CONCEPTUAL DESIGN AND MECHANISMS FOR FOLDABLE PYRAMIDAL PLATED STRUCTURES

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Degree of Doctor of Philosophy

By

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ABSTRACT

In spite of the presence of much research in the field of foldable structures whose applications have covered most of the requirements of academic and practical aspects of life, there is still a wide domain in which to undertake further studies. One of the required studies is to invest in foldable structures for the process of temporary accommodation. This study endeavours to find solutions for folding pyramidal shapes constructed from stiff panels that can be used as an upper part of temporary accommodation units, e.g., roofs.

Several attempts have been made to find a mechanism that realises the folding of a three-dimensional pyramid. These attempts led to suggest a design that represents an initial solution for folding the pyramid. It was taken into consideration in this design that the structure should deploy strain free when the thickness of its panels is not considered. Trigonometry was used to find mathematical equations that can be used to identify the lengths and angles of the proposed design plates. These equations theoretically proved the validity of the proposed mechanism.

The proposed design was applied to construct an actual model formed with thick panels. Considering the panel thickness of the model plates led to amendments and improvements to the proposed design. Two actual models were experimentally tested to make sure that they achieve the design concepts in the processes of full folding and deployment. The models were also tested in the laboratory to make sure of the integrity of the panel hinges and resistance of the elements to external loading.

The model was constructed in a simulation program in order to verify the foldability of the design, folding efficiency and absence of strain or collisions during the process of folding and deployment at all stages.

Key words: Foldable pyramid, Plate Structure, Folding Mechanism, Post-compression technique.

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CHAPTER ONE

INTRODUCTION

Although the terms 'foldable' and 'deployable', strictly have opposite meanings and are thus different, yet when applied to structures, foldable structures almost invariably also imply they are deployable. Some deployable structures are designed for only a single deployment and thereafter, due to some permanent locking mechanism, they then remain fully deployed. Most deployable structures are also foldable after the first deployment.

There are many studies undertaken on the different and varying types of foldable and deployable structure, which have been used in various aspects of life. Temporary accommodation, or specifically tents, is one of the applications of such studies, and they have involved tensegrity structures which are defined as structures dependent on an external "tensile skin" for structures integrity.

The specific application in mind behind this project is the provision of temporary accommodation to a large number of people in a remote and barren location in one of the stations of the Hajj pilgrimage. By all accounts the Hajj is more than just the fifth pillar of Islam. In their pilgrimage to Mecca (i.e. Hajj) Moslems do not only fulfil a religious duty but also participate in a unique public occasion that crosses the boundaries of social behaviour and national and international interaction.

1.1 Statement of the Problem

In order to fulfil the requirements of the Hajj pilgrimage, pilgrims must spend one specific day in Arafat and a further specific three days in Menna which is near the Mecca area. Considering that there are over two million pilgrims in any one year, the provision of accommodation and transport to enable all pilgrims to fulfil this requirement is a large logistical exercise. Arafat is an otherwise empty uninhabited place, which must be full of tents during the Hajj month every year in readiness for the pilgrims to stay overnight for this one day. According to Islamic regulations, it is prohibited to build a concrete permanent housing accommodation in this particular place. Therefore, each group of Motawefs (who are the local guides each responsible for 2,500 to 4,000 pilgrims) must establish the tents and arrange all pilgrim needs. These tents must then be removed after the end of this day, which is at a cost a lot of labour and storage.

In the absence of a suitable deployable/foldable temporary accommodation structure, in recent years, the Ministry of Accommodation and Works have chosen to use tensegrity structures to establish a new fire-resistant tent construction in Menna area. In fact this project was very costly in terms of maintenance and security concern after each Hajj season. There were some claims from pilgrims about some health problems caused by the tent materials. These are thus compelling reasons for undertaking this research.

1.2 Project Aims

There are two main aims of the present study. The first is to provide a structure for suitable temporary accommodation for the pilgrims at Menna and Arafat areas. This accommodation is required to be built with the same visual form as traditional tents, but should be fire-proof, and manufactured from stiff material, as well as being easily deployed, transported and stored. There are several solutions for two-dimensional deployment to span an area, for example, the accordion concertina, which can be used to fold tent walls; but, the present study is focused on finding solutions for the tent roof, which by tradition is pitched and hence, three-dimensional. The second aim arises from this point, which is an academic aim to review the fundamentals of folding three-dimensional shapes using plate structure, and then applying them to find the solution for folding pyramidal shape.

1.3 Outline of Thesis

Chapter Two reviews some of the research in the field of foldable structures, as well as explaining the fundamentals and rules of this discipline. Reviewing all types of deployable structures is necessary to discover their potential applications and uses. Therefore, Chapter Two does not only focus on plate structures but also focuses on other structures since the researcher is aware of the possibility of combining more than one type to resolve the problem under investigation.

The present study starts in Chapter Three, with trials on folding plane surfaces in a symmetrical way and then assembling all surfaces of the structure to form the three-dimensional model. This chapter explains all preliminary studies and the suggested solutions that can be used to achieve the solution for folding the pyramidal shape. In this chapter comparisons of the various final models are presented, whereby some will be eliminated due to factors that could affect the effectiveness of the final solution.

Chapter Four is the main part of the study which explains mathematical theories and their confirmations, as well as equations and their solution relating to the model measurements presented in Chapter Three. This chapter also illustrates the initial methods to prove the actual effectiveness of the design of this model.

Chapter Five concerns the applications of the design on the models with panels with finite thickness and the adverse impacts of this thickness of the design. It also explains additional requirements for these models with regard to the processes of linking and association between the model segments. The study reveals, for the first time, the process of combining post-compression techniques with the plated structure, due to the present aspiration to attain the smallest size possible after the complete folding process. This chapter thus provides further proving of the effectiveness of the model investigated.

Methods and results of the laboratory tests are explained and discussed in Chapter Six. This chapter demonstrates the most important points affecting the design. It also explains the reasons for adopting the final design due to the assessments of the models after discussion of the results of the laboratory tests.

Due to aspiration for a third method to prove the effectiveness of the design resulting from this study, several attempts have been made to simulate the design mechanism using computer simulation programmes. Detailed explanations and discussion of the findings of these attempts are presented in Chapter Seven of this study.

Chapter Eight summarises this thesis and also evaluates its findings in terms of the main aims of this study. Accordingly, some recommendations concerning issues that can possibly be studies in the future are also provided.

There is also a field survey conducted which evaluates current accommodation of pilgrims in Menna area and also demonstrates the requirements of its users. This study consists of two parts: Results from focus group interview, and the second from questionnaires. Although, the results from this field study with pilgrims are of a non-technical nature (which is why it is provided as an appendix), the end-users data were nonetheless relevant and used to inform technical decisions, particularly on structural shape, size and weight.

CHAPTER TWO

LITERATURE REVIEW

2.1 Foldable and Deployable Structures

The history of structural design has been divided by Skelton et al. (2001) into four eras, as classified by design objectives. These eras are the *prehistoric era*, the *classical era*, the *modern era*, and the *post-modern era.* In the prehistoric era which produced structures such as Stonehenge, the objective was simply to oppose gravity, and to take the static loads. The classical era, regarded the *dynamic* response of the structures and placed design constraints on the eigenvectors and the eigenvalues[1] as well. Design constraints in the modern era could be so demanding that the dynamic response objectives also require feedback control. In this era, as Skelton et al. (2001) claimed, the control discipline *followed* the classical structure design, in which the structure and control disciplines were constituents in a *multidisciplinary* system design. Nevertheless no *interdisciplinary* tools were developed to integrate the design of the structure and the control. Accordingly, in this modern era, the dynamics of the structure and control were not co-operating to the maximum extent possible. The post-modern era of structural systems is identified by attempts to unify the structure and control design to a common objective (Skelton et al., 2001).

This chapter presents an overview of the various foldable and deployable structures, with regard to their definition, principles and rules, uses, and classification.

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[1] Eigenvalues And Eigenvectors are properties of the equations that simulate the behavior of a real structure (http://www.comp-engineering.com/downloads/technical_papers/CSI/d.pdf).

Finally a discussion of the various issues rose; highlighting the present author's choices of structures and the reasons behind this choice.

2.1.1 Introduction

Hanaor and Levy (2001) maintain that the term 'deployable structure' is not well defined and differing structural systems have been introduced in the technical literature under this term. They add that the term clearly entails a transition, both in location and geometry, from a compact stowed form to the final functional state. The functionality and the feasibility of the design of such structures depend not only on the structural behaviour of the final configuration under service load but also on the structural response during deployment and during dismantling (Srivastava, 2002). Nonetheless, this overall categorization applies to almost any structure, and further limitations depend upon the nature of the stowed or deployed states and also depend on the nature of the deployment process, but particularly on the application (Hanaor and Levy, 2001).

A deployable structure is defined as an "assembly of prefabricated members or elements that can be transformed from a closed compact or folded configuration to a predetermined expanded form of a complete stable structure capable of supporting loads" (Srivastava, 2002). The multiple design criteria during deployment and during dismantling, and also in the deployed formation makes deployable structures very different from conventional structures. Tibert (2002) defines them as "structures capable of large configuration changes in an autonomous way." Tibert adds that most common is that the configuration changes from a packaged, compact state to a deployed, large state, and that such structure are used for easy storage and transportation. A well known example is the umbrella (Tibert, 2002). Deployable structures are also sometimes referred to as expandable, extendible, developable and unfurlable structures.

Hanaor and Levy (2001) maintain that deployable structures are commonly employed in two types of applications: as temporary structures, and in inaccessible or remote places, for example, outer space. Temporary structure application is a reversible process of deployment and undeployment, whereas in the second type of application it may not be reversible. However, according to Tibert (2002), deployable structures have a large number of potential applications both on Earth and in space (Tibert, 2002). In civil engineering, temporary or emergency structures have been employed for a long time; a more recent application is the retractable roofs of large sports stadia (Tibert, 2002), for example, the roof of the new Cardiff Millennium Stadium. Deployable structures have been used in space programmes since then former Soviet Union launched its first satellite *Sputnik* on 4th October 1957. Applications as temporary structures often imply repeated deployment that requires minimal damage to structural components during repeated deployment/undeployment.

