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TENSOR : Integration of Tensegrity and Origami to Generate Hybrid Structural Morphologies

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Abstract :This research re-evaluated the relationship between origami and tensegrity through computational means. Objective of this study is to study how geometrical principles of origami and structural principles of tensegrity can be integrated together to generate hybrid structural system through digital investigation. Origami folding has potential of developing deployable, reconfigurable structural system, where materiality plays a major role in the design. These techniques are researched using algorithmic tools and mathematics to attend geometric precision and complexity. With the help of simulation, certain origami folds had potential to integrate with tensegrity modules, where geometry is stabilized by adding another parameter will generate hybrid structural system.

Keywords: **Tensegrity, Deployable, Rigid, Origami, Structural stability, Hybrid system**

I. Introduction

The structural systems transfers the load through interconnected structural components or members. These structural systems are classified into 2 categories.

1. Rigid structural system
2. Deployable structural system

These two categories can be used to define the type of structural system in terms of their function. Right structural systems includes frame structures, load bearing structures, concrete structures, wood frame structures, tensile structures, space frames, etc whereas deployable structural system includes tensegrity structures and origami structures. Vast amount of research and practice uses rigid structural systems in building construction whereas deployable systems are being explored in smaller scale or as a product or installation purposes. This domain of research can be carried out further to explore the future possibilities of deployable structures from small scale product or large scale habitable spaces.

The advantage of deployable systems not only enables the possibility of innovative folding but also modular, functional, artistic structures which can be used for various functions.

This research was carried out forward in following steps:

1. Structural systems
2. Carpenter's rule theorem
3. Understanding tensegrity structures
4. Extracting structural principles of tensegrity structures
5. Finding the similarities between other structural systems which can be merged with it
6. Similarities between Origami geometrical principles with tensegrity structural principles for experimental research
7. Understanding origami folding
8. Extracting geometrical principles of origami folding
9. Case studies
10. Geometrical research of tensegrity and origami with materiality.
11. Evaluation of integration strategies and structural analysis
12. To generate hybrid structural morphology system and its applications.

The scope of tensegrity structure includes structural stability, multiple variations, long span structures, material optimisation, equilibrium forces acting on freeform tensegrity, small products where limitation of tensegrity is habitable space within the structure and usability of the space below. The outcome of this research is to explore structural resilience of tensegrity and allied with other principles that will help in scalability and usability of the space created by the structural system.

The structural principles of tensegrity can be merged with geometrical principles of origami to create a hybrid system where scope and limitations of both the system are merged together to form a hybrid structural system which has capacity of long span structure along with material optimisation and deployable nature of the system.

This hypothesis is based on **CARPENTER'S RULE THEOREM – TENSEGRITY**

1. Equilibrium stress

Linkages are edge connections of the assembly.

Bars have fixed length, strut can increase length and cable can decrease length in equilibrium – equilibrium stress

2. Equilibrium stress is non zero on strut or cable leads to rigidity hence stress is greater than zero is associated with cable and stress lesser than zero is associated with strut in tensegrity – duality

3. Non-crossing configurations in the structure leads to all planar surfaces, locked linkages and flexible distances between each members – polyhedral lifting

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4. Negative stress corresponds to valleys, positive stresses corresponds to mountains, zero stress corresponds to flat surface creating correspondence between stresses and polyhedral lifting - Maxwell Gremona theorem

 

This rule is used for further research in integration of geometrical principles of origami & structural principles of tensegrity to generate hybrid structural system through digital investigation.

II. Structure

Tensegrity

Tensegrity refers to structures where tension members only connect compression members to each other. This system involves 3 dimensional mechanical structure that maintain its stability due to an equilibrium of forces established between the compressive and tensile members. There are regular tensegrity structures and irregular tensegrity structures based on the morphology and connection logic. Regular geometries can be tested by analogue modelling whereas irregular geometries require digital investigation for better structural understanding. Tensegrity has five modules which can be repeated, modified to create various tensegrity structures.

1. X – module
2. 3 way prism
3. Square prism
4. Pentagonal
5. Hexagonal

The timeline of research in tensegrity structure elaborates the development of tensegrity in various domain such as arts & crafts, product design, architecture & engineering from Johannes Zebel, Kenneth Snelson, Buckminster Fuller, etc.

