**Structural Form
As
Morphogenetic Event**

By

Raymond Chow, B. Arch.

A thesis submitted to
the Faculty of Graduate Studies
in partial fulfillment for the requirements
for the degree of

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Abstract

This thesis presents the conception and generation of form as a dynamic interplay of opposing the force fields of tension and compression into a desired stable, equilibrated state. Tensegrity is one such analog system of form that offers a maximum amount of work performed through optimal conservation of materials and energy. The pursuit of form generation in this study challenges the idea of Tensegrity in the condition of a cantilever bridge construction with the intent of formulating and displaying the transmittal of forces into an optimal form. Stress analysis verified the mechanical performance of the structure with results yielding further observations for refinement. We conclude that the study of dynamic systems is a generative process of form that may be further realized through structural applications.

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Introduction

The ideologies surrounding our conception of form can be spoken of in a variety of manners. In the context of architecture, aside from any literary and artistic perspective, 'form' commonly denotes the physical nature of a building in terms of the static arrangement of individual elements that carry out the functional structure of its whole. For the topic of this research I would like to begin to address the physical nature and conception of form, where the morphological tendencies of Nature are a source of inspiration to form-generation, as well as to inform and define that scope of the study.

This thesis investigates the conception of a structural-mechanical idea and the process of simultaneously pursuing form. It is shown that this process is a dynamic one that achieves stability by equilibrating opposed fields of force. Form, taken here in its physical sense, is defined and studied in terms of its stabilizing behaviour through tension and compressive force fields. Tensegrity is one such analog system of form that offers maximum amount of work performed through optimal conservation of materials and energy. The pursuit of form generation challenges the idea of Tensegrity by situating it to the condition of a cantilever bridge construction with the intent of formulating and displaying the transmittal of forces into an optimal form. Most structures strive to achieve immobility or rigid stability as an essential condition. Stability here is approached as a state that can be derived by restricting motion beyond the displacements caused by the elastic behaviour of materials.

The bridge is cantilevered with a slight propping at its opposite end, where its particular task is to asymmetrically balance the weight of its horizontally projected length. One of the main goals is to describe as thoroughly as possible the composition and the inner-workings of the projected armature and to explain the way it is assembled together to resist any temptation of mobility or major change to the form of its structure.

In dealing with matter as a continuous medium, we begin to understand that form as a whole is comprised of many constituent parts, integrated together in sustaining the nature and behavior of its shape. It can be understood that the science of form-as-structure and structure-as-form is contingent upon the scale at which we access the nature of its definition.

According to the biologist Richard Dawkins in his book, "The Blind Watchmaker":

There is a hierarchy of subcomponents within components. We explain the behavior of a component at any given level, in terms of interactions between sub-components whose own internal organization, for the moment, is taken for granted. We peel our way down the hierarchy, until we reach units so simple that, for everyday purposes, we no longer feel the need to ask questions about them. Rightly or wrongly for instance, most of us are happy about the properties of rigid rods of iron, and we prepare to use them as units of explanation of more complex machines that contain them.¹

Structure and form imply a simultaneous definition that inevitably reflects our frame of reference to the object in identifying the hierarchical organization of its subordinate nature.

Dawkins continues this idea but with a critical limit in mind:

Physicists, of course, do not take iron rods for granted. They ask why things are rigid, and they continue the hierarchical peeling for several more layers, yet, down to the fundamental particles and quarks. But life is too short for most of us to follow them. For any given level of complex organization, satisfying explanations may normally be attained if we peel the hierarchy down one or two layers from our starting layer, but not more.

From Dawkins suggestion, it is obvious that we can accept the behaviour of materials as stable within the limits of the discussion and domain of interest. We will adopt Dawkins' "hierarchically reductive" approach as a conceptual device where our reading and comprehension of the bridge occurs at different levels.

In the architectural realm, a key aspect in shaping our conception of form is that the primacy of gravity is not a forgone conclusion, especially in natural structures. D'Arcy Thompson observes that, in the case of the water beetle's form, gravity is less persuasive than are the forces of the surface tension of water.² More importantly, the idea and conception of scale provides a framework within which one can more accurately define the science of form. At the macro scale of a building, the gravitational force field assumes its primary role in shaping the behavior of matter because of the building's substantial mass. The pursuit of harmony among the inertial forces and resistive physics of materials becomes the very essence of generative tendencies leading to the optimal form. We frame our inquiry here according to the nature of its formal stabilizing behavior, within the environment in which it is supposed to survive.

The attempt to generate form in the gravitational environment is guided by the morphological principles of geometry and physical rules of gravity. To engage these principles and rules, analytical methods have been derived to measure and document gravitational effects. This has resulted in the body of knowledge that we call the science of geometry, form and mechanical resistance. This investigation demonstrates, through

numerous foam modeling studies, that the ability of a continuous medium to stabilize the forces of tension and compression depends on the nature of its internal stress resistance field. It is through these modeling processes that reveal insight into further possibilities of an analogous and iconic synthesis between gravity and geometry.

Most building forms constructed at the macro-scale have been traditionally conceived through mental conceptions developed primarily from compressive material properties, since compressive materials offer more stability to larger-scale forces. This thesis puts forth the idea that in the pursuit of structural-formal efficiency, the primacy of mass needs to be challenged. The concept of structure as an *a priori* condition of its own generation is one that leads to the disintegration of continuous mass in search of ways to minimize the energy needed to carry out forces within a system. Doing so requires the conscious identification and differentiation of force flow between tension and compression zones.

Foam experiments demonstrate the mechanical relationship between tension and compression force fields working in the continuous medium. Observations lead to the assumption that if compression can be accepted as a partial recovery of pre-existing tension (i.e. that tension is relaxed slightly but still remains stretched), then it is possible to reduce the continuous compression field into an order of discrete and visibly discontinuous compression elements. Such an overlay of “invisible” compression on a pre-tensioned field leads to morphological fields of great visual and mechanical diversity and is most directly visible in tensegrity structures.

Discussions around the principles of tensegrity have evolved since its discovery by sculptor Kenneth Snelson³; Buckminster Fuller further advanced these principles through his work on Synergetics⁴; Anthony Pugh has provided greater technical detail in the construction of tensegrity structures⁵; Donald Ingber brings a collective view of tensegrity as a model of life's structures, through his discovery of modeling cell behavior and his work relating other biological structures through these models.⁶

The engineer Robert Le Ricolais has offered an approach contrary to the notion of continuous bulk mass, in which he equated the concept of “zero mass and infinite span” with the means of building efficiently with infinite capacity.⁷ His devotion to lightweight structural mechanics is a source of inspiration and precedence to some of the concepts explored in this thesis. Of particular importance to this work is Le Ricolais' pursuit of the dual distribution of matter and holes in space.

Also significant to this thesis are Haider and Strutt's investigations on polyhedral chains and spanning systems.⁸ Their results offer important information on the study of minimal structural systems that develops optimal form finding solutions through prestressing techniques that minimize the effects of gravity.

These concepts are brought together in this study of the distribution of forces, within the medium of the cantilever form which frames this investigation. In studying the patterns

and flow of tensile and compressive forces, tensegrity systems are adopted to re-frame the distribution of cantilever forces through its pre-stressed elements. Thus, a thorough investigation into principles and behavior of tensegrity is conducted to understand the mechanical system of forces in developing a structural framework that carries cantilever stresses.

To validate the aforementioned concepts, the proposed structure has been subjected to computer stress analysis. Performance and stability of the structure was determined through observations of the structure's deflections. These observations also revealed the stresses that occur within individual members. Since the bridge is a prestressed structure, tensile components must be verified to be continuously acting in tension, even under compressive stress. Thus it becomes important to identify the members under compressive stress and their values to input the prestress values. The thesis concludes by suggesting further research objectives and future implications.

- ¹ Dawkins, Richard. *The Blind Watchmaker*. London, Penguin Books, 1988.
- ² Thompson, D'Arcy Wentworth. *On Growth and Form*. New York: Dover Publications, Inc., 1992. pg 67
- ³ Pugh, Anthony. *An Introduction to Tensegrity*. Berkeley and Los Angeles, California: University of California Press, 1976. pg. 3.
- ⁴ Fuller, Buckminster R. *Synergetics Explorations in the Geometry of Thinking*. New York : MacMillan Publishing Co., Inc., 1975.
- ⁵ Pugh.
- ⁶ Ingber, Donald. E. "The Architecture of Life", Scientific American [online]. Issue 0198, 1998. <http://www.sciam.com/1998/0198issue/0198ingber.html>
- ⁷ Le Ricolais, Robert. *Visions and Paradox*. Madrid: Fundacion Cultural Coam, 1997.
- ⁸ Cotnam, Andy and Gulzar S. Haider. "Polyhedral Chains and Long Span Systems."
In: WCOSE-76 Proceedings: IASS World Congress on Space Enclosures July 4-9, 1976, Montreal, Canada. Montreal, Canada: Building Research Centre, Concordia University, 1976: 165-175.

V. Chapter One

V.1. Fields of Stress

The processes of Nature are an inspirational source of wonder to the growth and formation of organic and inorganic forms. D'Arcy Thompson presented the field of morphology in such a way that *form* became a *diagram* and reflection of its function and environment *of forces*. Form, in this sense, is understood by the way it sustains its shape through its ability to resist and balance external influences of force by an equalizing reaction from its internal force field. We begin to understand that the formation of shape and volume is comprised of a system of *subordinate actions*¹ that maintain a formal harmony and negotiation within its environment. To develop a conception of form suggests that it is dependant upon our grasp and correlation of its internal organizing behaviour to the influence to force.

Dawkins' suggestion positions "us" at the center of measuring our pursuit of knowledge and understanding when we come to the desire of explaining phenomena. It is therefore necessary to clearly define and limit the scope of investigation without spread our interest too far apart. To embrace this domain more clearly, it is also helpful to briefly step out to get a sense of the surrounding boundary. Taking the perspectives of both Thompson and Dawkins, our primary context of referring our inquiries of form to force is gravity. According to Thompson:

Gravitation influences both our bodies and minds. We owe it to our sense of the vertical, our knowledge of up-and-down; our conception of the horizontal plane on which we stand, and our discovery of two axes therein, related to the vertical as to one another; it was gravity which taught us to think of three-dimensional space. Our architecture is controlled by gravity,

but gravity has less influence over the architecture of the bee; a bee might even be commended, if it referred space to four dimensions instead of three!²

The cantilever is seen from this perspective in that it finds the ability to hang and project itself over a given distance in space by balancing gravitational forces through its internal stress field by understanding its subordinate interaction of tension and compression forces.

The scale and intensity of forces poses a unique influence on architecture. Structures at this scale produce immense forces resulting in constructions largely organized to balance those forces with compressive bearing materials. Tension exists, of course, but is often not as apparent or as overtly expressed in most building forms. With a few notable exceptions, tension forces remain a hidden character in the play dominated by compression but can be regarded as acting in different levels of a structure.

Tension and compression are common terms used to describe the direction of forces within the continuous medium of a form. In the analysis of structural behaviour, the reciprocal relationship between tensile and compressive forces forms the basis of all operations that describes the mechanical stability of form and structure. The equilibrium of a structure requires that the spatial arrangement of forces should be static, meaning that the interaction of tension and compression forces maintains a stable relationship even under the influence of external forces acting upon its form. The magnitude of the forces that act on the equilibrated structure is determined by the overall mass of the structure and any additional forces it may be subjected to. It is therefore necessary to fully comprehend the morphology

Fig. 1b: isolating a cubic dimension within the foam

Fig. 1: Foam Model for studies of mechanical distribution of material.

of tensile and compressive stresses in order to understand the stabilizing behaviour of the cantilever form.

A continuous medium subjected to compressive or tensile forces by either pushing in or pulling apart its form, causes it to either contract or expand. The ability for this medium to hold its shape together while countering these forces is determined by the strength of its internal force field of resistance or the amount of stress and strain it is capable of producing. (The different categories and ranges of performances that materials fall within constitute the science of materials.) The overall tensile and compressive capacity of our

imagined continuous medium depends thus on the material's characteristics, especially in tensile and compressive (and shear) resistance.

Foam experiments were modeled to visualize the mechanical behaviour of form to applied forces. Drawing a regular square grid on the surface of a long rectangular section of foam allowed for observation of ways in which the form would change when exposed to applied forces. To understand the cantilever forces, structural theory allows us to interpret half of a simply supported beam turned upside down and supported at mid-span to be an approximation of its behaviour. Hence the same assumptions were applied to the foam model. When the continuous medium is in the form of a cantilever, gravitational forces are resisted by locating the tension to the top portion of the form, and compression to the bottom, leaving the central axis to be a neutral zone of normal stress. Both the weight of the structure, as well as the imposed load, are transferred across the cantilever's length to the support while organizing the form of stresses to resist the gravitation field.

By isolating a cubic dimension within (Fig. 1b), we can begin to see how it deforms in the operations of shearing and gliding, where the contraction of the diagonal length across the face of the cube denotes compression, and expansion as tension. This is key to our conception of reducing the continuous form to fields of the orthogonal organization between tension and compression forces. In doing so, we arrive at the basis of how tensegrity equilibrates form through this mutual relationship.