Hanaor and Levy (2001) recognise two extreme types of deployable structures: fully deployable, and dismountable structures, also referred to as assemblable (Levy and Luebkeman, 1999). Fully deployable structures are fully assembled in the stowed states, and the deployment process involves no component assembly. In fully dismountable structures, the structure is stowed as separate components (at member level), and are assembled on site from these components and can be disassembled back into the stowed state (Hanaor and Levy, 2001). These two authors applied the term deployable structures to structures that are fully deployable, in accordance with the definition they provided above, or those composed of a relatively small number of deployable substructures. On the other hand, they used the term disamountable structures to refer to structures that are assembled from a large number of relatively small components.

2.1.2 Principles and Rules

While the classification systems proposed by some authors (for example, Levy and Luebkeman, 1999) focus on the deployment technology as the primary category, others, for example, Hanaor and Levy (2001), are concerned with the structural-morphological properties as the primary classification category. Yet, some other authors (for example, Gantes et al., 1994; Neogi et al., 1998) classify deployable structures designed and developed in the past into four major categories, depending on their initial stowed state, intermediate deployment state and final deployed configuration. These four categories are summarised by Neogi et al. (1998, p. 158) as follows:

1. Structures that are stress-free in the folded configuration, during deployment and in the deployed configuration.

2. Structures that are stress-free in the folded configuration, but develop stresses during deployment and have residual stresses and curved members in the deployed configuration, thus eliminating the need for external stabilisation.
3. Structures that are air inflated, either with air pressure inside the entire structure or with inflated parts.
4. Structures that are stress-free in both initial and final configuration, though stresses develop during deployment.

Hanaor and Levy's (2001) classification is adopted for the purposes of the present study, though reference to other classifications will also be indicated when applicable. Hanaor and Levy's system is presented in the form of a table, the columns representing the morphological aspect and the rows the kinematic properties, which, according to these two authors, are of primary significance in the context of deployable structures. In addition, the kinematic properties are closely related to deployment technology.

The two major morphological features of Hanaor and Levy's system are *lattice* or *skeletal* structures, and continuous or *stressed-skin* structures. All structures have a functional covering surface in terms of space enclosures. However, the difference between these two classes of structures is that in the skeletal structures the primary load-bearing structure consists of discrete members, whereas in the continuous surfaces the surface covering itself performs the major load-bearing function (Hanaor and Levy, 2001). There is a third class, that is, *hybrid structures*, which combines both skeletal and stressed-skin components with approximately equal roles in the load-bearing hierarchy.

The two major kinematic subcategories include systems consisting of *rigid links*, for example, bars and plates, and systems containing *deformable* components lacking flexible stiffness, for example, cables or fabric (Hanaor and Levy, 2001). Overall, the deployment of structures composed of rigid links can be more accurately controlled than that of deformable structures, though usually at a cost of increased mechanical complexity.

A kinematic structure is defined as one having only kinematic degree of freedom (KDOF), that is, the positioning of one node in the structure relative to the others, is not determined uniquely by the geometry of the structure (Kent, 1983). These systems, according to Hanaor and Levy (2001), represent the ultimate deployment control due to the fact that only one point has to be controlled in order to determine the geometry at any time during the deployment. This feature is of great advantage in outer space application whereas it is of lesser importance in terrestrial applications where several degrees of freedom are usually constrained, such as along the boundaries, and where manual intervention is feasible. This kinematic control is perceptibly possible only in structures having rigid links because deformable components have infinite degrees of freedom. Nonetheless, both systems can be applied together in one structure due to the conditions of the required design, as will be explained later concerning the design of the foldable and deployable pyramidal structures.

Two types of releases at the end of the rigid links facilitate the kinematic degrees of freedom of mechanisms, namely, a *hinge*, releasing a rotation degree of freedom (DOF), and a *slide*, releasing a translational DOF. Hanaor and Levy (2001) maintain that the majority of deployable space enclosure structures are based on rigid links employing hinges as releases. They also indicate that general design criteria for deployable structures are derivatives of the function of these structures as temporary, probably multi-purpose and of repeated use. They add that while individual criteria assume different weight, depending on particular applications, design criteria relate usually to three phases in the structure's life cycle, namely, design, storage and transport, and site operations (deployment/dismounting). Hanaor and Levi (2001) proposed nine design and evaluation criteria for the three phases, as described in Table 2.1.

Table 2.1.

Design and evaluation criteria for deployable structures

	Phase and criterion	Structure-morphological aspects and comments
1.	**Design** Architectural flexibility	Design enabling multi-purpose applications, implying modular design or periodic structures.
2.	Component uniformity	Regularity of the geometry and standardisation of components, such as regular grids. Affects manufacturing costs.
3.	**Storage and Transport** Stowed compactness	Affects cost of storage. May be defined as the ratio of the surface area of stowed components to the covered area when deployed to.
4.	Weight	Implies structural efficiency – ratio of load capacity to weight. Affects material, transport and erection costs inputs.
5.	Maintenance (wear & tear)	Wear and tear of material and of components is affected by degree of articulation –folding unfolding.
6.	**Site inputs** Site preparation	Includes foundations and anchorage, particularly of tension structures (membrane, air-supported), which do not form part of the structure itself.
7.	Connections	Involves assembly/disassembly operations. Depths on the degree of deployability/dismountability.
8.	Complexity/reliability	Relates chiefly to joint complexity and articulation. Reliability of deployment and repeatability are generally inversely related to complexity.
9.	Auxiliary equipment	Examples: special lifting equipment for deployment (related to weight); Compressors for air supported structures.

Source: Hanaor and Levy (2001, p. 214).

2.1.3 Uses of Foldable Structures

Foldable structures have been applied in various disciplines to serve various and different purposes, according to the method of application.

I. Applications in Science

In this field, deployable structures have been, and are still used in medical practices, underwater exploration and construction, and in space technology. One of the applications in medicine is the enclosed-form stent. Stents are a type of foldable tubular medical device used to open up weakened coronary vessels. Most existing stents are made of wire meshes which could be blocked again once tissue grows through them. A folding pattern has been discovered, and its geometry and mechanical behaviour is being investigated.

With the expansion of the aerospace industry, there has been an increase in the size of the instrumentation that needs to be placed into orbit. Neogi et al. (1998) maintain that as the size of such instruments and their supporting structures have grown, it has become more and more difficult to transport them in the limited cargo space of conventional launch vehicles. For instance, the Atlas launch vehicle payload fairing limits payload sizes to a cylinder of around 4 m in diameter and 5 m in length. Conversely, several proposed payloads are larger, such as a reflector antenna for radio frequency operation between 0.3 and 90 GHz requires a structure of up to 40 m in diameter (Freeland and Bilyeu, 1992). For large payloads, several launches may be required to place the structural elements in orbit, followed by slow and risky in-orbit assembly operations either by astronauts or remotely-operated served vehicle, both of which are extremely costly approaches. Neogi et al. (1998) argue that several launches for a single mission may not be practical, whereas manned missions are severely restricted by the level of extra-vehicular activity (EVA) allowed for this in-orbit assembly, critically compromising the cost-to-quality issues on such proposals.

In space technology, many concepts for large deployable space frames have been developed over the past three decades. Kwan and Pellegrino (1994) indicated that space antennae and reflectors for telecommunications and Earth sensing or multi-purpose Earth orbiting space platforms, respectively, are the main applications anticipated for these structures. In the aerospace industry there are three main types of deployable structures: masts, antennas, and solar panels (Tibert, 2002). Masts are typically used for separating electronic instruments to reduce interference (Mikulas and Thomson, 1994) or for supporting other structures such as solar arrays (Zwanenburg, 1984). A vast number of mast concepts exist (for example, see Mikulas and Thomson, 1994). All satellites need to communicate with Earth and therefore require some type of antenna. Amongst the many antenna types available, the parabolic reflector antenna is the most common one mainly due to its high gain, which enables high data rate transmission at low power (Stutzman and Thiele, 1998). Antennae are used not only for communication but also for Earth observation and astronomical studies. The current flexible solar cell technology can produce 223 W/m^2 (Reynolds, 2000), which means that the solar arrays need to be very large to produce enough power for the ever increasing number of instruments aboard a satellite. One of the most sophisticated spacecraft is the HST, which requires 4.7 kW for its instruments. Four 2.39×6.06 m^2 solar arrays provide this power (Kwan, 1991). Information concerning solar arrays is provided by Pellegrino (1995).

The problem pertaining to placing large structures in space can be overcome by employing deployable structures instead of conventional structures for these applications. Deployable spare structures, according to Neogi et al. (1998), are prefabricated structures that can be transformed from a closed compact configuration to a predetermined expanded form in which they are stable and can bear loads. They maintain that deployable structures offer major advantages over conventional structures as they can be stowed in a compact configuration, eliminating multiple launches, and then deployed in space with minimum human intervention. Nonetheless, deployable structures are usually complex due to their automatic deployment mechanisms, and hence, reliability is a critical issue when they are employed for space applications given that their failure could be detrimental to the mission.

II. Applications in Humanitarian Missions

Foldable, deployable structures have been used in humanitarian situations, where speed in deploying aid and shelter is of paramount importance. These structures include temporary structures, emergency shelters, emergency bridges, etc. Kwan (2000) maintains that foldable shelter structures have been constructed but they have not been made foldable so that they could be transported and re-deployed in alternative sites.

III. Applications in Commercial Fields

Deployable structures have also been applied in commercial fields such as in kitchens and shops, whereby utensils and other products are made from foldable parts that can be folded to help occupying a small space on selves or in kitchen cupboards.