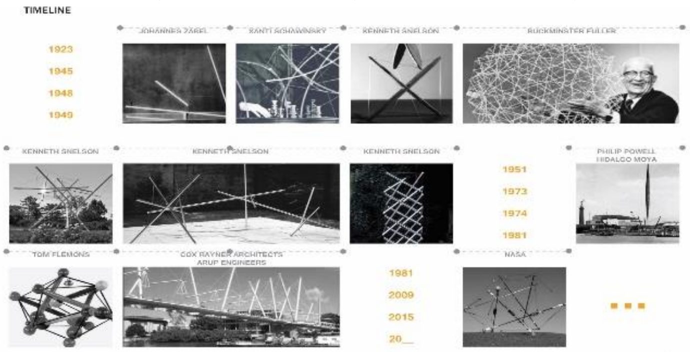

Chart 2.1

Origami

Origami is an art of paper folding in which valley, mountain folds, curved folding, pleats, reverse folding, sinks are used in construction of origami structure. This system has emerged as a method of creating deployable and reconfigurable structures used for emergency shelters, temporary habitat, product design, etc. There are 5 types or origami folding in which 3 types are extensively used in architecture – action, modular and tessellation.

1. Action origami
2. Modular origami
3. Wet origami
4. Pureland origami
5. Tessellation origami

The timeline of research in origami elaborates the development of origami in various domain such as arts & crafts, product design, medical, architecture & engineering, etc often associated with Japanese culture and applications by Akira Yoshizawa, Sadako Sasaki, face design by Al bahar, nestle chocolate museum, etc

Chart 2.2

The applications of origami folding techniques in architecture are majorly in form finding, emergency shelters and building facades whereas applications of tensegrity are in arts and crafts – sculpture, engineering and architecture. Scope of both the system is focused towards structural stability, material optimisation, responsive façade development, deployable structure, innovative techniques, computational optimisation, etc. Hence structural equilibrium can be achieved due to connection types and properties of tension cables and deployable character can be achieved due to folding techniques and material rigidity. These principles can be integrated with each other to generate hybrid structural morphological system.

III. Geometrical study and observations

3.1. Analytical modelling

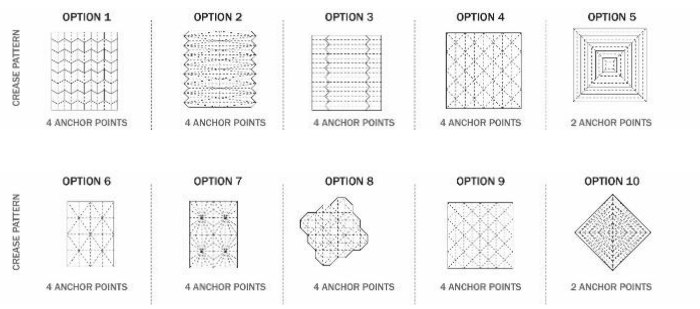

Table 3.1

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Analogue modelling of origami of a zipper tube, folded plate, diagrid folding, form finding with the help of origami folds had an application of folded plates, emergency shelter, tube structures, shell structures, façades, etc. These options were characterised by number of anchor points, types of fold, self folding and their function. Different crease pattern can be modified with few changes and the global geometry changes. These crease pattern is further explored with reference to number of connections at every joint.

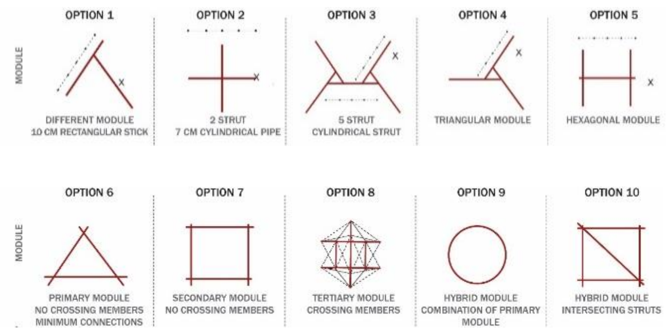

Table 3.2

A tensegrity structure is a tension- stabilised, self standing spatial structure composed of struts and cables, where every strut is connected to the other struts only via cable.