Fig. 2a: Fuller's Sketches of Balloon Structure. Synergetics

Fig. 2b: Fuller's Sketches of pairing directional forces as "swimmers" in a stabilizing interaction

V.2. Tensegrity

Coined by Buckminster Fuller as local compression and continuous tension, tensegrity structures demonstrate the phenomena that the stress fields of form can be mechanically comprised of both tensile and compressive components mutually organized to stabilize a volume in space. An analog form of demonstrating the tensegrity principle is through strut and cable members. In this condition, tensile and compressive forces are isolated into linear dimensions, arranged in such a way that their directions of force are woven together to stabilize shapes and forms in three-dimensional space. As such, understanding the integration between tensile and compressive elements is essential to our logic and experience of constructing with this structural-mechanical idea.

Fig. 3: Geodesic arrangement and stabilization of patterns of forces. Synergetics

This type of structure was first constructed by sculptor Kenneth Snelson³, who thus shares the discovery, if not the mechanical elucidation with Fuller.⁴ In Synergetics, Fuller equates this behaviour to that of the compressed air that pushes out on the inner surface of balloons where an outward force radiating out from a central point interacts with a network that arranges an optimally balanced form (Fig. 2a and b).⁵ This omnidirectional behaviour characterizes the principles of tensegrity structures.

The mutual exchange between tension and compression forces, whose optimal arrangement is characterized by Fuller's example of the air-filled balloon, is explored further in the principles of his geodesic domes. Moving from a continuous surface of tension, pathways of intersecting lines approximate the rendition of the sphere in subdividing the interaction between tensile and compressive forces (Fig. 3). A continuous tension network with compression members locally spaced throughout the structure stabilizes the form. Thus the geodesic arrangement of forces is portrayed as producing optimal amount of work with minimal means of materials and energy. Tensegrity structures are mechanical analogies of this phenomenon of an enclosed self-sustaining system of forces.⁶

In 1998, Donald E. Ingber, an associate professor of pathology at Harvard Medical School, published an article in *Scientific American* entitled, “*The Architecture of Life.*”⁷ In this article he describes the hierarchical nature of biological organization as systems within systems, parts that form larger functioning parts, comprising the whole of the body: this is a phenomena that he calls “self-assembly.” He discovered that the principles of tensegrity behavior could aid in explaining the nature of cell structures by constructing and observing their living behaviour through analogous tensegrity models. The discovery led to more precise observations of cell behaviour lesser known before his approach. Ingber notes the contrary belief in the 1970’s that cells were comprised of a fluid substance enclosed by a membrane. The condition of the cell actually balances out its form spherically through an arrangement of tension and compression forces that resist external forces from all directions. For Ingber, the principles of tensegrity are applicable in order to understand the self-assembling relationship of organic behaviour:

The principles of tensegrity apply at essentially every detectable size scale in the body. At the macroscopic level, the 206 bones that constitute our skeleton are pulled up against the force of gravity and stabilized in a vertical form by the pull of tensile muscles, tendons and ligaments (similar to the cables in Snelson’s sculptures). In other words, in the complex tensegrity structure inside every one of us, bones are the compression struts, and muscles, tendons and ligaments are the tension-bearing members. At the other end of the scale, proteins and other key molecules in the body also stabilize themselves through the principles of tensegrity.⁸

Since the structuring principles of tensegrity can be applied to the biological organization of forces, it implies the basis of how structures are arranged in three-dimensional space to stabilize form through tensile and compressive forces. The scales at which these principles

operate occur in environments with varying degrees of force, where the influence upon the formal generation of structures differs, making the behaviour of structures distinct as the scale shifts, for example, from the human body to cellular agglomeration.

According to Thompson the water beetle that dwells within the surface tension forces of water is marginally affected by the force of gravity and is different from the conditions of gravitational force for a human's body. What this basically illustrates is that tensile and compressive forces are orchestrated to mechanically stabilize form in a manner compatible with its own force environment. Tension and compression forces are transmitted differently through the bones, muscles and tendons where these larger components of the body are subjected to gravitational forces from the overall mass that it supports. At the other end of the scale, the form of the cell is mechanically structured to perform within an environment of forces that is much more different than that of the human body. The rules of assembly⁹ as well as the modes of structural behaviour, differ considerably.

As in the foam experiments, the flexible form will change its shape and adjust the internal structure of its field to an externally acting force, whether it simply bends or twists and separates. The same assumption can be made about tensegrity structures where the scale, size and shape of its field ultimately determine the mobility and mechanical behaviour of its structure to the scale of forces in a dynamic environment.

It is clear that gravity is a guiding factor of growth and organization to a particular range of forms in the way they mechanically behave through tension and compression. Form in the cellular environment and in the human environment undergoes different and, at times, converse processes of growth and formation. Their mechanical arrangement and geometric ordering of stress fields between tension and compression behave in accordance to their respective environments. The task of enclosing gravitational forces within the form of a cantilever through a tensegrity system requires that the mechanical organization of tensile and compressive elements be arranged to stabilize the horizontal and unidirectional force. Thus, the omnidirectional behaviour of tensegrity structures must also integrate the unidirectional force of gravity as an invisible vector or direction of force, as part of the organization of its elements.

Fig. 4: Illustrations (left) and model (above) from Anthony Pugh's "An Introduction to Tensegrity"

V.3. Composite Weaves

The type of tensegrity structures explored in this thesis are comprised, like those of Snelson and Pugh, of tensile and compressive members that mechanically interact together to equilibrate a stabilized volume in space. As mentioned earlier, all members are axially loaded, meaning that they transmit a force in a single direction or path. In the case of tensegrity structures, they are distinguished as only tension or compression bearing elements; as such they are prestressed elements. The following section explains the potential use of the self-stabilizing characteristic of tensegrity structures in the cantilever form and presents experiments to provide a general understanding of its mechanical behavior.

Fig. 5: Modelled explorations of tensegrity systems

To satisfy the requirements of a cantilevered bridge, a few considerations were used to assess the spatial organization of the structure to allow for pedestrian traffic. In order for a tensegrity system to carry cantilever force, a number of requirements had to be considered:

1. As mentioned in the previous chapter, tensegrity polyhedra are omnidirectional in their behavior like balloons as illustrated by Fuller. Thus, consideration of the stabilizing relationship between tension and compression is made to integrate the closed system of forces when joining additional polyhedra. This process is analogous to weaving a continually

porous surface of tension through and around floating elongated beads that are capable of compressive resistance. One can get a better sense of the morphological possibilities of these structures by constructing basic figures and combining them to form larger systems (Fig. 5-6).

2. With the awareness that tension exists in the top zone, compression along the bottom could be maintained as a pre-existing tension field in which the transfer of horizontal thrust must be considered and decided upon its axial dimension. In the example of the foam model the continuity of the foam maintains the axial dimension of the form through continuous compression. Tensegrity systems, however, transmit forces through the continuous weave of tension members with discrete members of compression spaced within in supporting the envelope. This would require that an axial compression force produced by the beam action be transmitted through the closed system of forces.

3. Another requirement was the desire to incorporate the stabilizing dynamics of tensegrity systems in resisting gravitational forces into the experience of the structure. The sketches shown in figures 6a and b, illustrate possible profiles for the form of the bridge. An asymmetrical cross-section was strongly considered as a possible configuration to mediate the requirement of the walking path for pedestrians. This will also introduce the possibility of having an off-centered balance of forces to resist torsion forces. Santiago Calatrava has constructed elegant examples of bridges demonstrating this principle where the relationship of the weight of the tread and supporting arc are counterbalanced around the center of gravity (Fig. 7).¹⁰

Fig. 6a: Sketchs of cantilever balance

Fig. 6b: sketch of possible form for bridge

Fig. 6c: formal studies of bridge form casted in plaster.

Fig. 7: photograph of early model for asymmetric bridge. Left: Photograph from the deck. Above: Cross-sections of bridge (photos and illustrations after "Calatrava Bridges".)

4. There was no initial commitment to a specific tensegrity configuration. Therefore initial explorations were attempts at finding close-packing relationships between tensegrity structures that could agglomerate together into a beam-like structure. A condition arises in a structure that utilizes continuous tension as the main distributive system subjected to a bending condition. Tension stresses within the cables of the structure begin to change. Cables on the bottom chord are subjected to the compressive forces, thus running the risk of force reversal and slack. This phenomenon, if treated as an advantageous outcome, can lead to generative methods for compensating for the deformation. Pre-stressing can be introduced to compensate for reduced tension values.

Many variations on these conditions have been explored and advanced by Robert Le Ricolais and by Haider and Strutt and are of great interest in furthering the knowledge and experience in this field of study. By addressing the above concerns, the following section discusses the ideas and observations recorded by Le Ricolais, Haider and Strutt, in their investigations on spanning systems.

Fig.8: FPR model and sketches. Visions and Paradox.

V.3.1 Robert Le Ricolais

Le Ricolais' theoretical ideal for the problem of spanning as “zero mass and infinite span” was certainly an impossible goal but was one that strove for maximum efficiency with minimum means of material use. If the mass of matter could be reduced to a minimum so as to diminish the effects of gravity, it would, therefore, increase the structural efficiency of the structure. A generation of modeled experiments approached the problem by differentiating tension and compression stresses through *their degree of isotropy*¹¹, in other words, the distribution of material in space. According to Le Ricolais:

Fig. 9a: Load test of hollow rope structure.

Fig. 9b: Photomicrograph of bone

Fig. 9c: FPR model with internal tube

we treated the structural dissymmetry with tension and compression not by following the conventional differentiation of alternating members, common in trusses, but by decomposing the whole structure into two groups acting massively and brought into equilibrium by tensioning. For the tension part of the structure, a network was substituted for separate cables, yielding a uniform distribution of material in space, distinguished from a continuous membrane only by holes... For the diaphragm compression members whose function was to maintain the undeformability of the network, the closed configuration of the torus gave the best use of material. But except when great tensile forces can be annulled by anchorages, a straight internal tube would be the most economical solution for the main compression part of the structure.¹²

Continuously tensioned *hollow rope*¹³ structures would assume large amounts of stressing to annul bending stresses that occur from lateral load situations. With the compression tube member prevented from buckling by securing its length to the spacing of diaphragms the structure could act as a prestressed column. Thus with an optimized prestressed skin, further optimization of the compression member would also make the structure more efficient in reducing the weight.

Fig. 10: Trihex bridges. Visions and Paradox

Another structurally interesting bridge by Le Ricolais utilized *trihex* partitioning structural members within a closed system of forces (Fig. 10). In this construction axial forces are transferred through a dilated compression core comprised of a further triangulated Warren truss system.¹⁴ Based on the idea of a *germinal cell* in generating the spanning form, the trihex system reduces the problematic elongation of tension members under extreme tensile forces (especially in larger constructions) and is more capable of dealing with large bending moments. Although it was not as efficient as the early FPR systems it still proved to be 30 percent stiffer than the classical Warren truss. For Le Ricolais, structural form was comprised of a dual interrelationship between structure and space.

It is perhaps his experiments with “columns suspended in the air”¹⁵ that brings dexterousness in comprehending the problem of bending. In using the verticality of columns to increase the leverage depth of spanning distances, tensile members were used to secure the regular spacing between columns, thus producing a resistant geometry of forces to bending. Load test upon these structures revealed uniform deformations in a waveform, verifying the control over the formation of stresses. Le Ricolais’ “search for an indestructible idea”¹⁶ certainly resulted from observations that carried his nascent theories by being able to control and advance structural genesis through its failure.

Fig. 11: Photographs of Maraldi Chain Span. Polyhedral Chains and Longspan Systems.

V.3.2 Polyhedral Chains

Working with similar issues as Le Ricolais several investigations was conducted with the Form Studies Unit at Carleton University 1976¹⁷. Experiment by Haider and Strutt utilized problems of the tube as a formal organization of polyhedral chains¹⁸ of modular units wrapped in a tension net (Fig. 11). A model was constructed with a Maraldi¹⁹ unit that denoted an implicit reference system forming the compression core of a span of 5.5 meters. The Maraldi star unit being the polyhedron is part of the four-connected family of networks. The tensile field enveloping the core consisted of double-helical cable geometries that were explored until a suitable configuration was found to give more stability to the form.

Prestressing or 'uplifting' with cables that are initially tensioned is one of the most elegant concepts in structural engineering. Whether it is manifest in the king or queen post, in Fink's bridge trusses or in Leonhardt's cable stay bridges, there is little doubt about its superiority in the use of properly placed force instead of mass in carrying transverse loads across a span.²⁰

One of the predicted outcomes was that the form would exhibit bending due to gravity and thus countermeasures were necessary to redistribute the gradient build up of force deformation through the system of tension cables. One of the main objectives to compensate for this problem was to change the behaviour of the span from acting as a beam to a column under some lateral load. This was achieved by increasing tension in the areas that exhibited the tendency to stretch apart in order to be able to decrease the bending effects of gravity by pre-tensioning the structure. Compression forces caused the top portion of the structure to collapse inwards. This occurred due to particular nodes of the network defined as hinged joints. Thus a secondary cable system was introduced to reduce the deflections but it was also remarked that the role of this system decreased when the primary cable families were highly tensioned.

The observations provided by Le Ricolais, and by Haider and Strutt are valuable lessons to evaluate, refine and verify some of the assumptions that have been made for the bridge conceived in this investigation. Although the experiments are not classified as tensegrity structures, their inherent nature of utilizing axially loaded members as force transmittal systems demonstrate their efficient advantages. An important point to be aware of is that their methods of referencing the organization and assembly of its components into a larger structure almost disappear visually, or lost, as Haider points out, where focus is drawn towards its overall form.

The next chapter discusses the evolution of the bridge structure from its geometric beginnings to its assumed optimal form.

¹ Thompson. pg. 1028.