IV. Applications in Military Operations

Deployable structures are widely used in applications where rapid deployment is necessary or desirable. Military applications include shelter, communication booms and antenna structures. There are a wide range of temporary sheds, storage that can be fabricated using this system for military, emergency and disaster relief applications. Exhibitions and outdoor events require temporary structures that can be fabricated and deployed rapidly using this system (Anandasivam and Richard, 2004).

Foster-Miller (2003) has recently completed projects for the US Air Force and NASA to design and build structures required to be stowed into a small volume for spacecraft transport, and then deployed over large areas in space. Other applications include deployable sun shields, solar reflectors, photovoltaic arrays, and solar sails.

Terrestrial applications for mobile bridges, emergency response shelters, lightweight security fences, and portable sound reflectors are being pursued (Foster-Miller, 2003).

Foster-Miller's deployable structures use one-piece design which reduces the complexity of mechanical linkages, actuators, and latches, and greatly reduces system mass. Thermal expansion and heat dissipation can be controlled to meet mission requirements. All of the materials used in Foster-Miller's structures have been flown in space for decades, and use manufacturing methods familiar to the composites industry (Foster-Miller, 2003).

2.2 Classification of Foldable Structures

In the following sections the types of foldable structures are explained in terms of describing them, recent developments, and their functions and applications.

2.2.1 Pantograph Structures

I Description

Lattice structures are of three major types: double-layer grids, single-layer grids forming curved surface to provide structural depth; and linear grids forming masts or spines, mainly for membrane or hybrid structures.

You (1994) reports that Deployable Space Frames are pantographic structures, which he describes as assemblies of cables and pairs of rods with intermediate connections (see Figure 2.1). You (1994) adds that the simplicity and reliability of pantographic structures make them competitive against more common structures, such as trusses, which can be folded only after introducing complex hinges or troublesome sliding elements.

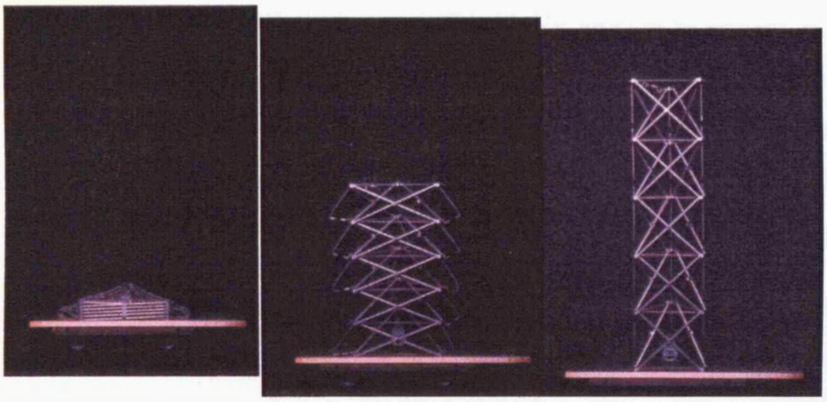


Figure 2.1

Assemblies of cables and pairs of rods with intermediate connections

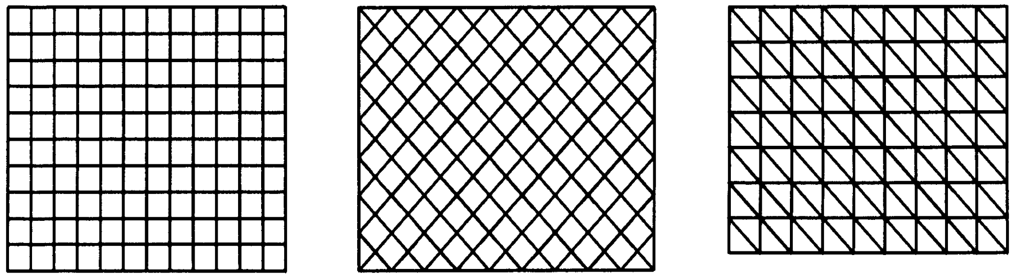
1. Single-Layered Grids

A *grid* is a structural system which involves one or more planar layers of elements (Makowski, 1981). Schueller (1983) defines it as a network of uniformly spaced horizontal and perpendicular lines (square-grid) or something resembling a network. A *single layer grid*, or *flat grid*, consists of a planar arrangement of rigidly connected beam elements. The external loading system for a flat grid comprises forces perpendicular to the plane of the grid and/or moments whose axes lie in the plane of the grid. The reason for classification of a flat grid as a space structure is due to the fact that its external loads and displacements do not lie in the plane containing its *idealised* configuration (Centre for Engineering Materials and Structures, 2002).

The simplest single-layer grids are formed from the closed packing of identical polygons. There are three major polygons and their mixture with which this is possible: the *triangle*, *square* and *hexagon*. The *triangle* is the most stable grid. A number of basic grid patterns are illustrated in Figure 2.2. The *two-way* pattern (Figure 2.2a) is the simplest pattern for a flat grid, consisting of two sets of interconnected beams which run parallel to the boundary lines. The diagonal pattern (Figure 2.2b) consists of two parallel sets of interconnected beams which are disposed obliquely with respect to the boundary lines. Figure 2.2 shows some basic three-way and four-way grid patterns.

The basic grid patterns of Figure 2.2 are frequently used in practice. Nonetheless, there are also many other grid patterns which are commonly employed. These patterns are normally derived by removal of some elements from the basic patterns illustrated in Figure 2.2. Two examples of this type of operation are shown in Figure 2.3. The grid pattern in Figure 2.3a is obtained from a three-way pattern by omitting every other beam line. This is illustrated in Figure 2.3c which shows a part of the grid of Figure 1.2a with the omitted beam lines shown by dotted lines. The grid of Figure 2.3b is obtained from a four-way pattern by removal of a number of beam lines as indicated in Figure 2.3d.

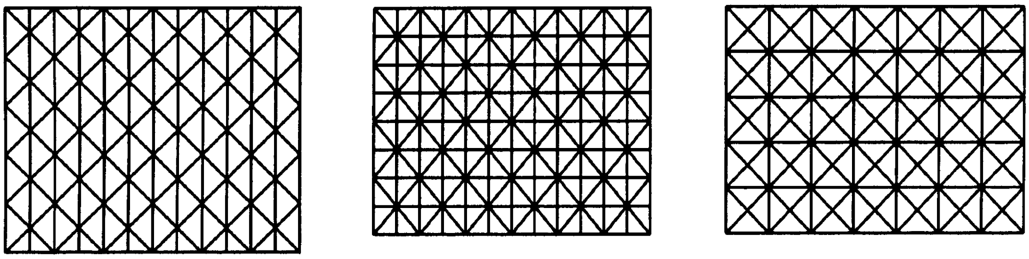
Hanaor and Levy (2001) maintain that single-layer configurations require curvature, usually double, for structural depth. However, despite the fact that certain pantographic configurations have been suggested that fold to bundles (for example, see Kent, 1983) these configurations generally lack sufficient stiffness for practical implementation.



(a) Two-way grid

(b) Diagonal grid

(c) Three-way grid

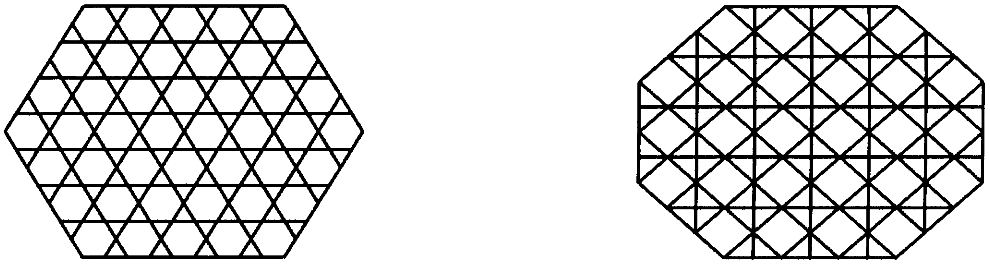


(d) Three-way grid

(e) Four-way grid

(f) Four-way grid

Figure 2.2
Some basic grid patterns



(a) A grid derived from a three-way pattern

(b) A grid derived from a four-way pattern

(c) Removal of dotted lines gives rise to the pattern of the grid above

(d) Removal of dotted lines gives rise to the pattern of the grid above

Figure 2.3
Pattern creation by element removal
(Source: Centre for Engineering Materials and Structures, 2002)

2. Double-Layered Grids

Kaveh and Davaran (1994) describes a pantograph as a foldable structure that consists of scissor-like units called duplets, introducing the term '*p-structure*' to refer to this structure. They maintain that a *duplet* consists of two elements, each called a *uniplet*, that have the ability to rotate about intermediate pivot node, as illustrated in Figure 2.4 below. Gantes (1997) refers to scissor-like elements (SLEs) as pairs of bars connected to each other at intermediate points with a pivotal connection and hinged at their end points to end points of other SLEs. Two uniplets forming a duplet are in fact beam elements with three nodes acting as pin-joints having only rotational degrees of freedom (Kaveh and Davaran, 1994).

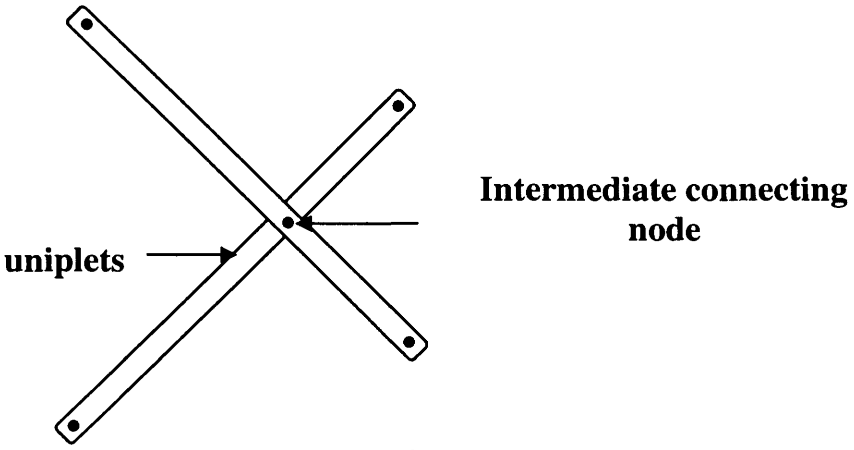


Figure 2.4.

