs. The way it heats and cools, the way it ventilates, as well as the way loads are transferred are all intimately related to the shape of an envelope and the spaces it encloses. It is clear that shape control within architectural structures possess enormous potential for producing new classes of buildings that adjust to support user actions while expending the minimum in resources. For example if a space needs to be heated through a winter night the height of a ceiling should be reduced to minimize the energy required to maintain a comfortable temperature within the space, while on a sunny winter morning, raising the ceiling and letting it track the movements of the sun should occur to assist direct sunlight in penetrating and warming a space. If spaces need to be ventilated the same building envelope should change shape to produce high and low pressure zones around the building. These pressure zones can be used to encourage higher ventilation rates though openings, or alternatively if the wind is too strong the building might reduce its aerodynamic profile to minimize harmful live loads caused by the same wind. It is here where the relationship between user comfort, building envelope, and the natural environment become most obvious. Building envelopes clearly mediate between our needs and the natural environment. Responsive building envelopes have an advantage over traditional building envelopes in that they may actively use several aspects of the natural environment to condition spaces. Responsive building envelopes also transmit loads in ways that traditional buildings cannot. They can help minimize unhelpful or dangerous loads and they can enable spaces to cooperate with air conditioning or other systems that support occupant needs.

Though similar, the methodologies that architects need to produce these types of buildings are not the same as those used by engineers. Architects require cladding methodologies as well as response methodologies that can adapt to subjective spatial desires as well as to rigid structural criteria. Subjective desires include aesthetic, psychological and environmental factors such as comfortable ranges of temperature, lighting and acoustic performance. To construct systems that respond to these desires, control mechanisms that are capable of building partial user models are required.(Sterk, 2006) These are contextual models that capture three types of input, environmental data, users activity data, and data about when users correct the system. Many outstanding challenges exist. To date methods for constraining subjective shape changes so that safe structural limits are not exceeded have yet to be developed.

These changes are made possible by recent developments in computing and engineering knowledge. Above and beyond structural and architectural abilities they demand knowledge of distributed computing processes, network structures and synchronization, control theory, intelligent systems and learning within AI. Methods for networking responsive structures are especially significant because through coordinating different shape control systems larger environmental gains should become feasible. Methodologies that preserve the private information of individuals who live within these new types of spaces are as critical as scalability, robustness, elegance and simplicity.

Essential Characteristics Within Structures

The essential characteristics of structural systems used within responsive building envelopes and exoskeleton frameworks are: 1) they must have controllable rigidity; 2) they must be lightweight; and 3) they must be capable of undergoing asymmetrical deformations. These characteristics work together to provide the most robust and flexible outcomes. They form a core set of principles that can be applied in the development of all successful responsive architectures. The following paragraphs explain these principles and methods for achieving each within built structures. Because actuated tensegrity structures are ideal at meeting all of these needs special attention will be given to their use.

The principle of controlling rigidity within responsive structures is clearly described by Brian Culshaw within a book called Smart Structures And Materials. Culshaw suggests that the key feature to any responsive structure is its ability to alter its stiffness rather than strength. “In most cases the adjustable strength aspects of the structure will involve more material, more weight, and certainly more complexity than the more simple structure designed to operate under the full range of loading condition.”(Culshaw, 1996) By controlling rigidity, load transmissions may be directed very naturally by localizing actuation to particular structural regions that require stiffening or softening. Softening results in the reduction of load transmission, while maintaining rigidity helps it. Likewise by controlling how soft particular parts of the structure are, different shapes will emerge. Within these types of systems very elegant dialogs between shape, load transmission, and rigidity result. Actuated tensegrity systems are ideally suited to producing these types of dialogs and do so very naturally when actuators are placed within key structural locations. Actuator placement has two important characteristics. Firstly actuators must be placed in areas to preserve the purity of a tensegrity structure. Secondly they must be placed to ensure that the control systems needed to drive them are distributed in sensible, easy to understand, and efficient ways. The ideal location for actuation also varies depending upon the class of tensegrity structure being used.