There are 5 types of tensegrity out of which X- module, 3 – way prism, square prism, pentagonal, hexagonal prism are characterised as regular tensegrity structures. Irregular tensegrity structure is a modified using these basic types. Lesser number of crossing joints provide number of resolved connections at a point. This strut- cable structure is achieves stability due to its connections and tension cables.

3.2. Selection of integration geometry

Folding pattern is selected based on the lesser concentrated folding and maximum deployablity to reduce number of connection nodes at a point. These folding patterns are used to create tension-compression members, which are then subjected to deployablity by adding tension cables to every point. These joints are used for lateral movement caused by angle variation in the assemble resulting deployable structure. Option 1-Miura ori crease pattern, option 4-Namako (waterbomb) crease patterns, option 2-2 strut module and option 4-polygonal module were chosen for the further study.

3.3. Connection Joint

Analytical modelling by paper folding and bars and strings allowed identifying two origami pattern which have potential to merge with tensegrity in terms of lesser joints at a point giving liberty to create a new type of structural joint where struts and cables can adjust within themselves to achieve stability of global assembly.

Considering maximum 4 struts at a point and cables passing through these joints with constrains, the structural pivot joint is identified into 3 types.

1. Corner Joint
2. Edge Joint
3. Mid Joint

The requirement of this joint is based on lateral movement and angular movement of a structure. If “a” is a strut length, “x” is a distance between joints horizontally, “k” is a angle between consecutive struts, “j” is a angle between horizontal and a strut then displacement “b” has a range of 15 degrees to 90 degrees where “b” is never zero and cos k = (x / 2) / a, J = 90 – (k / 2).

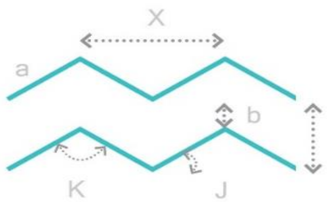

Figure 3.1 : joint angle range

Study model of this structure is based on angle range and material properties.

The model demonstrates Image 3.1 the flexibility of a morphology as well as potential of modular approach for fabrication where it is used as a semi-permanent structure.

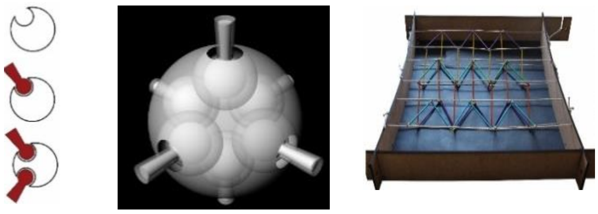

Image 3.1

3.4. Rule – set

Rule set of this system is based on tension factor in cables, angle range and location of anchor points. Diagrid pattern and miua ori patterns were identified for the further process of integration in which distance between every joint is dictated by the angle range and flexibility of connection joint.

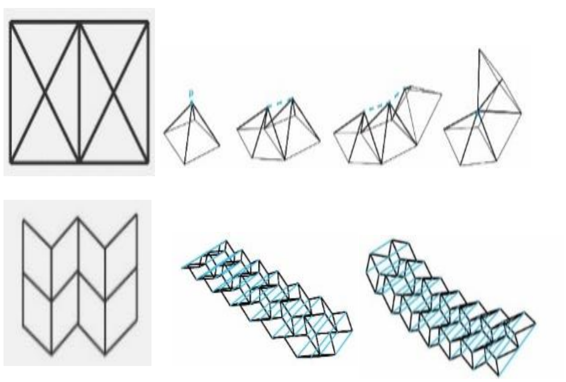

Figure 3.2 : Rule sets of different geometries

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Rule sets are used to generate hybrid structural morphology. To analyse these geometry, there are multiple simulation tools such as Ansys, IES, Push me pull me 3d, Kangaroo, Karamba, Scan and solve. Out of which Kangaroo simulation tool is used for this research.

System design is the following steps.