The structure of a duplet (Kaveh and Davaran, 1994, p. 132).

The kinematic motion of the scissors is propagated along the two-way or three way pantograph as a single degree of freedom (Hanaor and Levy, 2001). Nonetheless, they also indicate that units other than triangular have additional in-plane degrees of freedom, thus implying that the generated grid is not geometrically rigid and needs stiffening of the surface, especially when the surface is curved. A triangular grid, however, is geometrically rigid but kinematically incompatible, except at the deployed and folded states, and at intermediate states there is some resistance to motion which depends on the stiffness of the components and joints. According to Hanaor and Levy (2001), a 'clicking' effect is therefore generated for triangular grids.

Hanaor and Levy (2001) presented an evaluation of the double layer pantographic grids, according to the nine criteria presented in Table 2.2.

Table 2.2.

Evaluation of double-layer pantographic grids

Criterion	Evaluation
1	Flexible modular design is readily applicable. Large areas can be covered with relatively small modules connected on site.
2	High component uniformity can be maintained, although doubly curved surfaces may require some variation in unit cell dimension.
3	The structure folds to a compact bunch of bars. Compatible folding of the membrane covering needs to be considered (Escrig et al., 1996)
4	Structural efficiency is medium to low, depending on the surface geometry, constituent units and bracing.
5	Repeated deployment may cause significant wear and tear to the membrane and to connections.
6	Generally, self-supporting configurations can be designed, requiring minimal foundation and site preparation.
7	Degree of deployability is relatively high. Site connections involve connection of deployable modules and addition of bracing elements.
8	Medium mechanical complexity. Articulated joints and hinges are relatively simple (Escrig et al., 1996). Human assistance in deployment is usually required.
9	No auxiliary equipment is required other than relatively light lifting equipment to assist in deployment and folding.

Source: Hanaor and Levy (2001).

3. Mast and Spines

Masts and spines are grid structures which often do not cover the area enclosed; rather they support an active surface, usually membrane (Hanaor and Levy, 2001). The same concepts employed to generate double-layer grids can essentially be employed to generate linear spine elements. These concepts are categorised into two groups: rigid bar grid, of which the dominant type is pantographic (scissors) grid, and strut cable system.

There are several concepts of rigid bar grids, including the pantographic grids (for example, see Sastre, 1996; Tsutomu and Tokai, 1997), and other concept using articulated joints, such as booms in outer space (Chen et al., 1999; Natori et al., 1986).

Hanaor and Levy (2001) indicate that a pantographic spine is produced from any of the basic prismatic scissors units by joining them not side by side at the prism bases, and Escrig (1986) reports that straight or arched configurations can be generated. These configurations, according to Hanaor and Levi (2001), do not fold to form a bar bundle but to form a polygonal bundle, and the joints involved are also mechanically more complex than the essentially planar joints of the double-layer grids. Planar pantographs can also be used which fold into a bar bundle, and such configurations depend on the surface membrane to prevent lateral buckling (Sastre, 1996; Tsutomu and Tokai, 1997).

Using complex articulated joints are very costly; nonetheless, spine elements are used sparingly and far between so the cost is spread over the large area covered. Hanaor and Levy (2001) maintain that high stiffness and strength are usually required from such structures due to the high load they might be subjected to these requirements might not be satisfied by pantographic or strut-cable systems.

Pure tensegrity structures possess low structural efficiency and low stiffness, and hence they are not suitable for use as spines, which collect loads from a large area (Hanaor and Levy, 2001). Other types include generalised tensegrity grids, that is, involving strut-strut contact (see Adriaenssens et al, 1998; Furuya, 1992) as well as configurations combining rigid bar units with cables as means of deployment and prestress (Sircovich-Saar, 1984). A super-light application for fabric structures (see Burford et al., 1998) involves spines which consist of fibre-reinforced chords and fabric-web, rather than cables (Hanaore and Levy, 2001). These concepts are frequently semi-deployable or dismountable (Adriaenssens et al., 1998; Burford et al., 1998; Sircovich-Saar, 1984), however, because few elements are involved, the deployability of the system as a whole is not significantly affected (Hanaor and Levy, 2001).

II. Recent Developments

You (1997) has explored several concepts for pantographic structures, both straight and curved, and has made several working models.

The Deployable Structures Laboratory (DSL), Cambridge University developed the Cable-Stiffened Pantographic Deployable Antenna (CSPDA). The deployable ring structure consists of units made of three different pairs of rods connected by scissor joints. The pairs of rods are connected at their end points to form a circular pantographic structure which can be folded. Accurate positioning and manufacturing of the scissor and end joints is crucial for a successful folding. A 3.5 m diameter model has twelve sides and is composed of 48 pantograph elements (Figure 2.5). A double layer cable network, which supports the radio frequency (RF) reflective mesh, is attached to the ring structure. The layout of the network is chosen such that the total structure is statically determinate, or indeterminate to only a small degree.

An active cable is used to deploy the ring structure. In the stowed configuration, the diameter and height are 0.6 and 1.2 m, respectively (You and Pellegrino, 1997). Kwan and Pelligrino (1994) define an active cable as: "*a long, constant-tension cable element connecting two or more joints of a deployable structure.*"

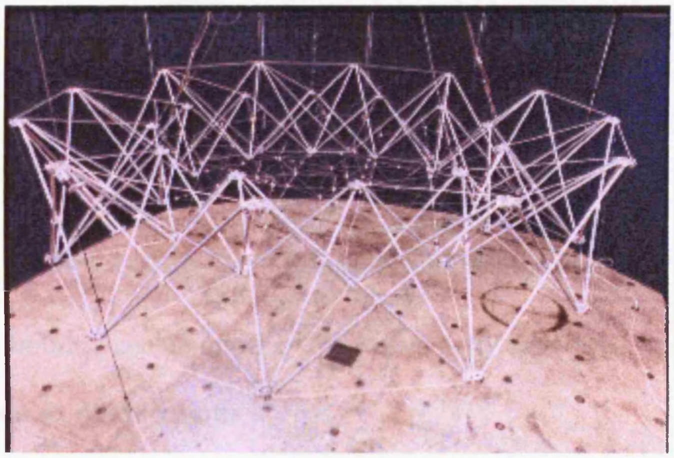


Figure 2.5

A 3.5 m diameter model of the cable-stiffened pantographic deployable antenna (You, 1997. http://www-civil.eng.ox.ac.uk/people/zy/ research/dsm.html.)

In 1990, Astro Aerospace Corporation (now known as TRW Astro Aerospace) started developing what is then the current state-of-the-art deployable reflector antenna, that is, the *AstroMesh* (Figure 2.6), which is based on the tension truss concept (Tibert, 2002). Two identical paraboloidal triangular networks are attached to a deployable ring truss. This assembly is prestressed by tension ties connected to mirroring nodes of the two networks. The RF reflective mesh is attached to the backside of the front net. The antenna is deployed by shortening a cable which continuously runs through the telescopic diagonal members of the ring truss. Deployment synchronisation is achieved through special joints at the truss connections where only three members meet (Thompson, 2000). This antenna has a diameter of 12.25 m and weighs 55 kg. In the stowed configuration, the diameter and height are 1.3 and 3.8 m, respectively (TRW, 2000).

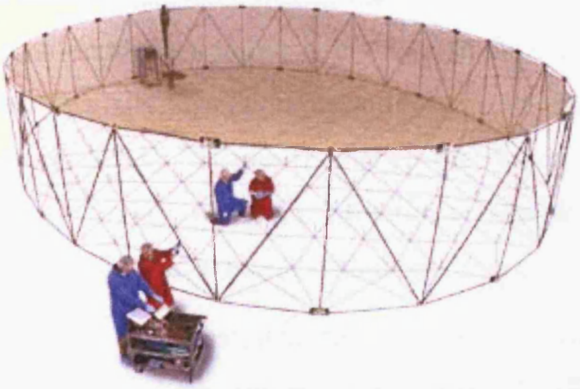


Figure 2.6.
AstroMesh™ Reflectors
(http://www.astro-aerospace.com/astromesh.html.)

Developments in mobile mast technology have been fully described by Kwan (2000).

III. Functions and Applications

Most applications of masts are suitable for retractable roofs having a rigid perimeter and for dismountable surfaces which involve long members.

Other pantographic configurations are applied for outer space purposes, as indicated earlier in the text (Section 2.1.3).

Most mast concepts have been applied in the space industry, such as the various types of coilable lattice masts, truss masts and telescopic masts (see Kwan, 2000 for description of these masts). Some concepts, however, are employed in terrestrial industry, such as the Thin Shell Masts, including storable tubular extensible members and collapsible tube masts, Elmar mast trucks, Mast System, Will-Burt, Salzgitter Maschinenbau, etc. (also see Kwan, 2000 for description of these types of terrestrial masts). Miura (1993) also reported developments in coilable longeron masts and Elastica. Elastica is a linear deployable structure constituting the basic building block for constructing space structures, such as telescopic automobile antennae, carpenter's reels, and foldable scales. (Miura, 1993)

2.2.2. Plate Structures

I. Description

Hanaor and Levy (2001) distinguish two sub-groups: folded plates and curved surfaces. Folded plates are inherently deployable through articulation of the hinges bonding each plate, and have structural depth even in planar configurations. Curved surface structures, on the other hand, are essentially dismountable and rely exclusively on surface curvature depth (Hanaor and Levy, 2001). However, due to the dimensions of the plates, the deployment efficiency is lower for plate structures than for membrane surfaced configurations, even for configurations with skeletal main structural systems.