Lightweight structural solutions are also significant to the development of building envelopes that have the ability to change shape. The overwhelming trend within the engineering of structures has been the increase in our ability to produce lighter and lighter, robust structures. By using fewer materials to transmit loads and by controlling deflection in new ways engineers have managed to completely change construction methodologies. The development of actuated structures has added to this trend. For architecture, lightweight structures are important because they play a crucial role in changing the types of spaces that architects can design. They enable larger spans, more open interiors and more transparent envelopes. For shape change lightweight structures are also significant because they enable greater degrees of motion at smaller actuation costs. Tensegrity structures use the minimum amount of mass to transmit loads because they separate tension from compression within distinct members. This enables all tensile forces to be identified and designed as mass efficient cable systems.

Perhaps the most interesting of the three essential characteristics are those to do with an ability to change shape asymmetrically. Asymmetrical changes are important within architecture for two fundamental reasons. Firstly because building envelopes are, by the nature of how they sit within an environment, never exposed to the same environmental conditions from one face to the other. Two clear examples of this can be given: those of lighting and ventilation. Light strikes buildings directionally. Within natural and built environments it comes from the direct sun or reflections from adjacent surfaces. As such, lighting conditions are never the same on different sides of a building. Likewise, air pressures also vary across the different sides of a building from windward to protected faces. From these two simple examples it is clear that any building aiming to take advantage of shape to condition its internal spaces must be capable of responding asymmetrically. This point is further compounded. Consider, for example, the potential for adjusting building forms to enable the tracking of sun movements or the dodging of wind. The second reason why building envelope systems and their structures need to enable asymmetrical shape control is to cater to dynamic changes in the way loads are transmitted through a building. Remembering that shape control is closely related to structural rigidity, it becomes obvious that in order to produce efficient structures that monitor their health and respond to external, unpredictable, loading conditions, asymmetrical shape control helps to improve the range of possible responses that structures can make. To put this simply, asymmetry enables loads to be transmitted along several dissimilar paths whereas symmetrical responses do not.

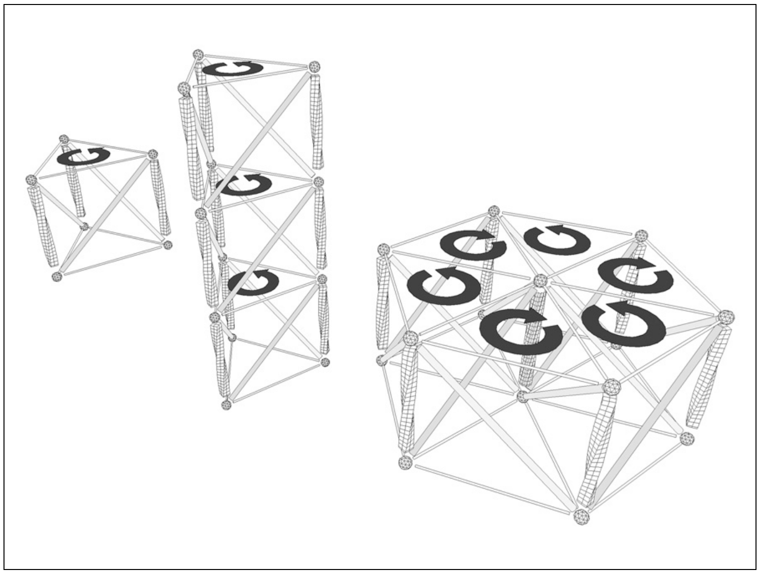
Actuated tensegrity structures form a unique class of structure because they may adopt symmetrical and asymmetrical forms by varying actuator activity. These structures are able to move asymmetrically because their joints are isolated and move in geometrically independent ways. This isolation provides a natural means for limiting the impact that any one actuator will have within the structure, greatly reducing any unwanted propagation of movement.

Types, Prototypes & Methodologies

Apart from offering variable rigidity, lightweight, and asymmetry in shape, actuated tensegrity structures are extremely useful within architecture because they can be configured in two fundamentally different ways to produce tube or surface structures. These two configurations are important because they provide the necessary diversity required for applications within large- as well as small-scale buildings.