1. Geometry exploration
2. Material exploration
3. Selection of geometry
4. Option
5. Rigid and deployable structures
6. Stress analysis of the options
7. Conclusion
8. Fabrication
9. Application
10. And system derivation

Based on different surface, simulation shows the loading diagram, stress points and displacement of a surface when subjected to load. This simulation was carried out further to generate a structural morphology which can be used in modular approach for fabrication, installation, transportation ease.

The system can be constructed by generating global assembly (surface) and then structural system to support that surface or structural system defines the global assembly.

The system is divided into 4 parts where channels are provided to create a structural system. With the help of retracting system these modular joints with their cable – strut structure can be mounted on a channel as per requirement of habitable space. Connection joint in this system is used to not only retractable system mounting but also modular tile laying where envelope of a structure will be generated as per figure 3.3

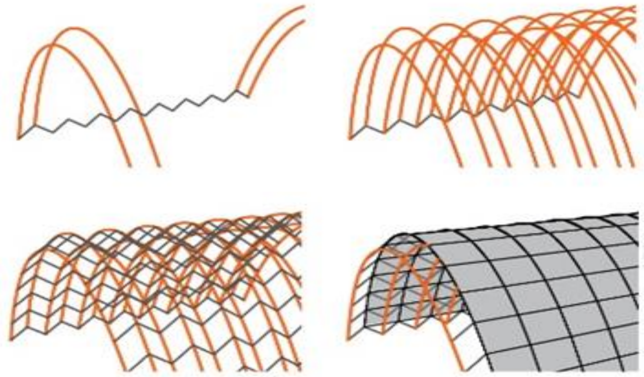

Figure 3.3 : Retractable roofing system

IV. Conclusion

This experimental research enabled to generate hybrid structural morphological system which has a potential of making habitable spaces with the use of retractable channel system with minimum joints and anchor points. Iterative process to achieve different proliferations with different tension factor in tension cable enables variations.

This system enables a possibility of modularity in its structure as well as envelope. Structural loading calculations allows material optimisation as well as use of deployable properties of a global assembly.

Reconfigurable roofs, stadium covering, canopies, airport roofs, structural systems, envelopes, semi – permanent structures, etc can be constructed with this system. Further potential of this structural system is changing morphologies with the help of automation.

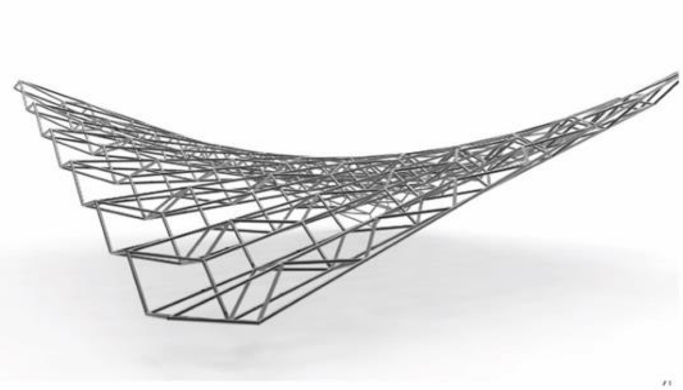

Image 4.1 : Hybrid structural morphology

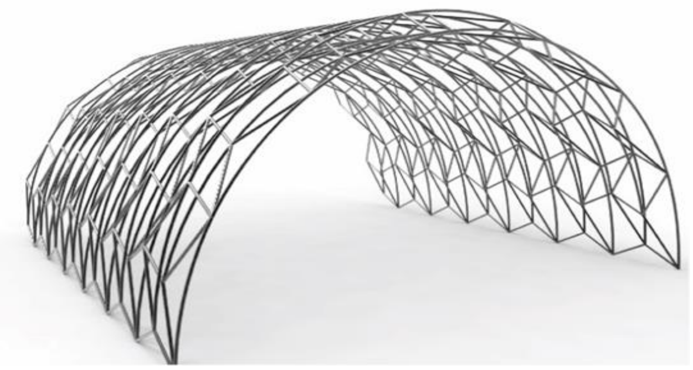

Image 4.2 : Hybrid structural morphology

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