The basic 'minimal' single kinematic degree of freedom (SKDOF) mechanism of plate structures comprises four plates connected by hinges (Figure 2.7). There are two configurations, one comprising parallel hinges and the other with hinges intersecting at a point. While intersecting fold gives rise to folded structures, the parallel fold gives rise to planar folded surfaces (Hanaor and Levy, 2001). Kent (1983) maintains that both structures fold to flat planes in two ways, provided certain geometric relations between the links are conformed to.

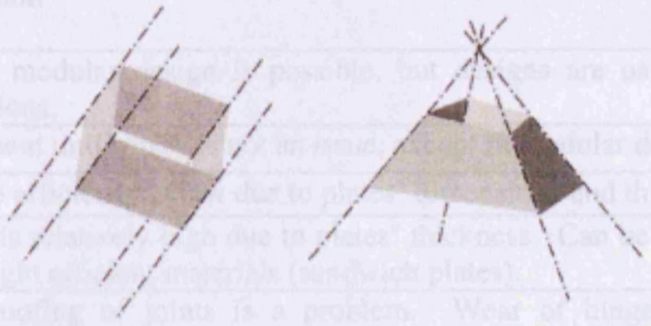


Figure 2.7.
Basic 'minimal' SKDOF mechanisms for generating folded plate structure
(Source: Hanaor and Levy, 2001)

Delarue (1993) and Kent (1983) explain that these basic units could be combined in different ways to generate a very wide range of folded surfaces. However, not all configurations are suitable for deployable structures because the folded configuration is not compact (Hanaor and Levy, 2001). These authors add that all such configurations have a single KDOF, and practically, folded surfaces are usually generated by six folds, but not four, which meet at a point.

Folded plate structures intrinsically possess high structural efficiency, which, nonetheless, does not translate automatically into light weight, due to the fact that the plates themselves, which are subject to compression and flexure, require minimum dimensions (Hanaor and Levy, 2001). The resultant general weight may be higher than in structures surfaced with membrane. Table 2.3 provides an evaluation of folded plate structures, again in accordance with the criteria reported in Table 2.1.

Table 2.3.
Evaluation of folded plate structures

Criterion	**Evaluation**
1	Limited modular design is possible, but designs are usually for specific applications.
2	Component uniformity is not an issue, except in modular design.
3	Stowage efficiency is low due to plates' dimensions and thickness.
4	Weight is relatively high due to plates' thickness. Can be reduced by using lightweight efficient materials (sandwich plates).
5	Waterproofing of joints is a problem. Wear of hinges with repetitive deployment. Little maintenance required for the individual plates
6	Minimal foundation and anchorage
7	Minimal site connections. Connections between modules in large structures. Some extra bracing is sometimes needed.
8	Low mechanical complexity, high deployment reliability
9	No auxiliary equipment

Source: Hanaor and Levy (2001, p. 223).

II. Developments

One of the developments in this field was that of the Solid Surface Deployable Antennas (SSDA) by Guest and Pellegrino (1996), based on their work on the wrapping fold pattern. The Wrapping Fold Pattern is a way of folding a membrane by wrapping it around a central hub. An example of the fold pattern is shown below (Figure 2.8), almost fully folded, and almost fully deployed.

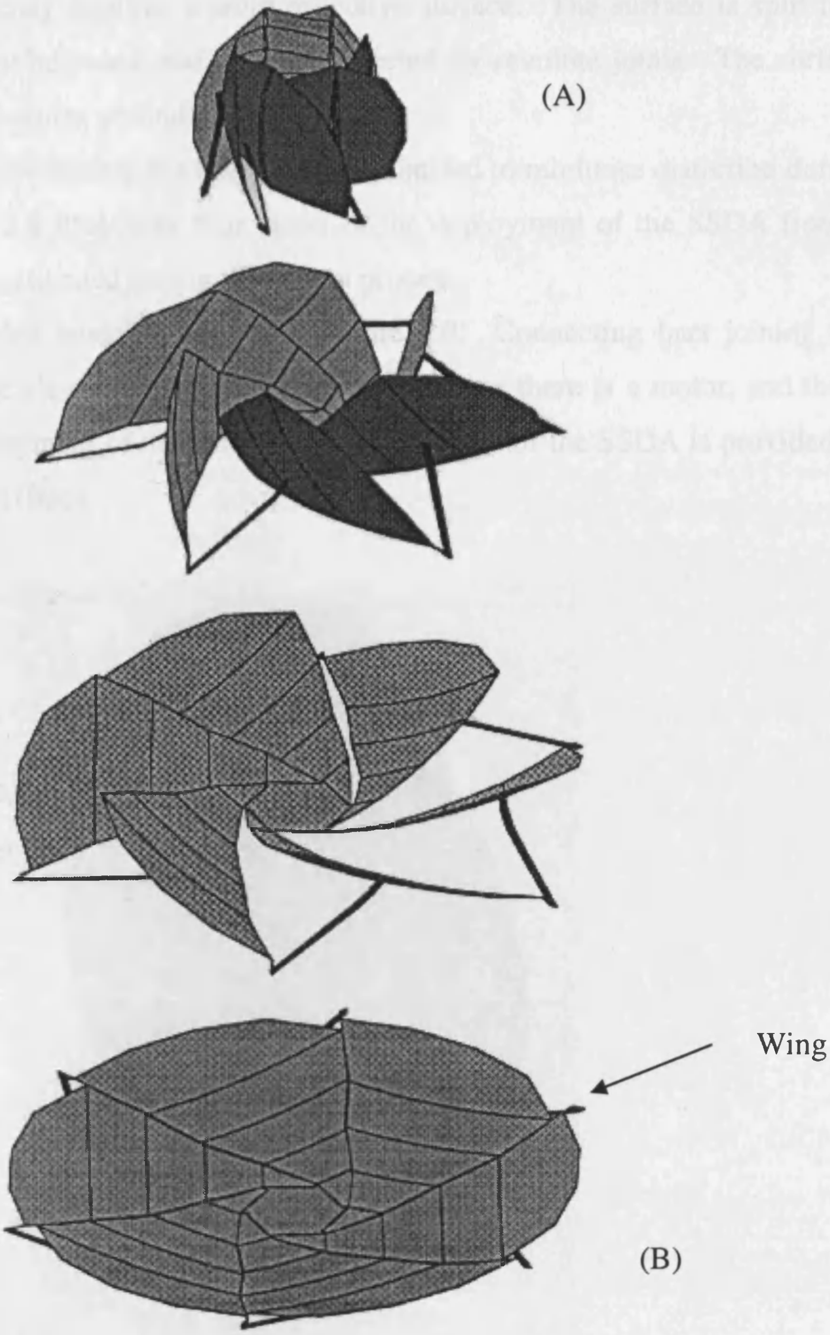


Figure 2.8.

The Wrapping Fold Pattern. (A) folded, (B) deployed.

(Guest, 2000)

The SSDA is a new concept for the folding of a parabolic antenna in which a high operating frequency requires a solid reflective surface. The surface is split into wings; each wing is subdivided into panels connected by revolute joints. The surface folds by wrapping the wings around a central hub.

The design of the SSDA has been highly optimised to minimise distortion during deployment. Figure 2.8 illustrates four views of the deployment of the SSDA from a computer simulation generated during the design process.

The fully folded model is shown in Figure 2.9. Connecting bars joining the wings together can be clearly seen. At the end of each bar there is a motor, and these motors drive the deployment of the antenna. A full account of the SSDA is provided in Guest and Pellegrino (1996).

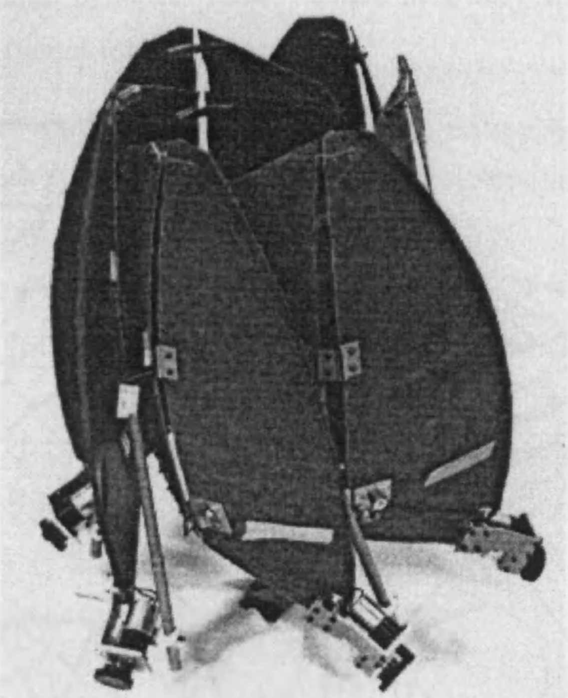


Figure 2.9.

A fully folded model, showing motors.

(Guest, 1996)

Another development was also presented by Guest and Pellegrino (1994a, b, 1996) in which they described the folding of triangulated cylinders. In Part I (1994a) they described geometric consideration, in Part II (1994b) the folding process, and in Part III (1996) they described an experimental investigation of a type of foldable cylindrical structure, which they have presented in the first two parts.

According to Guest (2003) foldable cylinders are a new way of packaging a cylinder. They consist of a number of triangular panels that are arranged in a helical pattern on a cylinder and when folded the cylinders are packaged as a compact stack of plates.

Figure 2.10 illustrates three simple designs. These cylinders fold down to the flat polygons shown underneath each cylinder. Nonetheless, the concept is much more general than these simple cylinders show. There is a very wide range of possible designs, which have different folding properties.