² *ibid.* pg. 67

³ Pugh. pg. 3

⁴ *ibid.*

⁵ Fuller. pg. 411

⁶ Anthony Pugh provides a most detailed description of the spherical tensegrities including construction of basic figures to higher frequency models illustrating the degrees of approximations.

⁷ Inbger

⁸ *ibid.*

⁹ *ibid.*

¹⁰ Frampton, Kenneth, Anthony Tischauser and Anthony C. Webster. *Calatrava Bridges*. Basel, Switzerland: Birkhauser Verlag, 1996.

¹¹ Le Ricolais 152

¹² *ibid.* 150.

¹³ *ibid.* 67

¹⁴ *ibid.* 150

¹⁵ *ibid.* 111

¹⁶ Peter Mc Cleary. *Robert Le Ricolais search for an 'indestructible idea'* in Visions and Paradox. 22.

¹⁷ Cotnam, Haider.

¹⁸ *Ibid.* 165. "This may also be looked upon as stringing 'polyhedral beads' on networks as 'threads'. This search has resulted into interesting families of form which have been given the general name of polyhedral chains."

¹⁹ The Maraldi unit is a geometric figure that sits within a hexahedron. This generation of this figure is further discussed in the next chapter.

²⁰ *Ibid.*

Chapter Two

Fig. 12: Sketch of unit before and after modification

VI.1. Breaking the Weave of Tension and Compression

Moving from the previous theories and principles of tensile and compressive fields the investigation now continues with study models and experiments used to develop the organization of a spatial order for the cantilever structure. By adopting the tensegrity model of the tetrahedral or Maraldi unit discussed in the previous chapter (Fig. 12), the structure for the cantilever was arranged to accommodate the pedestrian thoroughway and to ensure its integration into an optimal form resisting bending and shear forces.

To further the knowledge of the tensegrity principle, the investigation continued to construct an correspondence of force transmittal through geometrical operations. Matter is subject to the constraints of space and it is necessary to find an effective way of explaining it. The discipline of geometry formulates a science of configurations that ultimately define space through the transition from point, line, plane, volume and hyper-volume in Euclidean

space. When dealing with a body of matter, one can begin to simplify its overall form by explaining its spatial relationship through the language and tools of geometry. Cartesian coordinates assist to establish its formal position in global space through numbers. Through geometrization one can begin to formulate a subordinate grasp and correlation of its behaviour as a whole, as illustrated by Thompson's Theory of Transformations.

Further modification of the framework was applied towards optimizing its structural form and changes were recorded in a geometric tracing to quantify its transformation. The information obtained through this method was used for further structural development in calculating member forces and deformations. This will be discussed in the next chapter.

Fig. 13: "Interstabilizing" tetrahedrons. Synergetics.

VI.2. Genesis of the Essential Unit

The geometrical configuration found in the bridge can be traced to an aggregation of a cell, or a unit that germinates into the length of the bridge. As such is it necessary to understand the nature of the unit in order to comprehend its subordinate nature in comprising the structure. This configuration is recognizable as a variation of a family of body-centered polyhedral chains also used in the investigations with Professors Haider and Strutt. The four-connected network can be considered a tensegrity structure if tension members join the end of members that are extended out from a central point to the vertices of the tetrahedron. Forces of compression are then directed through the members where they terminate in the center of the polyhedra. Fuller describes the nature of this polyhedral configuration and utilizes it in constructing tensegrity columns as a series of stacked cubes. The four *radials* of Fuller's module are interpreted here as the four-connected module. A second tetrahedron is then stacked upon the first where tension members are then re-oriented to stabilize the column. This *interstabilizing relationship*¹ between two adjoining polyhedra describes the behaviour of the tensegrity figure that was developed for the cantilever structure (Fig. 13).

Fig. 14: Modified Maraldi unit

Moving from Fuller's stabilized volumes of tetrahedron, the same module was modified to form an arrangement for the cantilever bridge. The animation "1- Unit generation.mov" in the appendix demonstrates the generation of the unit. The following illustration shows the initial transformation stages of the unit (Fig. 15). The point of origin in the unit stems from the center of the hexahedron, also known as the cube, to four-out-of-its-eight nodes that sit on the vertices of the tetrahedron. In doing so we arrive at a figure with four radial lines known as a Maraldi star, the four-connected node of the diamond lattice. If we pair these members to form two "V" members, one upper and the other lower, we can assume an operation that separates and expands the V's from their center point of origin. Corresponding to the X , Y , Z coordinates assumed by the face centered axis of the cube, the upper V member may translate its position along the center axis to a lower position,

Fig. 15: Modification and Transformation of Maraldi/Four-connected and/or Stabilized Tetrahedron

Maraldi/Four-connected,
or Bucky's Stabilized
Tetrahedrons.

Tension members form
the edges of the
tetrahedron, in connected
the outer nodes of the
unit.

Separation of the center
node into 2 rigidly
connected "V" members
results in a modification
of the tensile member
arrangement. The upper
and lower members are
freed as a result of
rigidifying the "V" joint.

As a result of separating
the node, a tension
member is added to
secure the crossing "V"
members from moving
away from each other,
thus stabilizing the unit.

Transformation studies of
the unit explore possible
arrangements of tensile
and compressive
stabilization until a
suitable arrangement was
decided upon to fit the
desired cantilever form.

while the lower does the same in the opposite (upper) direction, thus forming a crossover relationship between the members.

To subject these lines to the tensegrity principle, they must be assigned a load direction to carry the forces of tension and compression. In this case the V members are assigned the task of carrying compression thus providing the outward pushing action. Tensional elements provide the simultaneous pulling action: in this case the role of the center member pulls the V's together by their center nodes while tension extends to connect this point to the father ends of opposing V members. This fixes and triangulates the interval between the center nodes and the outer ends of the V's. At this point, the assembly is still able to rotate about the center axis, thus to further secure their positions, tension is extended to connect the opposing end nodes of each V. These outer members sitting on 4 out-of-the-six edges of the tetrahedron stabilize the form of the unit by completing a triangulation of the forces. The final assemblage is the result of a process of interweaving self-contained forces; maximizing the ends of potential stored energy of tension and compression members in volumizing space, leading us to the optimal aspect of tensegrities.

Fig. 16a: Original unit

Fig. 16c: Coordinate system for transfer of unit

Fig. 16b: Agglomeration sketches

VI.3. Modification and Agglomeration

Moving to the next level of arrangement for the structure is the explanation of how the unit is modified to agglomerate as subcomponents or subsets within the cantilever. Their essential role in forming the length of the span constitutes the stress field that resists the cantilever forces through the internal organization of tensile and compressive members. Fulfilling the functionality of the bridge, the pedestrian walkway is integrated by shaping the individual unit in an asymmetric arrangement.

The spatial orders of the cube are once again utilized as invisible reference systems in deriving the space-filling network of the tensegrity system (please see "2- Unit

aggregation.mov” animation in appendix). To fill the 18-meter span, a succession of eight cubes is used to generate its length. Modification of the basic unit changes the relative location of nodal points within the cube from a body-centered-cubic packing to follow certain points and lattice paths of the face-centered and edge-centered-cubic packing patterns. This modification leads to an interpenetrating operation that extends and shares the closed system of forces between two successive units where the cubic domains of the unit share a crossover zone beginning the agglomeration.

The joining of the successive module contains an overlapping geometric sequence that links the forces of one unit to another. The stabilization between the units is dependent upon the bending forces generated by the rigid connection of the V members. The function of the compression elements is triggered into a bending state as the tension member connecting the end nodes of the V is subjected to the force of the preceding unit’s center node; this is much like the mechanical action of the bow and arrow. The additional tension members act as the cable-stays, holding the units in their relative positions producing a “polarizing effect”, and resisting any shearing action. This forms the basis of how the space frame germinates its projected length. Furthermore, one can see that the upper V of the previous unit is joined with the lower V of the next, forming a continuous bent line that wraps and crosses over the next. It can be said that the initial frame of reference of the basic unit has changed to a jogging line. As the stabilizing geometry of the aggregation is derived from the space filling networks of the cube, it also shares the subdividing paths of the square in plan (XY plane) and elevation (XZ plane).

Fig. 17: Generation of Unit - Planar Relationships

The matrix in Fig. 17 shows the relationship of the V members for the unit in each plane. It should be noted that although the dimensions of the unit's members change accordingly to the dimensions of the cube, the arrangement of the unit into a space frame was derived from modelling the geometry of two successive units as a stable extension. The compression member V1 is located relative to the YZ plane. Compression member V2 is sits relative to the XY plane where the pedestrian walkway is located.

The last step of this process occurs with the conscious understanding of how the forces stabilize the space frame structure to selectively edit specific members and their role

within the path of force in the structure. At this point, the fixed points of the foundation have not yet been specified and are of critical importance in defining the behavior and force transmittal in the structure. In securing the cantilever form with a fixed foundation, the lower V members in the first unit become anchor points where horizontal loads are transferred. This secures the structure's position in global space. The stabilizing function of one of the tension members is also fixed and anchored to the foundation so that its original point shifts from the opposing outer node of the V member to maintain a clear path for pedestrian traffic. Successive units follow the same operation by relocating its point of support off the center node of the preceding unit. Figure 18 shows how the unit begins to join to the next with alterations of the tension members. In merging the units into a space frame (Fig. 19), we can begin to address the gravitational forces that begin to stress the structure.

Fig. 18: Matrix of Successive Units

- A. Single Closed Unit
- B. Relationship of two units
- C. Arrangement of secondary stabilizing cables enclosing system of forces
- D. Final arrangement of successive units with redundant cable removed.
- E. Planar relationships

Fig.19: Space Frame Arrangement. A, B and C show the transition of two units from the cubic dimension to the space frame. Illustrations D, E and F show 8 units joined together. The Space frame in D shows the XZ plane and E the XY plane. F shows the 3-dimensional relationship.

Fig. 20: Top left: constructed model of bridge. Above right: computer drawing of bridge form and member arrangement in XZ plane. Below left: geometric tracing of bridge formation.

VI.4. Morphogenesis of Structural Form

In early explorations, the desired profile of the cantilever form was refined through modelling and drawing processes. The upper left figure shows a model for the cantilever span. Constructed from $\frac{1}{4}$ " steel rods and high-strength tensile thread, the model spanned approximately 28" (Fig. 20 top left). The model was constructed from trigonometric calculations of the lengths of its members and coordinates in space (Fig. 21). The final transformation of the structure is shaped to reduce excessive internal forces within the structure by methods of normalization. The final form of the bridge is arrived at through shearing and gliding operations. Adopting Thompson's *Theory of Transformations*², the final morphogenesis of the structure can be traced from its original shape to its optimal form. Starting as sketches that approximated spanning depths and bending curves, the

structure of the bridge was conceived from an intuitive process observed from natural inspiration and the foam experiments.

In discussing how the bending forces were optimally resisted through the structural frame all the forces are seen to be mutually dependent, thus bending moment, shear, axial and torsion forces were considered in a simultaneous composition. In showing how the unit is arranged into the structural frame, the coordinates of the space frame can now be shown in relation to the actual profile of the structure that was originally modelled. With a generalized sketch of mechanical ideas and principles in mind, geometric shapes are utilized to correlate a quantifiable measurement of its overall form and organization of its elements. (Please see “Geometric Tracing.mov” animation in appendix) The vertical arc of the bridge near its root formalizes the required or optimal depth in normalizing bending stresses and is drawn from a circle to standardize the lengths of its internal elements. Trajectory lines are extended from these members revealing a set of lines that intersect with the circumference of the circle used to draw the arc.

Working in three separate construction planes, XY, ZX, ZY and in the isometric view, the organization of the members are systematized by the ratios between the X, Y and Z coordinate measure. For instance, in the sketch provided, all members (seen in the plan view) are modified by notating their position relative to the dimensions of the module, relative to the whole of the structure. Lines are plotted to graph a path for the different sets of members in accord with the types of stresses that occur for each set within the cantilever.

Fig. 21: Working drawing for bridge model with calculations of member dimensions and coordinates

In doing so the value of bending forces are depicted by curved lines that begin to deform the grid of the structural framework.

The moment forces acting longitudinally along the length of the span vary from a maximum value at the support and diminish at its ends where its behavior changes to shearing action. The bending stresses that occur in the cantilever are largest at its root due to the accumulation of loads primarily under its self-weight and/or live load situations. This means that external gravitational loads produce tension and compressive forces that must be equally resisted by the internal force field to equilibrate the structure. The action of the moment force can be minimized by increasing the effective moment of inertia by increasing the depth of the span near the support. This can theoretically be achieved by lengthening the vertical compression member above the center axis of the first unit as the maximum depth that gradually tapers towards the last unit

Fig. 22: computer generated analysis of bridge proportions and transformation with unit highlighted in red.. Above: horizontal (XY) plane. Below: vertical (XZ) plane.

The vertical shear forces continually develop from the internal moment force where the action of pulling or stretching above the neutral axis and pushing or contracting below the neutral axis reaches a maximal point near the end of the beam. Beyond this point there is no continuity of material to resist the coupled action of tension and compression and tends to deform relative to the neutral axis with the material horizontally pulled back above and pushed forward below. Thus the entire form organizes in sliding like louvers where the end module would contract diagonally. In resisting this movement the angle of vertical compression member of the end unit is angled at 45 degrees to resist the diagonal movement of the shear. Since there are no shear forces at the support the vertical member of the first

Fig. 23: shear plane (XZ) of bridge with jogging compression member highlighted in red.

unit remains essentially the same, with a slight inclination towards the support, while the verticals in between of the first and last modules form a gradual transition.