The simplest tensegrity unit can be networked together to form more sophisticated structures that are classified according to a method first proposed by Robert E Skelton and Darrell Williamson in 2001. Williamson and Skelton refer to classes of tensegrity structures as special spatial trusses that are composed of a stable connection of axially-loaded members. Their definition for classes is described as thus “a class ‘k’ tensegrity structure is one in which at most 'k' compressive members are connected to any node”(Williamson & Skelton, 1998) Class one structures form the simplest tensegrity unit (figure 1a). This class of tensegrity structure makes the fundamental building block of most tensegrity systems. They consist of a ring of struts, each of which connects to a cable assembly. It is worth noting that a conventional tensegrity system can be converted into an actuated tensegrity system when any cable within the assembly is replaced with a tensile actuator.

Class two tensegrity structures emerge when two class one units are stacked on top of each other to produce coincident joints between struts. Sandwiched between these joints cables and actuators are stretched to produce actuated tube structures that are capable of changing shape. Figure 1b depicts class two structures. The degree and nature of shape change will vary depending upon the number of actuators, their location and the forces they can apply. Similarly to class two structures, class three structures emerge when several class one elements are connected to each other through horizontal packing processes. The geometry of these structures is shown within figure 1c. Class three structures are defined as tensegrity structures in which three struts meet at a single joint. Skelton refers to class three structures as plates. Once again, as tensile members within these structures are replaced with tensile actuators the resulting assembly will have an ability to change shape as its rigidity is varied.



Figures 1a, 1b & 1c) From left to right, class 1, class 2, & class 3 actuated tensegrity structures. The actuators have been placed vertically and are shown as elastic members. The orientation of each class 1 unit is shown because in order to build the class 3 system every other unit must orientate in an opposite direction.

Within the field of responsive architecture the way in which buildings change is critical. So while understanding the types of building forms that can be made efficiently with particular classes of structure is important, it is even more important to know the behavioral characteristics of each system and how behavior is tied to actuation and control. The conceptual model that we can use to describe behaviors within actuated tensegrity structures is built around actuation scope and the impact that changes in scope have upon structural rigidity. Scope is the term used to describe the extent or range of actuation from any particular point within the structure. As such, one can say that larger scopes actuate a larger region of a structure whereas smaller scopes actuate smaller regions. Larger scopes also require that larger numbers of actuators work together, while smaller scopes require fewer. Scope responses should relate to the internal and external forces that a structural system is exposed to, where internal forces are those that come from within the system itself (ie. the dead load of building materials) and external forces are those that come from beyond the system (ie. the live loads of wind or bodies moving within a structure). Scope is most easily understood as an actuation limit.

The scope of an actuated response caused by dead loads relates directly to the minimum rigidity required for holding a structure up without it buckling under a load. To give a simple example of how this concept works in practice let's use our own body to envision how our legs transmit load when rigid. By letting our muscles relax within one leg we cause that leg to be less rigid and also transmit less load. Our legs, because they carry more weight when we stand upright than our torso or arms do, need to be more rigid – a point that certainly becomes apparent when we consider what happens to the rigidity of our arms, torso, and legs when we do a hand stand. Within this new scenario our arms become very rigid while they support the weight of our body. At the same time our legs can soften because they transmit much less load. The optimal rigidity or for any structural system that carries a dead load to the ground is directly related to the load it carries. Thus, the larger the load, the larger the rigidity required becomes. The maximum rigidity of the system is limited to being less than the maximum compressive and tensile strengths of any member within the assembly. To summarize one can say that within this framework, actuation scope results in decreasing levels of rigidity, as loads become less. Alternatively one may say that actuated structures can get looser toward their top. This methodology of scope control produces structures that have a minimal degree of rigidity and maximum flexibility.