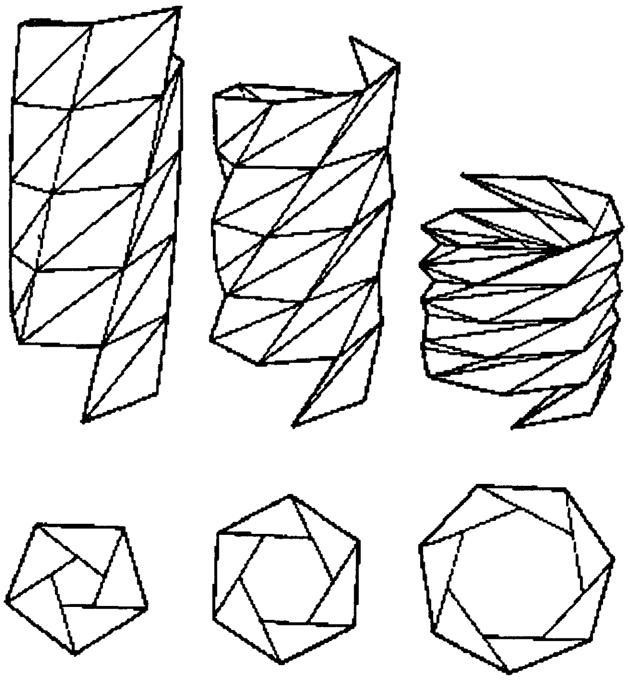


Figure 2.10.

Triangulated cylinders with $m = 1$ and (*a*) $n = 6$, (*b*) = 7, and (*c*) $n = 8$.[2]

(Source: Guest, 2003; Guest and Pellegrino, 1994a).

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[2] m, n = the number of starts of the *a* and *b* helices, respectively (Guest and Pellegrino, 1994a, p. 775).

III. Applications

There is a wide range of applications of plate structures, both in space and on the Earth. Some of the developed structures can be used in space satellites and space industry, such as the Solid Surface Deployable Antennas, and the cable-driven rigid panel solar array, mentioned above.

Foldable plate structures can also be used for terrestrial purposes, such as in the construction of the folding, or retractable roofs.

2.2.3 Tensegrity Structures

I. Description

Tensegrity structures are in general not deployable structures. Tibert (2002) indicated that the word *tensegrity*, which is a contraction of *tensile integrity*, was coined by R. B. Fuller (1962). Hanaor and Levy (2001) indicate that the term is ill defined and widely differing concepts have been proposed in the literature under this catchy label. Tibert (2002) also reports similar approach to that of Honaor and Levy, maintaining that the meaning of the word is unclear and different interpretations are possible. For example, while Fuller (1962) describes a tensegrity structure as "*an assemblage of tension and compression components arranged in a discontinuous compression system...*", Pugh (1976) defines a tensegrity system as: "A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space." Hanaor (1994) describes tensegrity structures as "internally prestressed, free-standing pin-jointed networks, in which the cables or tendons are tensioned against a system of bars or struts". Muira and Pellegrino (1999) report two interpretations for tensegrity structures, a broader interpretation as "any structure realized from cables and struts, to which *a state of prestress is imposed that imparts tension to all cables*", and a narrower interpretation which adds to the above definition the notion that "as well as imparting tension to all cables, the state of prestress serves the purpose of *stabilising the structure*, thus providing first-order stiffness to its infinitesimal mechanisms." Skelton et al. (2001) describe a tensegrity structure as a special truss structure in a stable equilibrium, with selected members designated for only tension loading, and the members in tension form a continuous network of cables separated by a set of compressive members. A truss, according to Skelton et al. (2001) is a structure whose compressive members are all connected with ball joints so that no torques can be transmitted. They add that tension members connected to compressive members do not transmit torques, so that truss is composed of members experiencing no moments. To this effect, they proposed some useful definitions, as follows:

"A given configuration of a structure is in a *stable equilibrium* if, in the absence of external forces, an arbitrarily small initial deformation returns to the given configuration." (p. 259).

"A tensegrity structure is a stable system of axially loaded-members." (p. 259).
"A stable structure is said to be a "Class 1" tensegrity structure if the members in tension form a continuous network, and the members in compression form a discontinuous set of members." (p. 260).

"A stable structure is said to be a "Class 2" tensegrity structure if the members in tension form a continuous series of members, and there are at most two members in compression connected to each node" (p. 260).

To explain the mechanical principle of tensegrity structures, Pugh (1976) uses a balloon analogy. If the enclosed air is at a higher pressure than the surrounding air it pushes outwards against the inwards-pulling balloon skin. If the air pressure inside the balloon is increased, the stresses in the skin become greater and the balloon will be harder to deform. In a tensegrity structure the struts have the role of the air and the cables that of the balloon skin. Increasing the forces in the elements of a tensegrity structure will decrease its stiffness and load bearing capacity.

A more extensive investigation into the origin of tensegrity is given by Lalvani (1996). Even though the concept of tensegrity is more than fifty years old, few applications exist, for example, Geiger's cable domes (Geiger et al., 1986; Pellegrino, 1992). In recent years, the concept has received new attention from mathematicians, engineers and biologists. Ingber (1998) argues that tensegrity is the fundamental architecture of life. From the deployable structures point of view, tensegrity structures are very interesting since the compressive elements are disjointed. This provides the possibility to fold these members and hence the structure can be compactly stowed (Tibert, 2002).

Hanaor and Levy (2001) report that a tensegrity structure, in its purest form, comprises a network of bars and cables, where any bar is connected only to cables and to no other bar. This restrictive definition is important in the context of deployable structures since it entails the complete absence of articulated joints between struts. The required kinematics is provided by the flexible cable. The deployment process of these structures requires the change in length of some members (Hanaor and Levy, 2001). Consequently, two deployment techniques have been proposed. One technique involves the change of bar length through energy supply (hydraulic or mechanical) to the telescoping bar. The second involves the pulling of cables over a system of pulleys attached to the bars. According to Hanaor and Levy (2001), each technique has its advantages and limitations regarding mechanical complexity, deployment reliability and structural efficiency.

Structural efficiency (that is, maximum mass the structure can hold divided by the structure mass[3]) of pure tensegrity structures is rather low, in comparison with conventional bar double-layer grid structures, due to the long unbraced bars. Hanaor and Levy (2001) maintain that structural efficiency of configurations with bars joined between the two layers, such as in Pedretti's configuration (illustrated in Hanaor and Levy, 2001, Figure 1, No. 68), is significantly improved. They add that employing the cover membrane to embrace struts in configurations that make this possible, such as in the Kwan and Pellegrino's (1994) octahedral grid, can further improve efficiency. Hanaor and Levy (2001) also presented an evaluation of the double layer strut-cable systems, according to the nine criteria presented in Table 2.4.

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[3] http://wiki.answers.com/Q/How_do_you_define_structural_efficiency_score.

Table 2.4.
Evaluation of double-layer strut-cable systems

Criterion	Evaluation
1	Flexible modular design is possible, depending on configuration. Large areas can be covered with relatively small modules connected on site.
2	High component uniformity can be maintained. Deployable tensegrity systems are essentially self-adapting
3	The structure folds to a compact bunch of bars. Compatible folding of the membrane needs to be considered
4	Structural efficiency varies from relatively low to high, depending on concept. High efficiency requires some bar inter-connection.
5	Repeated deployment may cause significant wear and tear to the membrane and to connections.
6	Generally, self-supporting configurations can be designed, requiring minimal foundation and site preparation.
7	Degree of deployability is relatively high. Site assembly involves connection of deployable modules and possibly, addition of bracing elements.
8	Low to medium mechanical complexity, depending on concept. A tradeoff between articulation and structural efficiency is possible.
9	No auxiliary equipment is required other than relatively light lifting equipment to assist in deployment and folding

Source: Hanaor and Levy (2001, p. 218).

II. Recent Developments

There had been a number of recent developments in tensegrity. For example, in 1998, Pedretti developed a variation on the telescoping bars technique. The bar system consists of groups of six bars joining at a common articulated joint although the bars are not telescoping. Instead the hydraulic energy that activates the deployment mechanism is applied to an external actuator mounted on each joint (Hanaor and Levy, 2001).

Kwan and Pellegrino (1994) proposed a new concept for space frame that can be automatically deployed and rigidified, primarily by means of electric motors. The new concept involves pantographic spines that in their deployment prestress a network of octahedral consisting of bars and cables. Kwan and Pellegrino's system has a single KDOF, which though proposed for outer space applications, it is readily implementable in terrestrial applications (Hanaor and Levy, 2001). The structure's configuration shows the lack of substantial chords, and to achieve structural depth, curved surfaces need to be generated or chords added, such as in the form of either bars or prestressed tendons.

New concepts have been developed by Tibert (2002), including stiffened hexagonal module, Hexagonal Tensegrity Module and Tension Trusses, Minimum Separation between Front and Rear Nets, and Three-Ring Axi-Symmetric Reflector.

An improved version of the regular hexagonal tensegrity module was developed by Tibert (2002), whose structure was obtained by connecting the nodes of the top and bottom hexagons to two interconnected, central joints. These internal joints are not coplanar with the hexagons, thus forming two triangulated surfaces that roughly approximate to a curved surface. The modified assembly has $j = 14$ joints and $b = 37$ bars. The extended Maxwell's rule yields:

$$m - s = -1,$$

(where m is the number of internal mechanisms and s is the number of states of self-stress, Tibert, 2002, p. 4), whereas the regular hexagonal tensegrity module has $j = 12$ joints and $b = 24$ bars. With $c = 6$, the extended Maxwell's rule gives:

$$m - s = 6.$$

III. Applications

There are several applications of tensegrity structures. For example, they can be applied in the space industry (see Tibert, 2002). They can also be applied in other areas, including the following: an extremely compact parabolic radio antenna for space-based vehicles; a support for extremely large scale parachutes; shelter for the needy of third world countries, for which no additional personnel would be necessary for assembly; a travel-worthy birdcage; toys; and a folding household barrier for small children and dogs (Bergen.org, 2002).