In the horizontal plane consisting of the pedestrian walkway, provisions are made to resist the deformation due to wind loads. In a similar manner as described above, the same diameter circle is used to inscribe the horizontal bending moments at the support where it is symmetrically balanced on both sides. The asymmetric cross-section of the structure holds that weight of the tread on one side while being counterbalanced on the other side by the structural members around the center of gravity.

The effect of torsion can be visualized from the interval ZX planes of the units where any off-center force from the centroid results in a twisting movement. Torsion deformation in the cantilever is the moment force that acts in the cross sectional plane

Fig. 24: horizontal plane (XY) of bridge with walkway and highlighted member

where the coupled force of tension and compression weave in orthogonal spirals around the length of the beam. As a result of three-dimensional movement torsion is framed and arrested with material resistance that is provided in the compressive and tensile directions of their twisting paths hence securing the relative positions of the planes (as demonstrated by foam experiments.) The stability of the structure resists torsion by the continuous crossing of tension members forming a counter-spiraling net with the compression members spaced within. (Please see “3- Morphing.mov” animation in appendix)

The result of the form appears as a tapered cantilever with a changing cross-section along its length. In defining the modulation of internal forces that occur into the structural system further calculation can be assessed to accurately understand the type of stresses that occur in its individual members.

Fig. 25: View of computer model with tension members in red and compression in black. Green members represent the plane for the walkway. The dotted blue lines are the geometric lines and shapes used to map the desired profile and organization of the structure.

Fig. 26: Analysis of Structure outlining relationship of the unit (A), and planar relationships (B and C).

Fig. 27a: Relative YZ displacement of arc to XZ plane

Fig. 27b: superimposed view of analysis layers

Fig. 27c: Transparent view of layers.

¹ Fuller pg. 404

² Thompson.1032.

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Chapter Three

VII.1. Stress Analysis

Before moving further, I must confess that the formal leap as an architect has been inspired by natural forms and not by any early calculated tests to verify the explored concepts. Therefore to further understand the assumptions of the structure's performance, the investigation continued with the collection of more information on its internal behaviour, with the aid of a computer stress analysis program. In the route towards optimization I collaborated with Professor Heng Khoo, and graduate student Shadi Ostovari of the Department of Civil and Environmental Engineering, to verify the static equilibrium of the bridge structure and analyze the behaviour of its internal stress field. The structure was analyzed using the Cosmos structural analysis software. Calculated results were then compared with the results from SAP 2000, another structural analysis program.

While establishing an approximated profile and dimensions of the space structure, the study continues to further develop the required process in the pursuit of its construction. This chapter discusses further analysis of the internal forces in the cantilever bridge and its individual members. It advances the degree of resolution to modeling the forces through the reactions of the members and their connections. The bending action of the "V" members determine the static behavior of the structure and become important to understand in deciding upon the desired results for stability. Thus the process undergoes trial and error development

to determine the appropriate variables to be utilized in the structure. In resolving these conditions, the structure can be considered for further development in construction detailing.

3.1_Numerical and Graphical Modelling

In the Cosmos program interface, the user is exposed to a numerical and graphical environment to define various parameters required to obtain the results such as: the coordinates of joints and members, the condition of the connections and support, cross-sectional dimensions, material properties, and load conditions.

The approach taken led to the modeling of the structure in an AutoCAD environment, where more advanced modeling features are available for construction. With the bridge's coordinates plotted in Cartesian space, information about the structure and form was transferred into the environment of the software and graphed. In observing the input process, the computer requires a description of how the structure behaves through common parameters, beginning with the plotting of points in space, to join the lines of the load paths that triangulate into planes and volumes.

As seen in the spreadsheet data (see Fig. 31 at the end of section), each individual member has a start- and end- point with corresponding coordinates that help in determination of location and length of members. As vectors, they do not yet possess any directions of tensile and compressive forces; direction cannot be assigned until the condition of the foundation support is determined. This requirement enables the structure to be fixed in a relative position in space through the selected points of support, and determines the way forces flow throughout the structure. In this case joints, 1, 3 and 4 were selected as fixed

positions in global space; the remainder of the cantilever is locally supported from these points. With the supports in place, the analysis establishes both the nature (i.e. tension or compression), and the magnitude of the forces.

To ensure that the structure is a stable form, the degree of movement at each joint is established and tested. The degrees of freedom for a joint are referenced around the three cardinal axes of X, Y, and Z, and are either fixed, or allowed to translate and rotate with respect to that axis. Since the stability of the structure is dependent upon the bending moment occurring at the joint for each “V” member, the joints for each of the bent lines are fixed against rotation. This will allow for the analysis to recognize and compute the results for each joint. The degrees of movement of the members and joints of the bent lines are initially defined as fully fixed in the local coordinate system of the structure. Through successive analysis the joints are selectively released to remove excessive redundancy in the structure.

The material dimensions of the members have been selected from the database as 25cm steel pipes with a 1cm thickness for the compression members and 1cm cables for the tensile ones. These dimensions determine the value of the overall mass of the structure in the gravitational field and the calculation of its deflection. It would be favorable to reduce the dead weight of the structure without reducing the local and global stiffness to keep deflections and displacements within serviceable limits.

We then move from the sub-component level to the application of load conditions across the deck of the structure. Live loads and self-weight loads are distributed through the internal components that activate the stress field of resistance. The computer must also know how the members connecting to the joints behave so that it can properly distinguish whether it is mechanically stable as a structure. If the structure is not in equilibrium, the analysis program will generate errors as a result of its failure. With the structure equilibrated with materials carrying tensile and compressive forces under its dead weight, additional live load is applied to test the performance of the structure.

It is important to know that all the cables of the structure remain in tension after loading to prevent catastrophic reversal of a tension member to a “compression member” with no compressive resistance. Tension and compression forces due to bending change the internal behaviour of the structure. Since the mechanical behaviour of the tensegrity structure transmits the bending forces through continuous tension stress, the most obvious recovery of compression through tension is along the bottom chord of the structure below the neutral axis. As a result the tension members in the bottom chord will receive an increase in compressive force thus reducing the amount of tensile stressing in the members. Axial compression forces also produce deflections that may cause specific sets of tension members to become redundant.

To prevent the tension members from going slack, members can be selectively pre-tensioned. The amount of prestressing is determined by initial analysis of the amount by

which it is compressed. For example, analysis of the structure under its self-weight will reveal the amount of force that is exerted upon each member. Tension members that receive compressive forces result in a gain of negative tension that must be kept above a value that secures its tensile ability. The analysis will reveal the magnitudes of these values for each member where the amount of pre-tensioning can be identified when necessary. Stress analysis must then be run again to test these trials of modifying the selected members.

Fig.30: image of deflection with exaggeration

It was informed by Professor Haider that the results, which showed a maximum deflection of 8cm, were within an approximate allowable limit of 10cm (Please see “Deflection.gif” animation in appendix). This indicates a favourable and promising position towards the realization of the bridge. Calculating the amount of force each member receives and finding more suitable dimensions can achieve further optimization of the structure and sectional properties to best resist them. The structural compression members would most likely be refined to change in diameter of the cross section: beginning with heavier members from the abutment of the structure and tapering to a smaller dimension near the opposite end. This most probably will change the dynamic behaviour of the bridge and present different results in the analysis, but will reveal more optimally favorable results.

Fig. 29: images of stress distribution in structural elements. Top left: shows both tension and compression members. Bottom left: compression only Bottom right: tension only Top right: image of steel model

The results verify the structure's geometric stability. The images shown in Fig. 29 reveals the stresses of the bridge as a whole, and with tension and compression members as separated. Compression stresses are coded in red and tension ones in yellow. We begin to see the internal force field resisting the bending forces of the cantilever form to gravitational and self-weight loads.

Fig. 31: Joint coordinate input for stress analysis program

```

JOINT
1  X=0  Y=0  Z=0
2  X=3  Y=2.7902  Z=0
3  X=2  Y=4.67031  Z=-2.64961
4  X=1  Y=3.64806  Z=3.71646
5  X=2  Y=2.7902  Z=-2.64961
6  X=2  Y=-.20146  Z=-.09914
7  X=5  Y=2.7902  Z=.16969
8  X=3.89773  Y=4.78493  Z=-1.69351
9  X=3.6259  Y=2.97927  Z=3.83733
10 X=4  Y=2.7902  Z=-1.64961
11 X=4  Y=-.13461  Z=.09914
12 X=7  Y=2.7902  Z=.27852
13 X=6  Y=4.57856  Z=-.92937
14 X=6.06183  Y=2.7902  Z=3.53457
15 X=6  Y=2.7902  Z=-.93256
16 X=5.98529  Y=.31407  Z=.24023
17 X=9  Y=2.7902  Z=.32168
18 X=8.02904  Y=4.09012  Z=-.45954
19 X=8.30774  Y=2.98156  Z=2.874
20 X=8  Y=2.7902  Z=-.46461
21 X=8.04302  Y=.83491  Z=.31716
22 X=11  Y=2.7902  Z=.29759
23 X=10.0176  Y=3.54752  Z=-.22546
24 X=10.4958  Y=3.38987  Z=1.94744
25 X=10  Y=2.7902  Z=-.22656
26 X=10  Y=1.24131  Z=.30963
27 X=13  Y=2.7902  Z=.20559
28 X=12.0231  Y=3.28169  Z=-.21052
29 X=12.6204  Y=3.78633  Z=1.39732
30 X=12  Y=2.7902  Z=-.20943
31 X=12  Y=1.37524  Z=.26863
32 X=15  Y=2.7902  Z=.04516
33 X=14.1596  Y=3.29662  Z=-.43846
34 X=14.9464  Y=4.22037  Z=1.14666
35 X=14  Y=2.7902  Z=-.41259
36 X=14  Y=1.24131  Z=.14255
37 X=17  Y=2.7902  Z=-.14961
38 X=16.6327  Y=3.70051  Z=-1.02993
39 X=18  Y=4.7902  Z=1.35039
40 X=16  Y=2.7902  Z=-.84364
41 X=16  Y=.83207  Z=-.05222
42 X=19 Y=2.7902 Z=-.05222

```

Fig. 32: Frame elements of structure. Frames 1-33 are compression, while the rest are tension

```

FRAME
1  J=1,2  SEC=PIPE1  NSEG=2  ANG=0
2  J=2,3  SEC=PIPE1  NSEG=2  ANG=0
3  J=4,5  SEC=PIPE1  NSEG=2  ANG=0
4  J=5,6  SEC=PIPE1  NSEG=2  ANG=0
5  J=6,7  SEC=PIPE1  NSEG=2  ANG=0
6  J=7,8  SEC=PIPE1  NSEG=2  ANG=0
7  J=9,10 SEC=PIPE1  NSEG=2  ANG=0
8  J=10,11 SEC=PIPE1 NSEG=2  ANG=0
9  J=11,12 SEC=PIPE1 NSEG=2  ANG=0
10 J=12,13 SEC=PIPE1 NSEG=2  ANG=0
11 J=14,15 SEC=PIPE1 NSEG=2  ANG=0
12 J=15,16 SEC=PIPE1 NSEG=2  ANG=0
13 J=16,17 SEC=PIPE1 NSEG=2  ANG=0
14 J=17,18 SEC=PIPE1 NSEG=2  ANG=0
15 J=19,20 SEC=PIPE1 NSEG=2  ANG=0
16 J=20,21 SEC=PIPE1 NSEG=2  ANG=0
17 J=21,22 SEC=PIPE1 NSEG=2  ANG=0
18 J=22,23 SEC=PIPE1 NSEG=2  ANG=0
19 J=24,25 SEC=PIPE1 NSEG=2  ANG=0
20 J=25,26 SEC=PIPE1 NSEG=2  ANG=0
21 J=26,27 SEC=PIPE1 NSEG=2  ANG=0
22 J=27,28 SEC=PIPE1 NSEG=2  ANG=0
23 J=29,30 SEC=PIPE1 NSEG=2  ANG=0
24 J=30,31 SEC=PIPE1 NSEG=2  ANG=0
25 J=31,32 SEC=PIPE1 NSEG=2  ANG=0
26 J=32,33 SEC=PIPE1 NSEG=2  ANG=0
27 J=34,35 SEC=PIPE1 NSEG=2  ANG=0
28 J=35,36 SEC=PIPE1 NSEG=2  ANG=0
29 J=36,37 SEC=PIPE1 NSEG=2  ANG=0
30 J=37,38 SEC=PIPE1 NSEG=2  ANG=0
31 J=39,40 SEC=PIPE1 NSEG=2  ANG=0
32 J=40,41 SEC=PIPE1 NSEG=2  ANG=0
33 J=41,42 SEC=PIPE1 NSEG=2  ANG=0
34 J=1,5  SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
35 J=1,6  SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
36 J=6,2  SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
37 J=6,10 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
38 J=6,11 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
39 J=11,7  SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
40 J=11,15 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
41 J=11,16 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
42 J=16,12 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
43 J=16,20 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
44 J=16,21 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
45 J=21,17 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
46 J=21,25 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
47 J=21,26 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3
48 J=26,22 SEC=CABLE  NSEG=2  ANG=0  JREL=U2,U3,R1,R2,R3

```


Fig. 32 (con't)