Scope in relation to shape control can also be discussed. Within class three prototypes shape changes that include leaning, extension, collapse, and flattening are all correlated to scope. Scope becomes a tool for enabling different regions of a structural system to become more or less rigid and affect the shape of the structure. For example, by limiting the scope of actuation to one half of a structure, leaning can be induced, while by enabling a global scope, expansion or contraction result. Limiting factors of rigidity, still apply to this system. Rigidity limits impact by restricting the degree of freedom that a structure has to move.

Figures 2a & 2b) Depicting class 3 systems as actuated systems changing shape via expansion and leaning. Figure 2b Depicts a full-scale actuated class 3 structure built by this author using cast aluminium components, pneumatic air muscles, stainless steel cable and hardware (2004). The small-scale prototypes contained in figure 2a were produced by this author in 2003.

Actuation scope and shape control relate directly to each other but they also are associated to the ways in which structures compensate or respond to live loads. Scope becomes useful in these scenarios because dissimilar building shapes respond differently under the same loading condition. Within this paradigm of control, variable scopes are used to control building shapes that help produce minimally loaded structures when loads are composed of live as well as dead loads. It is most beneficial to think of these types of scope actuation as being complementary to those induced by internal forces. For example, one can consider how a building covered in snow might be able to use shape changes to shake the snow from its roof. Alternatively one might envisage a tower that has a wind load exerted upon it might respond by reducing its aerodynamic profile to minimize shear. Buildings might also use shape changes to subtly shift their centre of gravity and better position themselves to further reduce shear. Each of these scenarios connects shape control to actuator scope. Within class two systems this can be demonstrated by increasing the rigidity of one string of actuators that run in series up a tube structure. When scope is limited to serial actuation these structures respond by shifting their center mass through twisting actions. Figure 3a provides a trace of just such a change.

Figures 3a & 3b) Depicting class 2 systems changing shape via twisting. Figure 3b (lower) Depicts a prototype, ultra lightweight tower for Chicago Illinois, by this author ("Filamentosa" 2004).

Integrated Knowledge Requirements

Any approach to producing responsive architectural structures that have the ability to change shape must consider both architectural and engineering knowledge bases to ensure robustness. At this point in time integrated methodologies for controlling structural shapes do not exist and robustness cannot be guaranteed. This means that strategies for scaffolding each knowledge type into a comprehensive control framework are becoming increasingly important. The key features of such methodologies are now discussed.

The primary goal of any shared methodology to designing responsive architectural structures that change shape must be to meet the subjective spatial desires of users as well as the safety requirements for correct load transfer. The control methodology required to do this must meld architectural responses to structural ones by placing them within an envelope that guarantees safe maximum and minimum rigidities. The likely result of this process will be the development of a subsumptive architecture for control. Subsumptive control systems (Brooks, 1986) are useful to the development of responsive architectures because they enable several simple behaviors to scaffold into larger processes. These processes provide very natural methods for the integration and support of different types of knowledge.

One other basic control methodology is needed – a methodology for the control of partially complete structures. Here partially complete structures are defined as those that are in the process of being built. Though important, this control methodology is not discussed in detail within this paper because it is not a methodology that requires joint architectural and engineering knowledge. However, it is worth mentioning that the control methodology used for partially complete structures may still be applicable to the subsumptive model of control just discussed. A point worth noting because the control methodology for partial structures may be thought of as an application of pure structural (engineering) control, onto which spatial control methodologies from architecture scaffold at a later date.

Conclusion

Perhaps the most important component within architecture is that of structure. For well over the past one hundred years architects have been developing structures, building envelopes and architectural spaces from a pallet of methodologies that consist of inside out and outside in approaches to design. Engineers have, more-or-less, passively fit into this process. Today this approach to design is proving limited and tired. No better example of this limit can be found than in the production of responsive architectures where structural shape control plays a major role in design outcomes. New design and control methodologies are needed to ensure that architects and engineers can guarantee safety and comfort within these emerging classes of building. The fundamental nature of these problems will ensure that future direction of architectural and engineering practices are driven by how each respond to these common responsibilities – it is hoped that this paper provides some assistance in the definition of this task.

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