2.2.4 Membrane Structures

I. Description

Membrane structures are typified by the use of tensile sheets. These structures are extremely lightweight where the thin tensile surfaces are supported by air-pressure or rigid members, for example, masts, arches or frames. The stability of tensile structures depend on the intricate, curved three dimensional geometry in which the skin is prestretched (Schueller, 1983).

According to Hanaor and Levy (2001), a tensioned membrane structure is a deformable structure which relies on prestress for stability and adequate stiffness. Essentially, there are two main types of membrane structures, based on the means of prestress application, namely, fabric structures and pneumatic structures. Fabric structures require a surface of negative Gaussian curvature, that is, saddle shape, obtained through a suitable boundary and suitable cutting patterns, often in conjunction with compression and anchorage elements. Pneumatic structures, on the other hand, use air pressure to prestress a suitable patterned membrane. The membrane itself is deformable and inherently deployable, and due to the relatively small thickness of the material, stowage efficiency is very high and weight is low (Hanaor and Levy, 2001).

As a rule, pure tension structures do not exist. To maintain equilibrium some compressive elements or forces should be present. In fabric structures such elements are composed of rigid bars, singly or as skeletal elements, whereas pressure is the compressive element in pneumatic structures.

There are two main types of fabric structures; tents and ribbed structures (Hanaor and Levy, 2001). Tent compression elements, usually in the form of masts, are external to the fabric surface and act separately from it, whereas the compression elements in ribbed structures are part of the surface, and usually interact structurally with the membrane. Structural efficiency is very high when adequate structural curvature is provided by the surface.

Pneumatic structures are tension membrane structures in which compression needed to balance the membrane tension is provided by air pressure. They are probably the most efficient deployable structures regarding stowage efficiency, especially if auxiliary equipment-compressors and anchorage components are ignored. There are also two types; low pressure and high pressure. Evaluation of both fabric structures and pneumatic structures are presented in Table 2.5.

II. Recent Developments

De Focatiis and Guest (2002) have recently investigated the effect of combining several corrugated leaf patterns in order to produce deployable surfaces, for example, solar panels, antennae, solar sails, folding tents and roof structures. These thin membrane structures are biomimetic, developed by considering how the folding of natural structures, a leaf, could be extended to engineering structures.

III. Applications

These structures are used in making tents, shelters, and flexible roofs. They can also be developed to be manufacture solar panels, antennae, and solar sails. Folding patterns for membranes have been considered in the aerospace structures (De Focatiis and Guest, 2002), for example, the two-dimensional deployable array, the *Miura-Ori*, which has application as a solar panel (Miura and Natori, 1985), and the wrapping of a membrane around a central hub, the *wrapping-fold pattern*, which has been considered for a solar sail structure (Guest and Pellegrino, 1992).

Table 2.5.
Evaluation of tensioned membrane systems

(A) Fabric structures

Criterion	Evaluation
1	Modular design is possible 125 to a limited extent, e.g., by combining tents, combining arched units, etc., but architectural flexibility is limited.
2	Component uniformity applies to some extent to the spines/masts and to modules in modular design.
3	Generally extremely efficient stowage, depending on the compression element.
4	Extremely low weight, depending on skeletal structure.
5	Wear and tear to membrane and to skeletal structure is applicable.
6	Some systems (particularly tents) require ground anchorage, others (ribbed) are free-standing.
7	Limited connections – between modules and to dismountable spines/masts. Sometimes connection of membrane to spine/mast and to anchors.
8	Complexity in skeletal elements only. Deployment is not controlled but reliable in the final deployable state.
9	No auxiliary equipment.

Source: Hanaor and Levy (2001, p. 223).

(B) Pneumatic structures

Criterion	Evaluation
1	Low pressure: Generally low architectural flexibility. Structures are purpose designed, although modules can be joined. High pressure: High architectural flexibility. Components (tubes) can be combined in different ways.
2	Component uniformity is not an issue as they are individually manufactured.
3	Low pressure: Very high stowage efficiency of membrane. High pressure: Medium efficiency of membrane stowage.
4	Low pressure: Very light, high structural efficiency. High pressure: Medium. Heavier than other membrane systems.
5	Possibility of punctures, air tightness loss, eathering and waring of membrane.
6	Low pressure: Anvhorage and or weighting down of perimeter required. High pressure: No special site preparation required.
7	Minimal site connections – connections between modules, to anchorage components.
8	No mechanical complexity, high deployment reliability ensured by air compression.
9	Low pressure: Constant air pumping required and safety devices against power loss. High pressure: Pumping required only at deployment.

Source: Hanaor and Levy (2001, p. 224).

2.3 Summary

The discussion in the preceding sections attempted to define the term 'deployable structures', and showed that deployable structures are employed in two types of applications, namely, as temporary structures, and in inaccessible or remote places, such as in outer space application, where minimal human intervention is required. This implies that deployable structures have a wide range of potential applications and uses, both terrestrially and in outer space. They are also widely used in civil engineering as temporary and retractable structures.

There are two types of deployable structures; the fully deployable structures, and the dismountable structures (the assemblables).

Foldable and deployable structures have been, and are still widely applied in various disciplines of science, in humanitarian missions, in commercial fields, and in military operations.

Four types of foldable structures were explained in some details in terms of their descriptions, new developments and applications. These are: pantographic structures (single-layered grids, double-layer grids, and masts and spines), plate structures (folded plates and curved surfaces), tensegrity structures, and membrane structures (fabric structures and pneumatic structures). All four types were evaluated in terms of nine criteria, that is, design (architecture and flexibility), competent uniformity, stowage and transport (stowed and compactness), weight, maintenance (wear and tear), site inputs (site preparation), connections, complexity/reliability, and auxiliary equipment.

Deployable structures are used for a number of reasons, such as mobile use, use in different geometries, remote assembly, and speed of assembly (Kwan, 2000).

Out of the four deployable structures, the author has decided to use plate structures, for several reasons. For instance, regarding design, a limited modular design is possible, and component uniformity is not important, except in modular. Further reasons include the following: little maintenance is required for individual plates, minimal foundation and anchorage, and minimal site connections are required, plate structures are characterised by low mechanical complexity and high deployment reliability, and they do not require any auxiliary equipment. However, there are certain setbacks when deployable plate structures are used, such as low stowage efficiency due to the dimensions and thickness of plates, which make their weight relatively high, though this can be minimised by using lightweight efficient materials, such as sandwich panels, the problem of waterproofing of joints, and wear of hinges with repeated deployment. These setbacks need to be considered carefully and solutions sought to overcome them. However, the author has also decided to introduce tensegrity structures to help solve the problem of lack of space during deployment steps, which will be addressed in Chapter 5.

CHAPTER THREE

PRELIMINARY STUDIES AND MODEL DESIGN

3.1 Introduction

This part of study resumes with taking the most essential points from the previous work, discussed in Chapter 2, to design the desirable model and testing it. This chapter explains the various trials carried out to design the foldable pyramid, which is the roof of the accommodation unit that was meant to be designed. Every structure needs to be designed according to some overall parameters. In this case some of them are technical and the rest would be the user needs. Table 3.1 shows the technical parameters that should be taken into account during the design process. At the early stage of this design some conditions must be appointed and chosen, which will affect the designed model; also the needs of the users which have been taken from the field study, and thus ultimately the type of foldable structure.

Table 3.1 General parameters of the design

Parameter	Specifications
Volume and Area Dimensions	Side walls height=2.8 m Pyramid height > 1 m
Materials	Aluminium, steel, fabrics and sandwich panels. Fire resistance, isolator
Weight	Two parts, each part not more than 50 kg
Construction Time and Workers Number	20 to 30 minutes and not more than 4 workers required for each unit
Ground Situation	Sand, silt. max α= 10° (α is ground slope angle)

The conditions are: firstly, that the pyramid model will have a square base, which means that the model will be symmetrical, where this will help ease in designing calculations just for one face and then applying the theories to the other faces. Secondly, the model must be well concealed without leaving gaps at the final designed model. This is to prevent water or air from entering into the shaped design while considering the availability of using the model for different purposes, such as an operation theatre unit. Finally plate structures will be used, whereby this would highlight some of the points, such as the importance of the dividing angles plus reducing the movement freedom and difficulties of imparting the model.

It is possible for these conditions to be determined at the early stage of the desirable design and then proceeding further until reaching the final design, while experiencing some difficulties during the process. The design starts by trials on models with "zero-thickness" materials which are hereby called (A) models. This chapter deals with A model trials, while Chapter Five deals with models made of materials with thickness called (B) models.

3.2 Trials and Ideas

3.2.1 Flat Surface (Model A1)

De Focatiis and Guest (2002) employed tree leaves to benefit from them in the design of foldable structures. This experiment was on a flat square surface divided into four symmetrically equal leaves, provided that the shape should fold towards the centre of the square. For the sake of simplicity of this folding, the Miura-Ori's Map (Bain, 1980), illustrated in Figure 3.1, has been taken into consideration. In Figure 3.2, the parts of the four square angles must be less than 90°; the reason behind that is to prevent and reduce strain during the deployment of the model. This trial for obtaining the pyramid shape of the three dimensions indicates that small changes in the right angle as well as removing some part in the middle of each side of the square should be made (Figure 3.2).