49	J=26,30	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
50	J=26,31	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
51	J=31,27	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
52	J=31,35	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
53	J=31,36	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
54	J=36,32	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
55	J=36,40	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
56	J=36,41	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
57	J=41,37	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
58	J=5,2	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
59	J=5,3	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
60	J=5,8	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
61	J=2,10	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
62	J=2,9	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
63	J=2,4	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
64	J=2,8	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
65	J=10,7	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
66	J=10,8	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
67	J=10,13	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
68	J=7,15	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
69	J=7,14	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
70	J=7,13	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
71	J=7,9	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
72	J=15,12	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
73	J=15,13	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
74	J=15,18	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
75	J=12,20	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
76	J=12,19	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
77	J=12,18	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
78	J=12,14	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
79	J=20,17	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
80	J=20,18	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
81	J=20,23	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
82	J=17,25	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
83	J=17,24	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
84	J=17,23	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
85	J=17,19	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
86	J=25,22	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
87	J=25,23	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
88	J=25,28	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
89	J=22,30	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
90	J=22,29	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
91	J=22,28	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
92	J=22,24	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
93	J=30,27	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
94	J=30,33	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
95	J=30,28	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
96	J=27,35	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3

Fig. 32 (con't)

97	J=27,33	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
98	J=27,34	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
99	J=27,29	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
100	J=35,32	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
101	J=35,38	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
102	J=35,33	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
103	J=32,40	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
104	J=32,39	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
105	J=32,38	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
106	J=32,34	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
107	J=40,37	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
108	J=40,38	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
109	J=37,42	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
110	J=37,39	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
111	J=9,4	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
112	J=9,3	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
113	J=9,8	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
114	J=9,13	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
115	J=14,19	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
116	J=14,18	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
117	J=14,13	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
118	J=14,8	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
119	J=14,9	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
120	J=19,24	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
121	J=19,23	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
122	J=19,18	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
123	J=19,13	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
124	J=24,29	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
125	J=24,28	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
126	J=24,23	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
127	J=24,18	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
128	J=29,34	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
129	J=29,33	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
130	J=29,28	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
131	J=29,23	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
132	J=34,39	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
133	J=34,38	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
134	J=34,33	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
135	J=34,28	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
136	J=39,38	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
137	J=39,33	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
138	J=3,8	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
139	J=8,13	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
140	J=13,18	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
141	J=18,23	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
142	J=23,28	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
143	J=28,33	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
144	J=33,38	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3

Fig. 32 (con't)

145	J=38,42	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
146	J=39,42	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
147	J=5,10	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
148	J=10,15	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
149	J=15,20	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
150	J=20,25	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
151	J=25,30	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
152	J=30,35	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
153	J=35,40	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
154	J=2,7	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
155	J=7,12	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
156	J=12,17	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
157	J=17,22	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
158	J=22,27	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
159	J=27,32	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
160	J=32,37	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3
161	J=4,8	SEC=CABLE	NSEG=2	ANG=0	JREL=U2,U3,R1,R2,R3

Fig. 33: Displacements of joints

JOINT DISPLACEMENTS

JOINT LOAD	UX	UY	UZ	RX	RY	RZ
1 LOAD1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2 LOAD1	6.640E-05	-5.021E-04	-7.519E-04	3.180E-04	4.827E-06	-8.699E-05
3 LOAD1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4 LOAD1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5 LOAD1	-2.723E-03	6.291E-04	-4.962E-04	6.726E-04	1.024E-03	-6.536E-04
6 LOAD1	-5.263E-04	-8.999E-04	-2.457E-03	-7.859E-05	2.501E-03	-5.895E-04
7 LOAD1	1.914E-04	-1.667E-03	-4.037E-03	1.671E-03	-1.220E-04	3.184E-04
8 LOAD1	-9.776E-04	3.858E-04	-1.160E-03	1.333E-03	1.393E-04	6.711E-04
9 LOAD1	3.571E-03	2.362E-03	-1.711E-03	-1.326E-03	7.166E-04	-8.608E-04
10 LOAD1	-2.714E-03	6.185E-04	-2.292E-03	1.272E-03	1.888E-03	-8.292E-04
11 LOAD1	-2.718E-04	-2.224E-03	-7.255E-03	1.179E-03	3.498E-03	-5.560E-04
12 LOAD1	4.206E-04	-3.250E-03	-8.754E-03	2.575E-03	6.632E-04	1.263E-04
13 LOAD1	-7.727E-04	-5.075E-04	-3.831E-03	2.334E-03	6.873E-04	2.423E-04
14 LOAD1	4.719E-03	-4.794E-03	-6.248E-03	6.764E-06	1.096E-03	-4.395E-04
15 LOAD1	-2.230E-03	-1.885E-04	-6.254E-03	2.653E-03	2.409E-03	-4.608E-04
16 LOAD1	5.030E-04	-3.995E-03	-0.0145	3.229E-03	4.211E-03	-3.272E-04
17 LOAD1	6.719E-04	-4.833E-03	-0.0151	4.728E-03	2.188E-03	-4.759E-05
18 LOAD1	-9.154E-04	-1.033E-03	-6.867E-03	4.729E-03	2.198E-03	-1.222E-04
19 LOAD1	5.681E-03	-0.0125	-0.0119	2.534E-03	1.849E-03	5.218E-04
20 LOAD1	-1.823E-03	-8.815E-04	-0.0119	5.362E-03	3.130E-03	2.289E-04
21 LOAD1	1.519E-03	-5.828E-03	-0.0246	6.739E-03	5.065E-03	6.534E-05
22 LOAD1	8.544E-04	-5.478E-03	-0.0242	8.519E-03	4.308E-03	-4.056E-05
23 LOAD1	-1.283E-03	-8.509E-04	-0.0134	8.651E-03	4.412E-03	-1.990E-04
24 LOAD1	6.322E-03	-0.0183	-0.0169	7.607E-03	3.834E-03	1.752E-03
25 LOAD1	-1.734E-03	-8.280E-04	-0.0198	0.0100	4.740E-03	9.746E-04
26 LOAD1	2.135E-03	-6.792E-03	-0.0371	0.0117	6.542E-03	4.172E-04

27	LOAD1	6.020E-04	-4.321E-03	-0.0378	0.0139	6.842E-03	1.086E-04
28	LOAD1	-2.232E-03	1.517E-03	-0.0241	0.0141	7.093E-03	-9.482E-05
29	LOAD1	6.843E-03	-0.0218	-0.0204	0.0147	6.735E-03	2.101E-03
30	LOAD1	-2.407E-03	1.523E-03	-0.0312	0.0163	7.220E-03	1.152E-03
31	LOAD1	2.229E-03	-6.627E-03	-0.0555	0.0175	8.421E-03	5.011E-04
32	LOAD1	-5.596E-04	-8.695E-04	-0.0547	0.0192	8.188E-03	3.437E-04
33	LOAD1	-4.645E-03	8.277E-03	-0.0380	0.0194	8.339E-03	1.790E-04
34	LOAD1	6.985E-03	-0.0226	-0.0256	0.0201	8.478E-03	1.539E-03
35	LOAD1	-4.471E-03	7.797E-03	-0.0464	0.0207	8.735E-03	7.910E-04
36	LOAD1	1.209E-03	-3.813E-03	-0.0790	0.0210	9.366E-03	3.369E-04
37	LOAD1	-2.282E-03	4.171E-03	-0.0723	0.0215	7.977E-03	8.500E-04
38	LOAD1	-0.0102	0.0227	-0.0497	0.0215	8.107E-03	9.394E-04
39	LOAD1	8.990E-03	-0.0270	-0.0379	0.0216	8.418E-03	9.319E-04
40	LOAD1	-8.338E-03	0.0186	-0.0636	0.0216	8.853E-03	6.017E-04
41	LOAD1	-2.832E-04	1.413E-03	-0.1061	0.0217	9.112E-03	5.024E-04
42	LOAD1	-1.522E-03	3.361E-03	-0.0889	0.0224	8.014E-03	7.138E-04

Fig. 33: (con't)

Fig. 34: Results of forces in elements of structure**FRAME ELEMENT FORCES**

FRAME	LOAD	LOC	P	V2	V3	T	M2	M3
1 LOAD1								
	0.00	-107959.34	-11580.22	434.43	482.20	1120.85	-10345.92	
	2.05	-107959.34	-2199.76	434.43	482.20	230.93	3768.14	
	4.10	-107959.34	7180.70	434.43	482.20	-659.00	-1333.55	
2 LOAD1								
	0.00	-127365.60	536.65	-345.06	56.78	-1122.60	705.42	
	1.70	-128132.94	1153.37	-345.06	56.78	-536.13	-730.80	
	3.40	-128900.27	1770.09	-345.06	56.78	50.35	-3215.23	
3 LOAD1								
	0.00	-1843.55	288.85	172.53	782.82	1038.67	-267.60	
	3.25	-3687.19	670.42	172.53	782.82	477.86	-1826.66	
	6.50	-5530.83	1051.99	172.53	782.82	-82.95	-4625.99	
4 LOAD1								
	0.00	-42333.24	-3618.57	919.26	-2302.81	-977.96	-3899.12	
	1.97	-41594.61	-2752.17	919.26	-2302.81	-2784.88	2362.16	
	3.93	-40855.99	-1885.77	919.26	-2302.81	-4591.81	6920.41	
5 LOAD1								
	0.00	-48520.57	-18817.20	163.57	-1092.39	-2073.67	-6300.87	
	2.12	-47367.39	-643.23	163.57	-1092.39	-2420.87	14352.81	
	4.25	-46214.22	17530.75	163.57	-1092.39	-2768.07	-3570.21	
6 LOAD1								
	0.00	4558.57	-1443.07	-1181.80	228.25	-3665.47	-2102.24	
	1.47	4018.98	-783.06	-1181.80	228.25	-1926.04	-463.97	
	2.94	3479.39	-123.04	-1181.80	228.25	-186.60	202.86	
7 LOAD1								
	0.00	59503.20	1018.03	525.49	159.41	-2086.71	-1358.06	
	2.75	57914.15	1139.42	525.49	159.41	-3532.58	-4326.14	
	5.50	56325.11	1260.82	525.49	159.41	-4978.44	-7628.22	
8 LOAD1								
	0.00	-47942.94	-5760.73	766.48	-3047.97	-2079.02	-8557.19	
	1.70	-47436.49	-4913.69	766.48	-3047.97	-3384.99	536.70	
	3.41	-46930.05	-4066.65	766.48	-3047.97	-4690.97	8187.35	
9 LOAD1								
	0.00	-102787.11	-19243.71	-318.99	-1892.51	-2545.35	-7435.39	
	2.10	-102017.64	-1271.08	-318.99	-1892.51	-1876.49	14072.56	
	4.19	-101248.17	16701.55	-318.99	-1892.51	-1207.63	-2104.94	
10 LOAD1								
	0.00	40472.06	-1747.17	-549.34	213.00	-1432.18	-2515.72	
	1.19	40122.25	-1153.79	-549.34	213.00	-778.87	-790.75	
	2.38	39772.44	-560.40	-549.34	213.00	-125.57	228.55	

11 LOAD1

0.00	35963.08	-1278.43	-1955.70	-28.72	2074.73	367.94
2.23	34669.38	-1260.52	-1955.70	-28.72	6443.33	3203.66
4.47	33375.68	-1242.62	-1955.70	-28.72	10811.93	5999.39

Fig. 34 (con't)

12 LOAD1

0.00	-54095.64	-7062.10	1024.64	-4807.63	-2143.24	-11262.18
1.37	-53756.00	-6344.99	1024.64	-4807.63	-3546.93	-2078.77
2.74	-53416.35	-5627.88	1024.64	-4807.63	-4950.61	6122.24

13 LOAD1

0.00	-160431.19	-18505.08	-838.35	-257.04	-2422.16	-7330.01
1.95	-160081.81	-1770.29	-838.35	-257.04	-786.49	12449.08
3.90	-159732.42	14964.50	-838.35	-257.04	849.18	-422.18

14 LOAD1

0.00	17028.11	-860.27	526.56	178.81	862.14	-448.79
9.0E-01	16801.86	-390.38	526.56	178.81	388.02	114.24
1.80	16575.62	79.51	526.56	178.81	-86.10	254.20

15 LOAD1

0.00	-8362.19	386.55	-5402.17	-102.08	940.44	-545.12
1.68	-9329.07	491.50	-5402.17	-102.08	10011.27	-1282.29
3.36	-10295.95	596.44	-5402.17	-102.08	19082.10	-2195.67

16 LOAD1

0.00	-47697.84	-10214.67	1965.01	-7262.73	-794.84	-17689.28
1.05	-47471.43	-9648.27	1965.01	-7262.73	-2864.21	-7230.34
2.11	-47245.03	-9081.88	1965.01	-7262.73	-4933.59	2632.13

17 LOAD1

0.00	-154437.50	-17156.54	-1244.67	2520.64	-1899.38	-7493.85
1.77	-154521.44	-1949.97	-1244.67	2520.64	306.82	9439.46
3.55	-154605.39	13256.59	-1244.67	2520.64	2513.02	-581.13

18 LOAD1

0.00	-51888.32	1076.15	2037.13	142.54	2682.26	2199.40
6.7E-01	-52039.79	1435.38	2037.13	142.54	1311.08	1354.15
1.35	-52191.27	1794.61	2037.13	142.54	-60.11	267.11

19 LOAD1

0.00	-53847.18	4937.87	-9467.36	-74.11	207.07	-152.08
1.15	-54476.78	5163.21	-9467.36	-74.11	11137.36	-5983.05
2.31	-55106.38	5388.55	-9467.36	-74.11	22067.65	-12074.17

