



# **DEVELOPMENT AND EVALUATION OF NEW PROPOSED MODULES FOR DEPLOYABLE TENSION-STRUT STRUCTURES**

By

**Abdelrahman Abdelalim Abdelwahab Taha**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
**in**  
**Structural Engineering**

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
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**Title of Thesis:**

Development and Evaluation of new proposed modules for deployable tension-strut structures

**Key Words:**

Deployable structures; Structural mechanisms; Cable-strut structures; Tension-strut structures

**Summary:**

This thesis is concerned with the development of new basic units for deployable tension-strut structures (DTSSs). These structural systems are a special type of deployable structures that have the ability to fold into a single vertical line. They are specifically used as roof structures to cover large span spaces. A form-creation method lately proposed in the literature was utilized to form the novel modules for DTSSs. Subsequently, the new modules underwent verification of their efficiency that demonstrated high structural efficiency.

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# Abstract

A need for a new alternative of long-span structures that has high level of transformability has evolved for many years. This led to the invention of “deployable/retractable structures” which have the ability to transform between multiple configurations. One of the most promising recently developed types is termed “deployable tension-strut structures (DTSSs)”. They are space roof structures composed of continuous steel elements as well as another continuous net of cable elements. The motivation beyond this new concept was the lack of structural efficiency and form flexibility of conventional space trusses that are used for similar applications. DTSSs consist of multiple modules put together to form the whole structure.

What differentiates DTSSs from other deployable structures is the capability of each basic unit to retract from the fully deployed position into a single vertical line, which makes such structures occupy the tiniest storage area after folding. Liew et al. in their paper “Deployable tension-strut structures: structural morphology study and alternative form creations” came up with an algorithm for the creation of modules. Some modules were proposed in the literature based on this algorithm, and then the behavior of created structures were compared to the conventional space truss.

In the current work, this algorithm has been used to form new modules other than what were proposed in the literature. Fourteen new modules were created based on this method that meet all deployability and stability requirements. Preliminary analysis and design were conducted to compare the novel modules to the previously introduced in the literature and the space truss. The majority of proposed modules proved to be more efficient. Then, the most two efficient modules of the new ones were picked for further study. Parametric studies were conducted on these two systems under gravity loads and wind loads considering the following parameters: no. of modules, span/depth ratio and pre-stress level. Generally, the optimal values for the number of modules and prestress strain are 6 and -0.001 respectively, after which the structural behavior decreases significantly. In addition, the performance is at its peak as long as the span/depth ratio lies within 20 and 25. Subsequently, the dynamic behavior of these new systems was studied by performing free-vibration and forced-vibration analyses using three realistic ground motions. The free-vibration analysis showed that the behavior of new systems is dominated by the downward displacements of internal nodes as well as the high tensile stresses of corner elements. On the other hand, the forced-vibration analysis and seismic design demonstrated high structural efficiency compared to the the corresponding DTSSs proposed in the literature and the space truss.

# Chapter 1 : Introduction

Deployable structures can be perceived as multi-configuration systems unlike traditional ones that remain in their initial position after construction throughout their entire lifespan. The main characteristic of these structures is the ability to transform between multiple states, particularly the fully deployed and the fully retracted states. Hence, they are also well known as “retractable structures” or “transformable structures”. Based on this intrinsic feature, deployable structures have the ability to change their size for storage or transportation.

There are many everyday applications of this novel concept. One of these applications is the pantographic umbrella. It has the ability to deploy so that it forms a shelter for its user from the rain and then package into a bundle. The foldable chair is also a simple application that can be open for having a seat and then be folded to occupy a small space for storage. Industrial Applications of this novel concept are so many and can be divided into space-based and ground-based applications. In space satellites, there is a limited-size space during the launch operation for a structure to hold the satellite and put it into space later. As a result, a retractable structure is required in its folded configuration during launch and then be deployed into space. It can also sustain the high level of vibrations occurring during launch. Another use of deployable structures in space applications is the deployable solar panels used by modern satellites to produce the required power such as the Hubble Space Telescope 1990. On earth, there are recently varieties of applications that exploit this novel concept. For instance, they are used temporarily as a shelter during catastrophic events such as earthquakes and giant storms. Retractable roofs for large sports antennas are also a type of deployable structures. The deployable anti-prismatic column/mast is used to deliver things from the ground to another higher level. It can be retracted to a nearly flat state and then be deployed to reach the required height. Another application is covering large span spaces. In the latter case, cables are often added to the deployable structure to increase its stiffness at the fully deployed state.