20 LOAD1

0.00	-37483.16	-14194.09	5955.67	-9622.63	4464.22	-22681.03
8.2E-01	-37327.88	-13745.52	5955.67	-9622.63	-416.67	-11232.27
1.64	-37172.60	-13296.96	5955.67	-9622.63	-5297.56	-151.12

21 LOAD1

0.00	-91402.11	-16114.72	-1661.24	5137.39	-2017.43	-8565.53
1.69	-91848.40	-1631.95	-1661.24	5137.39	788.29	6420.87
3.38	-92294.69	12850.83	-1661.24	5137.39	3594.00	-3053.06

22 LOAD1

0.00	-101754.93	3952.89	3429.62	147.45	3956.76	5303.88
5.9E-01	-101875.44	4269.60	3429.62	147.45	1950.33	2898.68
1.17	-101995.95	4586.30	3429.62	147.45	-56.11	308.19

Fig. 34 (con't)

23 LOAD1							
0.00	-59679.57	6128.90	-8821.22	50.77	-69.52	106.46	
9.9E-01	-60144.89	6468.76	-8821.22	50.77	8706.17	-6159.86	
1.99	-60610.21	6808.62	-8821.22	50.77	17481.86	-12764.29	
24 LOAD1							
0.00	-61108.54	-12692.91	8954.13	-7539.74	8379.45	-18385.62	
7.5E-01	-60970.09	-12283.13	8954.13	-7539.74	1692.79	-9059.97	
1.49	-60831.64	-11873.35	8954.13	-7539.74	-4993.87	-40.32	
25 LOAD1							
0.00	-51845.80	-15519.50	-1663.72	3646.85	-2568.73	-6963.86	
1.66	-52804.40	-1291.13	-1663.72	3646.85	196.76	7007.72	
3.32	-53763.00	12937.25	-1663.72	3646.85	2962.25	-2671.56	
26 LOAD1							
0.00	-63757.08	2584.46	3262.05	282.57	3429.09	3508.82	
5.5E-01	-63897.14	2868.61	3262.05	282.57	1644.90	2017.54	
1.09	-64037.20	3152.77	3262.05	282.57	-139.28	370.84	
27 LOAD1							
0.00	-42697.78	1458.41	-4028.43	276.54	-251.43	175.72	
1.16	-43149.34	1955.07	-4028.43	276.54	4417.16	-1802.25	
2.32	-43600.91	2451.73	-4028.43	276.54	9085.76	-4355.80	
28 LOAD1							
0.00	-54366.90	-6533.06	5541.69	-3797.89	5977.68	-7108.78	
8.2E-01	-54206.13	-6084.50	5541.69	-3797.89	1418.62	-1918.64	
1.65	-54045.36	-5635.93	5541.69	-3797.89	-3140.44	2902.47	
29 LOAD1							
0.00	-9198.57	-15071.58	-25.56	-572.02	-1631.67	-4471.94	
1.69	-10451.83	-588.80	-25.56	-572.02	-1588.35	8795.79	
3.39	-11705.08	13893.97	-25.56	-572.02	-1545.04	-2476.57	
30 LOAD1							
0.00	-18176.17	-915.30	-1618.35	283.06	-2387.70	-477.37	
6.6E-01	-18431.11	-631.02	-1618.35	283.06	-1320.78	32.35	
1.32	-18686.06	-346.74	-1618.35	283.06	-253.85	354.65	
31 LOAD1							
0.00	-18616.10	-12.88	-728.27	-145.10	112.55	1805.55	
1.79	-19251.50	806.24	-728.27	-145.10	1416.02	1095.57	
3.58	-19886.90	1625.37	-728.27	-145.10	2719.49	-1080.50	
32 LOAD1							
0.00	-19097.66	-2190.26	1707.45	-1096.58	1778.53	-2100.90	
1.06	-18868.46	-1623.18	1707.45	-1096.58	-24.55	-87.38	
2.11	-18639.26	-1056.10	1707.45	-1096.58	-1827.63	1327.29	
33 LOAD1							
0.00	11470.56	-8714.35	-358.28	0.00	-1283.55	-1833.70	
1.79	11470.56	-511.85	-358.28	0.00	-641.77	6429.50	
3.58	11470.56	7690.65	-358.28	0.00	0.00	0.00	
34 LOAD1							
0.00	-49401.00	-517.81	0.00	0.00	0.00	-1122.76	
2.17	-49600.83	-258.91	0.00	0.00	0.00	-280.69	
4.34	-49800.65	0.00	0.00	0.00	0.00	0.00	

35 LOAD1							
0.00	-60861.67	-303.20	0.00	0.00	0.00	-305.10	
1.01	-60869.15	-151.60	0.00	0.00	0.00	-76.28	
2.01	-60876.63	0.00	0.00	0.00	0.00	0.00	
36 LOAD1							
0.00	76954.63	-475.79	0.00	0.00	0.00	-750.78	
1.58	76962.10	-237.90	0.00	0.00	0.00	-187.70	
3.16	76969.58	0.00	0.00	0.00	0.00	0.00	
37 LOAD1							
0.00	-2151.99	-542.80	0.00	0.00	0.00	-1063.46	
1.96	-2268.93	-271.40	0.00	0.00	0.00	-265.86	
3.92	-2385.86	0.00	0.00	0.00	0.00	0.00	
38 LOAD1							
0.00	-51567.93	-301.84	0.00	0.00	0.00	-303.49	
1.01	-51552.98	-150.92	0.00	0.00	0.00	-75.87	
2.01	-51538.02	0.00	0.00	0.00	0.00	0.00	
39 LOAD1							
0.00	95341.13	-466.24	0.00	0.00	0.00	-720.77	
1.55	95346.45	-233.12	0.00	0.00	0.00	-180.19	
3.09	95351.77	0.00	0.00	0.00	0.00	0.00	
40 LOAD1							
0.00	29041.80	-534.45	0.00	0.00	0.00	-986.16	
1.85	28963.99	-267.22	0.00	0.00	0.00	-246.54	
3.69	28886.18	0.00	0.00	0.00	0.00	0.00	
41 LOAD1							
0.00	-26078.65	-307.01	0.00	0.00	0.00	-313.18	
1.02	-26068.01	-153.50	0.00	0.00	0.00	-78.30	
2.04	-26057.37	0.00	0.00	0.00	0.00	0.00	
42 LOAD1							
0.00	108648.25	-403.63	0.00	0.00	0.00	-540.11	
1.34	108651.13	-201.82	0.00	0.00	0.00	-135.03	
2.68	108654.02	0.00	0.00	0.00	0.00	0.00	
43 LOAD1							
0.00	43546.49	-481.50	0.00	0.00	0.00	-787.04	
1.63	43493.34	-240.75	0.00	0.00	0.00	-196.76	
3.27	43440.18	0.00	0.00	0.00	0.00	0.00	
44 LOAD1							
0.00	31063.17	-320.17	0.00	0.00	0.00	-340.02	
1.06	31068.97	-160.08	0.00	0.00	0.00	-85.01	
2.12	31074.77	0.00	0.00	0.00	0.00	0.00	
45 LOAD1							
0.00	97597.09	-328.36	0.00	0.00	0.00	-357.40	
1.09	97597.43	-164.18	0.00	0.00	0.00	-89.35	
2.18	97597.77	0.00	0.00	0.00	0.00	0.00	
46 LOAD1							
0.00	38198.05	-417.27	0.00	0.00	0.00	-588.21	
1.41	38157.05	-208.64	0.00	0.00	0.00	-147.05	
2.82	38116.04	0.00	0.00	0.00	0.00	0.00	

Fig. 34 (con't)

Fig. 34 (con't)

47 LOAD1							
0.00	89340.58	-301.48	0.00	0.00	0.00	0.00	-301.29
1.0E+00	89340.01	-150.74	0.00	0.00	0.00	0.00	-75.32
2.00	89339.45	0.00	0.00	0.00	0.00	0.00	0.00
48 LOAD1							
0.00	69259.28	-278.09	0.00	0.00	0.00	0.00	-256.36
9.2E-01	69258.38	-139.04	0.00	0.00	0.00	0.00	-64.09
1.84	69257.47	0.00	0.00	0.00	0.00	0.00	0.00
49 LOAD1							
0.00	41986.06	-381.56	0.00	0.00	0.00	0.00	-492.66
1.29	41946.91	-190.78	0.00	0.00	0.00	0.00	-123.16
2.58	41907.77	0.00	0.00	0.00	0.00	0.00	0.00
50 LOAD1							
0.00	94112.16	-302.35	0.00	0.00	0.00	0.00	-303.09
1.00	94109.06	-151.17	0.00	0.00	0.00	0.00	-75.77
2.00	94105.97	0.00	0.00	0.00	0.00	0.00	0.00
51 LOAD1							
0.00	68516.23	-261.35	0.00	0.00	0.00	0.00	-226.56
8.7E-01	68511.48	-130.67	0.00	0.00	0.00	0.00	-56.64
1.73	68506.73	0.00	0.00	0.00	0.00	0.00	0.00
52 LOAD1							
0.00	51817.84	-369.54	0.00	0.00	0.00	0.00	-469.84
1.27	51766.46	-184.77	0.00	0.00	0.00	0.00	-117.46
2.54	51715.09	0.00	0.00	0.00	0.00	0.00	0.00
53 LOAD1							
0.00	53417.38	-302.35	0.00	0.00	0.00	0.00	-303.62
1.00	53407.86	-151.17	0.00	0.00	0.00	0.00	-75.91
2.01	53398.36	0.00	0.00	0.00	0.00	0.00	0.00
54 LOAD1							
0.00	49166.46	-278.09	0.00	0.00	0.00	0.00	-256.71
9.2E-01	49159.12	-139.04	0.00	0.00	0.00	0.00	-64.18
1.85	49151.77	0.00	0.00	0.00	0.00	0.00	0.00
55 LOAD1							
0.00	21168.41	-381.56	0.00	0.00	0.00	0.00	-517.98
1.36	21094.03	-190.78	0.00	0.00	0.00	0.00	-129.50
2.72	21019.65	0.00	0.00	0.00	0.00	0.00	0.00
56 LOAD1							
0.00	15240.59	-307.92	0.00	0.00	0.00	0.00	-315.73
1.03	15225.90	-153.96	0.00	0.00	0.00	0.00	-78.93
2.05	15211.21	0.00	0.00	0.00	0.00	0.00	0.00
57 LOAD1							
0.00	8197.35	-331.64	0.00	0.00	0.00	0.00	-364.95
1.10	8190.00	-165.82	0.00	0.00	0.00	0.00	-91.24
2.20	8182.66	0.00	0.00	0.00	0.00	0.00	0.00

58 LOAD1

0.00	103187.41	-150.84	0.00	0.00	0.00	-213.59
1.42	103387.24	-75.42	0.00	0.00	0.00	-53.40
2.83	103587.07	0.00	0.00	0.00	0.00	0.00

59 LOAD1

0.00	-131390.09	-283.59	0.00	0.00	0.00	-266.59
9.4E-01	-131390.09	-141.79	0.00	0.00	0.00	-66.65
1.88	-131390.09	0.00	0.00	0.00	0.00	0.00

60 LOAD1

0.00	101268.96	-415.29	0.00	0.00	0.00	-605.18
1.46	101341.07	-207.64	0.00	0.00	0.00	-151.30
2.91	101413.18	0.00	0.00	0.00	0.00	0.00

61 LOAD1

0.00	-25247.82	-150.84	0.00	0.00	0.00	-145.48
9.6E-01	-25372.23	-75.42	0.00	0.00	0.00	-36.37
1.93	-25496.64	0.00	0.00	0.00	0.00	0.00

62 LOAD1

0.00	-24823.19	-98.62	0.00	0.00	0.00	-191.95
1.95	-24533.79	-49.31	0.00	0.00	0.00	-47.99
3.89	-24244.38	0.00	0.00	0.00	0.00	0.00

63 LOAD1

0.00	70813.07	-328.25	0.00	0.00	0.00	-706.85
2.15	71093.36	-164.13	0.00	0.00	0.00	-176.71
4.31	71373.65	0.00	0.00	0.00	0.00	0.00

64 LOAD1

0.00	78360.23	-329.94	0.00	0.00	0.00	-456.37
1.38	78232.51	-164.97	0.00	0.00	0.00	-114.09
2.77	78104.79	0.00	0.00	0.00	0.00	0.00

65 LOAD1

0.00	-24660.33	-150.84	0.00	0.00	0.00	-156.57
1.04	-24523.13	-75.42	0.00	0.00	0.00	-39.14
2.08	-24385.92	0.00	0.00	0.00	0.00	0.00

66 LOAD1

0.00	-68028.74	-301.27	0.00	0.00	0.00	-300.95
1.0E+00	-68032.05	-150.64	0.00	0.00	0.00	-75.24
2.00	-68035.37	0.00	0.00	0.00	0.00	0.00

67 LOAD1

0.00	38638.59	-404.69	0.00	0.00	0.00	-562.10
1.39	38692.91	-202.34	0.00	0.00	0.00	-140.52
2.78	38747.23	0.00	0.00	0.00	0.00	0.00

68 LOAD1

0.00	4077.08	-150.84	0.00	0.00	0.00	-112.24
7.4E-01	3993.95	-75.42	0.00	0.00	0.00	-28.06
1.49	3910.82	0.00	0.00	0.00	0.00	0.00

Fig. 34 (con't)

Fig. 34 (con't)

69 LOAD1							
0.00	-83289.29	-160.16	0.00	0.00	0.00	-282.56	
1.76	-83035.52	-80.08	0.00	0.00	0.00	-70.64	
3.53	-82781.74	0.00	0.00	0.00	0.00	0.00	
70 LOAD1							
0.00	64236.23	-309.06	0.00	0.00	0.00	-359.30	
1.16	64153.35	-154.53	0.00	0.00	0.00	-89.82	
2.33	64070.46	0.00	0.00	0.00	0.00	0.00	
71 LOAD1							
0.00	118401.83	-209.22	0.00	0.00	0.00	-410.18	
1.96	118678.43	-104.61	0.00	0.00	0.00	-102.55	
3.92	118955.04	0.00	0.00	0.00	0.00	0.00	
72 LOAD1							
0.00	-59978.24	-150.84	0.00	0.00	0.00	-118.45	
7.9E-01	-59886.91	-75.42	0.00	0.00	0.00	-29.61	
1.57	-59795.57	0.00	0.00	0.00	0.00	0.00	
73 LOAD1							
0.00	-69106.44	-269.75	0.00	0.00	0.00	-241.20	
8.9E-01	-69106.20	-134.87	0.00	0.00	0.00	-60.30	
1.79	-69105.95	0.00	0.00	0.00	0.00	0.00	
74 LOAD1							
0.00	83375.62	-363.47	0.00	0.00	0.00	-446.29	
1.23	83411.30	-181.74	0.00	0.00	0.00	-111.57	
2.46	83446.97	0.00	0.00	0.00	0.00	0.00	
75 LOAD1							
0.00	19209.74	-150.84	0.00	0.00	0.00	-93.96	
6.2E-01	19153.69	-75.42	0.00	0.00	0.00	-23.49	
1.25	19097.65	0.00	0.00	0.00	0.00	0.00	
76 LOAD1							
0.00	-144234.83	-199.35	0.00	0.00	0.00	-290.32	
1.46	-144039.09	-99.68	0.00	0.00	0.00	-72.58	
2.91	-143843.34	0.00	0.00	0.00	0.00	0.00	
77 LOAD1							
0.00	13663.39	-250.07	0.00	0.00	0.00	-226.92	
9.1E-01	13607.72	-125.04	0.00	0.00	0.00	-56.73	
1.81	13552.06	0.00	0.00	0.00	0.00	0.00	
78 LOAD1							
0.00	140919.38	-141.51	0.00	0.00	0.00	-239.75	
1.69	141164.94	-70.75	0.00	0.00	0.00	-59.94	
3.39	141410.50	0.00	0.00	0.00	0.00	0.00	
79 LOAD1							
0.00	-13137.84	-150.84	0.00	0.00	0.00	-95.94	
6.4E-01	-13078.54	-75.42	0.00	0.00	0.00	-23.98	
1.27	-13019.24	0.00	0.00	0.00	0.00	0.00	

Fig. 34 (con't)

80 LOAD1							
0.00	-33674.81	-196.12	0.00	0.00	0.00	-127.51	
6.5E-01	-33674.43	-98.06	0.00	0.00	0.00	-31.88	
1.30	-33674.04	0.00	0.00	0.00	0.00	0.00	
81 LOAD1							
0.00	62403.21	-325.06	0.00	0.00	0.00	-352.41	
1.08	62421.25	-162.53	0.00	0.00	0.00	-88.10	
2.17	62439.28	0.00	0.00	0.00	0.00	0.00	
82 LOAD1							
0.00	41879.64	-150.84	0.00	0.00	0.00	-86.01	
5.7E-01	41838.29	-75.42	0.00	0.00	0.00	-21.50	
1.14	41796.94	0.00	0.00	0.00	0.00	0.00	
83 LOAD1							
0.00	-185396.39	-243.08	0.00	0.00	0.00	-278.22	
1.14	-185273.77	-121.54	0.00	0.00	0.00	-69.55	
2.29	-185151.16	0.00	0.00	0.00	0.00	0.00	
84 LOAD1							
0.00	18233.35	-191.33	0.00	0.00	0.00	-132.16	
6.9E-01	18192.09	-95.67	0.00	0.00	0.00	-33.04	
1.38	18150.82	0.00	0.00	0.00	0.00	0.00	
85 LOAD1							
0.00	179670.83	-108.33	0.00	0.00	0.00	-143.62	
1.33	179863.31	-54.17	0.00	0.00	0.00	-35.91	
2.65	180055.81	0.00	0.00	0.00	0.00	0.00	
86 LOAD1							
0.00	74517.70	-150.84	0.00	0.00	0.00	-85.15	
5.6E-01	74557.23	-75.42	0.00	0.00	0.00	-21.29	
1.13	74596.77	0.00	0.00	0.00	0.00	0.00	
87 LOAD1							
0.00	-1629.38	-114.26	0.00	0.00	0.00	-43.28	
3.8E-01	-1629.30	-57.13	0.00	0.00	0.00	-10.82	
7.6E-01	-1629.21	0.00	0.00	0.00	0.00	0.00	
88 LOAD1							
0.00	7007.05	-314.03	0.00	0.00	0.00	-326.91	
1.04	7008.26	-157.02	0.00	0.00	0.00	-81.73	
2.08	7009.47	0.00	0.00	0.00	0.00	0.00	
89 LOAD1							
0.00	80070.38	-150.84	0.00	0.00	0.00	-84.56	
5.6E-01	80032.14	-75.42	0.00	0.00	0.00	-21.14	
1.12	79993.90	0.00	0.00	0.00	0.00	0.00	
90 LOAD1							
0.00	-187652.02	-286.90	0.00	0.00	0.00	-315.18	
1.10	-187569.08	-143.45	0.00	0.00	0.00	-78.80	
2.20	-187486.14	0.00	0.00	0.00	0.00	0.00	

Fig. 34 (con't)

91 LOAD1							
0.00	51129.95	-171.20	0.00	0.00	0.00	-106.45	
6.2E-01	51091.63	-85.60	0.00	0.00	0.00	-26.61	
1.24	51053.31	0.00	0.00	0.00	0.00	0.00	
92 LOAD1							
0.00	201178.58	-118.17	0.00	0.00	0.00	-107.92	
9.1E-01	201303.00	-59.09	0.00	0.00	0.00	-26.98	
1.83	201427.44	0.00	0.00	0.00	0.00	0.00	
93 LOAD1							
0.00	79747.88	-150.84	0.00	0.00	0.00	-81.66	
5.4E-01	79779.18	-75.42	0.00	0.00	0.00	-20.41	
1.08	79810.48	0.00	0.00	0.00	0.00	0.00	
94 LOAD1							
0.00	11202.62	-334.58	0.00	0.00	0.00	-373.05	
1.11	11185.35	-167.29	0.00	0.00	0.00	-93.26	
2.23	11168.08	0.00	0.00	0.00	0.00	0.00	
95 LOAD1							
0.00	-10227.87	-74.22	0.00	0.00	0.00	-18.26	
2.5E-01	-10227.96	-37.11	0.00	0.00	0.00	-4.56	
4.9E-01	-10228.04	0.00	0.00	0.00	0.00	0.00	
96 LOAD1							
0.00	68471.21	-150.84	0.00	0.00	0.00	-88.66	
5.9E-01	68424.59	-75.42	0.00	0.00	0.00	-22.17	
1.18	68377.97	0.00	0.00	0.00	0.00	0.00	
97 LOAD1							
0.00	70904.44	-190.86	0.00	0.00	0.00	-135.50	
7.1E-01	70855.87	-95.43	0.00	0.00	0.00	-33.87	
1.42	70807.30	0.00	0.00	0.00	0.00	0.00	
98 LOAD1							
0.00	-128790.88	-364.32	0.00	0.00	0.00	-472.19	
1.30	-128719.91	-182.16	0.00	0.00	0.00	-118.05	
2.59	-128648.94	0.00	0.00	0.00	0.00	0.00	
99 LOAD1							
0.00	160359.48	-160.79	0.00	0.00	0.00	-128.55	
8.0E-01	160449.36	-80.40	0.00	0.00	0.00	-32.14	
1.60	160539.23	0.00	0.00	0.00	0.00	0.00	
100 LOAD1							
0.00	37395.82	-150.84	0.00	0.00	0.00	-82.94	
5.5E-01	37430.34	-75.42	0.00	0.00	0.00	-20.74	
1.10	37464.86	0.00	0.00	0.00	0.00	0.00	
101 LOAD1							
0.00	26249.42	-420.17	0.00	0.00	0.00	-599.42	
1.43	26202.86	-210.09	0.00	0.00	0.00	-149.86	
2.85	26156.30	0.00	0.00	0.00	0.00	0.00	

Fig. 34 (con't)

102 LOAD1							
0.00	-5495.41	-80.09	0.00	0.00	0.00	-21.29	
2.7E-01	-5497.36	-40.04	0.00	0.00	0.00	-5.32	
5.3E-01	-5499.31	0.00	0.00	0.00	0.00	0.00	
103 LOAD1							
0.00	23351.14	-150.84	0.00	0.00	0.00	-100.90	
6.7E-01	23284.11	-75.42	0.00	0.00	0.00	-25.23	
1.34	23217.07	0.00	0.00	0.00	0.00	0.00	
104 LOAD1							
0.00	-45748.31	-543.85	0.00	0.00	0.00	-1042.70	
1.92	-45649.87	-271.92	0.00	0.00	0.00	-260.67	
3.83	-45551.43	0.00	0.00	0.00	0.00	0.00	
105 LOAD1							
0.00	31353.95	-281.96	0.00	0.00	0.00	-304.01	
1.08	31272.87	-140.98	0.00	0.00	0.00	-76.00	
2.16	31191.78	0.00	0.00	0.00	0.00	0.00	
106 LOAD1							
0.00	71752.28	-215.87	0.00	0.00	0.00	-194.93	
9.0E-01	71835.35	-107.94	0.00	0.00	0.00	-48.73	
1.81	71918.43	0.00	0.00	0.00	0.00	0.00	
107 LOAD1							
0.00	13315.73	-150.84	0.00	0.00	0.00	-91.80	
6.1E-01	13368.07	-75.42	0.00	0.00	0.00	-22.95	
1.22	13420.42	0.00	0.00	0.00	0.00	0.00	
108 LOAD1							
0.00	6199.57	-167.22	0.00	0.00	0.00	-93.99	
5.6E-01	6185.52	-83.61	0.00	0.00	0.00	-23.50	
1.12	6171.47	0.00	0.00	0.00	0.00	0.00	
109 LOAD1							
0.00	-9625.51	-301.67	0.00	0.00	0.00	-302.03	
1.00	-9618.17	-150.84	0.00	0.00	0.00	-75.51	
2.00	-9610.82	0.00	0.00	0.00	0.00	0.00	
110 LOAD1							
0.00	21615.44	-337.28	0.00	0.00	0.00	-454.08	
1.35	21728.57	-168.64	0.00	0.00	0.00	-113.52	
2.69	21841.69	0.00	0.00	0.00	0.00	0.00	
111 LOAD1							
0.00	405095.75	-408.72	0.00	0.00	0.00	-554.32	
1.36	405086.63	-204.36	0.00	0.00	0.00	-138.58	
2.71	405077.53	0.00	0.00	0.00	0.00	0.00	
112 LOAD1							
0.00	-76176.48	-353.84	0.00	0.00	0.00	-1220.42	
3.45	-76665.71	-176.92	0.00	0.00	0.00	-305.10	
6.90	-77154.94	0.00	0.00	0.00	0.00	0.00	

Fig. 34 (con't)

113 LOAD1

0.00	-90509.30	-275.43	0.00	0.00	0.00	-802.11
2.91	-90926.42	-137.71	0.00	0.00	0.00	-200.53
5.82	-91343.54	0.00	0.00	0.00	0.00	0.00

114 LOAD1

0.00	-60580.68	-431.77	0.00	0.00	0.00	-1200.36
2.78	-60940.18	-215.89	0.00	0.00	0.00	-300.09
5.56	-61299.67	0.00	0.00	0.00	0.00	0.00

115 LOAD1

0.00	315887.59	-339.99	0.00	0.00	0.00	-399.29
1.17	315837.78	-170.00	0.00	0.00	0.00	-99.82
2.35	315787.97	0.00	0.00	0.00	0.00	0.00

116 LOAD1

0.00	-67643.73	-355.66	0.00	0.00	0.00	-824.80
2.32	-67944.95	-177.83	0.00	0.00	0.00	-206.20
4.64	-68246.18	0.00	0.00	0.00	0.00	0.00

117 LOAD1

0.00	-46937.64	-269.91	0.00	0.00	0.00	-649.03
2.40	-47274.31	-134.95	0.00	0.00	0.00	-162.26
4.81	-47610.97	0.00	0.00	0.00	0.00	0.00

118 LOAD1

0.00	-42597.20	-443.94	0.00	0.00	0.00	-1331.72
3.00	-42991.49	-221.97	0.00	0.00	0.00	-332.93
6.00	-43385.78	0.00	0.00	0.00	0.00	0.00

119 LOAD1

0.00	357845.19	-368.53	0.00	0.00	0.00	-453.65
1.23	357868.03	-184.27	0.00	0.00	0.00	-113.41
2.46	357890.84	0.00	0.00	0.00	0.00	0.00

120 LOAD1

0.00	242376.27	-335.73	0.00	0.00	0.00	-404.73
1.21	242306.39	-167.87	0.00	0.00	0.00	-101.18
2.41	242236.50	0.00	0.00	0.00	0.00	0.00