## 1.1. Background

The main characteristic of this new type of structural systems is their high form flexibility that makes them be able to transform between multiple configurations and be stable at each one of them. Unfortunately, this transformability is normally achieved at expense of the stiffness of the deployable structure. Therefore, it can be stated that the evolution of deployable structures is basically driven by the need for structural systems that acquire the highest possible level of deployability and robustness simultaneously. The first attempt to achieve this aim was the generation of “Pantographic lattice bar structures”. These structures are composed of basic units that take the form of scissors. This scissor-like element is a single-degree of freedom element through which the

deployability can be generated by employing this degree of freedom. It consists of two bar elements connected together using a revolute joint which allows rotation about its axis. This element was utilized to build up various deployable applications such as a movable theater and a retractable swimming pool. Nevertheless, this new discovery exhibited some shortcomings: low stiffness that it is limited to small-scale applications as well as the moving foundation system. To solve the latter issue, i.e. the need for permanent foundation supports, a new element termed “angulated element” was discovered. The angulated element resulted in more structural complexity due to the large number of elements required to compose the structure. As a result, this element was further developed to overcome this obstacle through pioneering the “multi-angulated element” that was employed in constructing the “Iris Dome”.

Despite all the aforementioned efforts, all structural systems composed of these elements still share the same structural deficiencies: low form flexibility and low stiffness. The first problem means that these retractable structures are only stable at the fully deployed and fully retracted configurations. To overcome this obstacle, the “modified scissor-like element” was pioneered. The novel characteristic of this element is the existence of three revolute joints instead of one at the connecting node of the former scissor-element. This helps increase the degrees of freedom of the whole structure and makes it capable of being stabilized at many intermediate states in addition to the fully open and the fully closed states.

Although this modified scissor-like element increased the deployability of retractable structures, it is still not robust enough to be utilized in long-span structural systems. For this sake, the need to add cable elements to the steel bar elements has been recognized as an effective solution to this restriction by employing the prestressing technology at the fully deployed state. Furthermore, it can be utilized to activate the deployment process (using active cables) and terminate the deployment at the final configuration (using passive cables). One of the first attempts to apply this novel concept is the “cable-stiffened deployable mast”. It is a retractable column capable of folding into a flat surface and deploying to a definite height.

For large-span structures, two ways of integrating cables into deployable bar structures were developed. Firstly, the cables are simply added to the scissor elements as lower, upper or inclined elements. This type of deployable systems is termed “tensioned scissor-hinge structures” and many structural forms were generated based on this idea. The other approach is the generation of hybrid structures consisting of a combination of bar steel elements and cables arranged in certain ways. The so-called “tensegrity structures” were the first application of this new concept. These structures are composed of a connected group of cables as well as a group of disconnected bar elements. This new discovery was intended to provide more flexible, more stiffened and light weight structures. In contrast, they were proven to be structural systems of heavyweight with large cross-section steel bars. Moreover, their stiffness is relatively low and they exhibit structural complexity that hinders the production of complex shapes. As a result, there has been a need for a new system to fulfil the requirement of simultaneous high deployability and robustness. Consequently, tensegrity structures were evolved to the well known “cable-strut structures”. These new structures consist of continuous network of cables combined by another continuous network of bar elements. They exhibited high structural performance and high flexibility as compared to tensegrity structures.

It has been mentioned that the most important two characteristics of any deployable system is the high level of transformability and stiffness. However, another important factor to be considered when assessing any deployable structure is the