121 LOAD1

0.00	-22170.41	-271.67	0.00	0.00	0.00	-486.94
1.79	-22404.16	-135.83	0.00	0.00	0.00	-121.73
3.58	-22637.92	0.00	0.00	0.00	0.00	0.00

122 LOAD1

0.00	-72906.52	-172.41	0.00	0.00	0.00	-303.80
1.76	-73157.94	-86.21	0.00	0.00	0.00	-75.95
3.52	-73409.34	0.00	0.00	0.00	0.00	0.00

123 LOAD1

0.00	57483.74	-423.31	0.00	0.00	0.00	-1000.43
2.36	57196.90	-211.66	0.00	0.00	0.00	-250.11
4.73	56910.05	0.00	0.00	0.00	0.00	0.00

Fig. 34 (con't)

124 LOAD1							
0.00	134695.19	-326.00	0.00	0.00	0.00	-363.52	
1.12	134653.69	-163.00	0.00	0.00	0.00	-90.88	
2.23	134612.20	0.00	0.00	0.00	0.00	0.00	
125 LOAD1							
0.00	21305.97	-230.95	0.00	0.00	0.00	-305.54	
1.32	21143.22	-115.47	0.00	0.00	0.00	-76.39	
2.65	20980.47	0.00	0.00	0.00	0.00	0.00	
126 LOAD1							
0.00	-87489.37	-75.95	0.00	0.00	0.00	-84.70	
1.12	-87653.24	-37.97	0.00	0.00	0.00	-21.18	
2.23	-87817.12	0.00	0.00	0.00	0.00	0.00	
127 LOAD1							
0.00	188308.50	-386.78	0.00	0.00	0.00	-680.13	
1.76	188126.98	-193.39	0.00	0.00	0.00	-170.03	
3.52	187945.45	0.00	0.00	0.00	0.00	0.00	
128 LOAD1							
0.00	88352.34	-356.90	0.00	0.00	0.00	-424.60	
1.19	88333.45	-178.45	0.00	0.00	0.00	-106.15	
2.38	88314.54	0.00	0.00	0.00	0.00	0.00	
129 LOAD1							
0.00	-11796.87	-243.63	0.00	0.00	0.00	-297.87	
1.22	-11935.32	-121.82	0.00	0.00	0.00	-74.47	
2.45	-12073.77	0.00	0.00	0.00	0.00	0.00	
130 LOAD1							
0.00	-52209.10	-117.94	0.00	0.00	0.00	-105.44	
8.9E-01	-52330.36	-58.97	0.00	0.00	0.00	-26.36	
1.79	-52451.62	0.00	0.00	0.00	0.00	0.00	
131 LOAD1							
0.00	198682.83	-394.24	0.00	0.00	0.00	-606.45	
1.54	198560.44	-197.12	0.00	0.00	0.00	-151.61	
3.08	198438.05	0.00	0.00	0.00	0.00	0.00	
132 LOAD1							
0.00	44072.58	-468.54	0.00	0.00	0.00	-729.28	
1.56	44087.95	-234.27	0.00	0.00	0.00	-182.32	
3.11	44103.31	0.00	0.00	0.00	0.00	0.00	
133 LOAD1							
0.00	-2521.93	-266.17	0.00	0.00	0.00	-372.90	
1.40	-2686.09	-133.08	0.00	0.00	0.00	-93.23	
2.80	-2850.24	0.00	0.00	0.00	0.00	0.00	
134 LOAD1							
0.00	18076.10	-183.03	0.00	0.00	0.00	-182.68	
1.0E+00	17956.55	-91.51	0.00	0.00	0.00	-45.67	
2.00	17837.00	0.00	0.00	0.00	0.00	0.00	

Fig. 34 (con't)

135 LOAD1							
0.00	77336.05	-463.11	0.00	0.00	0.00	-777.31	
1.68	77233.70	-231.56	0.00	0.00	0.00	-194.33	
3.36	77131.34	0.00	0.00	0.00	0.00	0.00	
136 LOAD1							
0.00	8928.39	-263.72	0.00	0.00	0.00	-389.45	
1.48	8748.87	-131.86	0.00	0.00	0.00	-97.36	
2.95	8569.35	0.00	0.00	0.00	0.00	0.00	
137 LOAD1							
0.00	-5297.88	-621.54	0.00	0.00	0.00	-1396.02	
2.25	-5432.79	-310.77	0.00	0.00	0.00	-349.00	
4.49	-5567.71	0.00	0.00	0.00	0.00	0.00	
138 LOAD1							
0.00	-253253.66	-286.77	0.00	0.00	0.00	-305.13	
1.06	-253181.56	-143.38	0.00	0.00	0.00	-76.28	
2.13	-253109.45	0.00	0.00	0.00	0.00	0.00	
139 LOAD1							
0.00	-111025.11	-318.62	0.00	0.00	0.00	-357.87	
1.12	-110967.48	-159.31	0.00	0.00	0.00	-89.47	
2.25	-110909.84	0.00	0.00	0.00	0.00	0.00	
140 LOAD1							
0.00	-125274.23	-314.79	0.00	0.00	0.00	-336.71	
1.07	-125238.80	-157.40	0.00	0.00	0.00	-84.18	
2.14	-125203.37	0.00	0.00	0.00	0.00	0.00	
141 LOAD1							
0.00	-215328.66	-310.91	0.00	0.00	0.00	-322.49	
1.04	-215311.00	-155.46	0.00	0.00	0.00	-80.62	
2.07	-215293.34	0.00	0.00	0.00	0.00	0.00	
142 LOAD1							
0.00	-258263.67	-305.15	0.00	0.00	0.00	-308.67	
1.01	-258262.55	-152.57	0.00	0.00	0.00	-77.17	
2.02	-258261.42	0.00	0.00	0.00	0.00	0.00	
143 LOAD1							
0.00	-160852.59	-322.27	0.00	0.00	0.00	-346.23	
1.07	-160869.78	-161.13	0.00	0.00	0.00	-86.56	
2.15	-160886.98	0.00	0.00	0.00	0.00	0.00	
144 LOAD1							
0.00	-55260.26	-377.97	0.00	0.00	0.00	-486.59	
1.29	-55304.87	-188.99	0.00	0.00	0.00	-121.65	
2.57	-55349.47	0.00	0.00	0.00	0.00	0.00	
145 LOAD1							
0.00	-4547.24	-382.56	0.00	0.00	0.00	-519.94	
1.36	-4473.51	-191.28	0.00	0.00	0.00	-129.99	
2.72	-4399.77	0.00	0.00	0.00	0.00	0.00	

146 LOAD1

0.00	10826.70	-337.28	0.00	0.00	0.00	-445.14
1.32	10720.92	-168.64	0.00	0.00	0.00	-111.28
2.64	10615.13	0.00	0.00	0.00	0.00	0.00

Fig. 34 (con't)

147 LOAD1

0.00	-139725.91	-301.67	0.00	0.00	0.00	-337.28
1.12	-139650.48	-150.84	0.00	0.00	0.00	-84.32
2.24	-139575.06	0.00	0.00	0.00	0.00	0.00

148 LOAD1

0.00	-163097.70	-301.67	0.00	0.00	0.00	-320.47
1.06	-163043.63	-150.84	0.00	0.00	0.00	-80.12
2.12	-162989.55	0.00	0.00	0.00	0.00	0.00

149 LOAD1

0.00	-169000.31	-301.67	0.00	0.00	0.00	-309.82
1.03	-168965.02	-150.84	0.00	0.00	0.00	-77.45
2.05	-168929.72	0.00	0.00	0.00	0.00	0.00

150 LOAD1

0.00	-164541.89	-301.67	0.00	0.00	0.00	-303.80
1.01	-164523.94	-150.84	0.00	0.00	0.00	-75.95
2.01	-164505.98	0.00	0.00	0.00	0.00	0.00

151 LOAD1

0.00	-151245.55	-301.67	0.00	0.00	0.00	-301.68
1.00	-151244.25	-150.84	0.00	0.00	0.00	-75.42
2.00	-151242.95	0.00	0.00	0.00	0.00	0.00

152 LOAD1

0.00	-99527.72	-301.67	0.00	0.00	0.00	-303.22
1.01	-99543.05	-150.84	0.00	0.00	0.00	-75.81
2.01	-99558.37	0.00	0.00	0.00	0.00	0.00

153 LOAD1

0.00	-31613.48	-301.67	0.00	0.00	0.00	-308.60
1.02	-31645.99	-150.84	0.00	0.00	0.00	-77.15
2.05	-31678.50	0.00	0.00	0.00	0.00	0.00

154 LOAD1

0.00	-29976.73	-301.67	0.00	0.00	0.00	-302.76
1.00	-29963.93	-150.84	0.00	0.00	0.00	-75.69
2.01	-29951.13	0.00	0.00	0.00	0.00	0.00

155 LOAD1

0.00	-5390.14	-301.67	0.00	0.00	0.00	-302.12
1.00	-5381.93	-150.84	0.00	0.00	0.00	-75.53
2.00	-5373.73	0.00	0.00	0.00	0.00	0.00

156 LOAD1

0.00	22379.09	-301.67	0.00	0.00	0.00	-301.74
1.00	22382.34	-150.84	0.00	0.00	0.00	-75.44
2.00	22385.60	0.00	0.00	0.00	0.00	0.00

157 LOAD1

0.00	57387.43	-301.67	0.00	0.00	0.00	-301.69
1.00	57385.61	-150.84	0.00	0.00	0.00	-75.42
2.00	57383.80	0.00	0.00	0.00	0.00	0.00

Fig. 34 (con't)

158 LOAD1

0.00	73271.70	-301.67	0.00	0.00	0.00	-301.99
1.00	73264.77	-150.84	0.00	0.00	0.00	-75.50
2.00	73257.83	0.00	0.00	0.00	0.00	0.00

159 LOAD1

0.00	37649.22	-301.67	0.00	0.00	0.00	-302.64
1.00	37637.13	-150.84	0.00	0.00	0.00	-75.66
2.01	37625.02	0.00	0.00	0.00	0.00	0.00

160 LOAD1

0.00	-3115.81	-301.67	0.00	0.00	0.00	-303.10
1.00	-3130.50	-150.84	0.00	0.00	0.00	-75.77
2.01	-3145.19	0.00	0.00	0.00	0.00	0.00

161 LOAD1

0.00	39519.29	-469.52	0.00	0.00	0.00	-1465.26
3.12	39111.29	-234.76	0.00	0.00	0.00	-366.31
6.24	38703.28	0.00	0.00	0.00	0.00	0.00

Fig.35: collage

VII.4 Conclusion

This thesis began as an investigation of form generation through the modelling of stabilizing systems of tensile and compressive forces. The structural-mechanical systems of tensegrity challenged the form of the cantilever span as the topology to investigate the contextual forces of gravity. The essential pursuit was to develop an optimal form that would equally challenge the amount of mass organized to stabilize form.

Throughout the research it was found that the principles of tensegrity systems as a means of optimal efficiency posed a challenge by nature of its stabilizing requirements: mainly that of continuous tension in a gravitational environment, and at a scale of which the structure's mass reveals itself to be its own adversary of compression. The cantilever bridge was developed with the awareness that extreme tensile stresses would occur more in certain members than in others, as shown in the observations by Le Ricolais and by Haider and Strutt experiments. Stress analysis confirmed some of the observations and revealed

new aspects to be considered for further refinement of the bridge. It was during this stage of development that the analysis had allowed for observation into the actual deformations of the structural system, leading to another degree of resolution in structural formation. Techniques for prestressing certainly need to be considered.

The desire and pursuit of form has been playful, resulting in a scientifically-driven process that has inspired an imaginative perspective to form generation. Such inspiration has led to many intuitive assumptions of how things behave physically and how a balance of forces is used to maintain their stability in space. As an architect of form, we begin to define the hierarchy of the complex machine - the assembly of parts and/or units so to speak - by assuming that their function is satisfactory to explain and make a working structure. The laws of physics inform us of their rules of assembly, where the geometric discipline of the tensegrity principle correlates its affects in spatial parameters.

The stress analysis performed by the computer is seen as a critique to the prescribed analytical methods used throughout this pursuit. In other words, whether it verifies or invalidates, formal conclusions are refined through this process. As such the degree of resolution increases the frame of reference by, to borrow from Dawkins again, a few more layers: statistically, but more importantly, I feel, the evolution and final confrontation to the nature of its physics.

The process has been a dynamically interwoven process, both literally in the physical making of the investigation and generally as precedent theories and observations have shown valuable importance and contribution to this field of study and to this thesis. The ideas and concepts explored were advanced through computer analysis, leading to another realm of insight into the behaviour of structural systems. Future implications are surely promising, moving towards further development of the bridge into a fully resolved structure ready for construction and full function.

The expenditure of energy, as an undercurrent theme throughout this process, is a profound concept. The bridge has brought about an immersive engagement with its formative environment. I have found that organizing the cantilever through the tensegrity principle has not only mediated the knowledge of gravitational forces, but has also brought about a greater insight towards formalizing an iconic and analog interpretation.

The evolution of natural formalizing systems, their patterns of growth and complexity in organization is most impressive compared to the forms created by the mind and the hand. The most significant aspect of this investigation has been the adoption of the role by which a cartographer and morphologist may find correlation with the nature of its behaviour, its mechanical aspects, and self-organizing principles to better understand the nature of the force that guides its organization or its rules of assembly. Any rheological comprehension of the structural morphology of form results in the search for the causes of its formation; such as search is inevitably inspiring to the imagination, one that arouses astonishment for the generative tendencies and prescription of structural form in space.

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