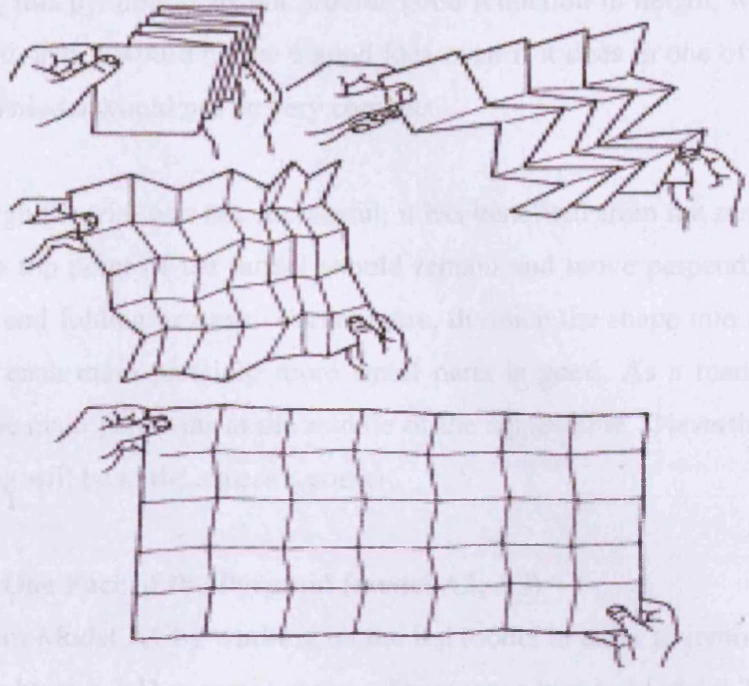

Figure 3.1. Miura-Ori Map (Bain, 1980)

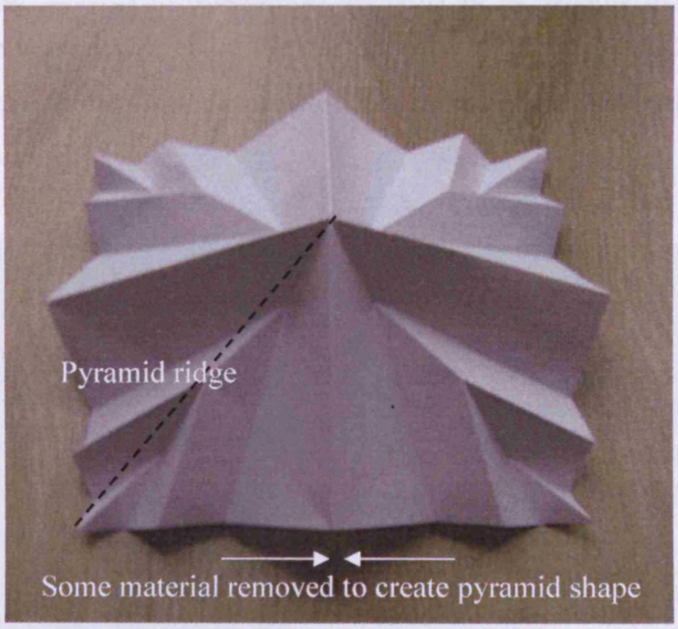

Figure 3.2 Model A1 (pyramid shape from a flat surface)

In fact, this pyramid does not provide good reduction in height, width and depth at the final fold, and it would not be a good idea even if it does in one of them, because the fold in this model would not be very compact.

Although the trial was not successful, it has benefited from the same main points in design. The top point of the model should remain and move perpendicularly during the deploying and folding process. Furthermore, dividing the shape into main parts and then dividing each main part into more small parts is good. As a matter of fact, the division for the main parts was at the middle of the square side. Nevertheless, the next trial of dividing will be in the square's corner.

3.2.2 Folding One Face of the Pyramid (model A2, A3)

We benefit from Model A1 by working on the flat model in order to remove some of the parts so as to obtain a 3-D pyramid shape. This means that in Model A2 we start from the final shape, that is, the pyramid, which is divided into four main parts that forms four identical triangles which meet at one point, that is, the top point of the pyramid. This is in comparison with four squares in Model A1. In order to be capable of making this shape foldable then we must divide every triangle into smaller parts. When the parts are divided to the tree leaves, the final shape shows high reduction in width and some increase in height (Figure 3.3).

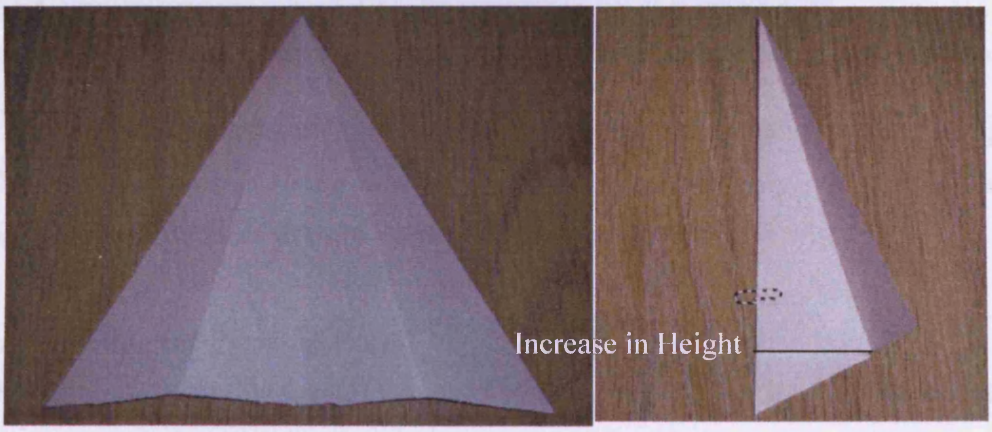

Figure 3.3 Model A2 (One pyramid face with tree leaves division)

Due to height increase in Model A2, the idea of dividing perpendicularly and horizontally appears more logical. This would support the notion that more division gives more reduction in area.

Miura Map uses the zigzag divisions rather than straight vertical and horizontal divisions. This makes the fold easier and reduces the strain. Zigzag fold changes the structure of plate shape from square to rectangular. In other words, changing the right angle in a foldable surface leads to strain reduction during folding.

Miura Map is rectangular or square surface while the pyramid face is triangular. This makes vertical fold in triangle shape not the same as in a four edged-shape. It is better to add zigzag horizontal folds to model A2 to get a high reduction in both width and height (Figure 3.4, Model A3).

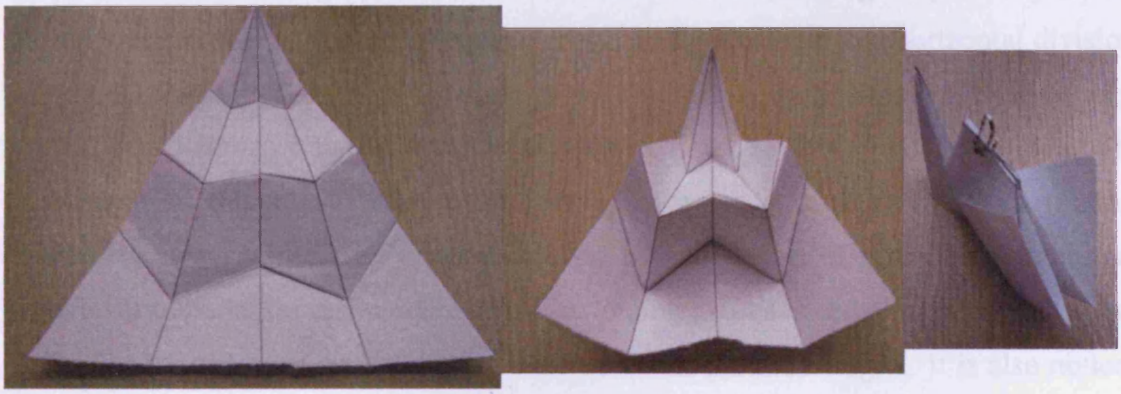

Figure 3.4 Model A3 (A pyramid face with vertical and zigzag horizontal divisions

In this way the structure's 3-D volume is reduced, thus achieving a very compact model. However, this is so far working on one flat surface only. In the following section, joining those faces to form a complete pyramid will be dealt with.

3.2.3 Assembling the Pyramid Faces

Important points should be taken in account to achieve a closed 3D foldable structure. At the beginning, folding and deploying mechanism should be with no flexible material and as strain free as possible. On the other hand, a structure with less freedom will occur, which means that there would be neither free ends, that is, no connections between the segments, nor flexible joints between these segments, especially those on the critical position like a pyramid ridge line. Moreover, symmetrical movement should be applied throughout the folding and deploying process. In a pyramid case, the head point of the pyramid would be the central point of the symmetrical movement. In other words, during folding every point in the structure moves in a particular path to the central point and uses the same path with opposite direction during deploying.

When assembling the four faces of the pyramid for folding, we should make sure that the joints between plates provide free movement for all plates during deploying and folding based on the perpendicular movement of pyramid's top point. Thus, at this stage cutting will be made according to the theory of Miura Maps which follows zigzag line in horizontal cutting and straight lines stretching from the top point in the pyramid down to the base side forming vertical cutting. Lengths at base side are equidistant (Figure 3.4).

In model A4 (Figure 3.5), the base side will be cut into eight equal lengths, i.e., the slope angle will not be equal in each cross between vertical and horizontal division. Horizontal fold is made into five levels, while the vertical fold is made into eight main pieces. The height of the pyramid equals one quarter of the square base side. The assessment in this model requires review of each stage of deploying and folding. Therefore, stages should be divided into A, B, and C (see Figure 3.5). The most significant remarks on this model is that the folding process needs more force at points located in contact areas between the four faces of the pyramid ridges. It is also noticed that in this model the movement is a sequence, i.e., stress is made on the contact point located at the pyramid ridge. Subsequently, the next point starts moving but with less stress until shifting from A to B in a sequence movement. (See Figure 3.6).

In this trial, there is no device to tackle the problem of "high strain" except by cutting the material at the pyramid ridge before the deploying process. Then, deploying of the model in a sequence is made, starting from the divergent contact point to the next one until reaching the same point on the next face. So, connection starts from here to form the final shape of the pyramid.

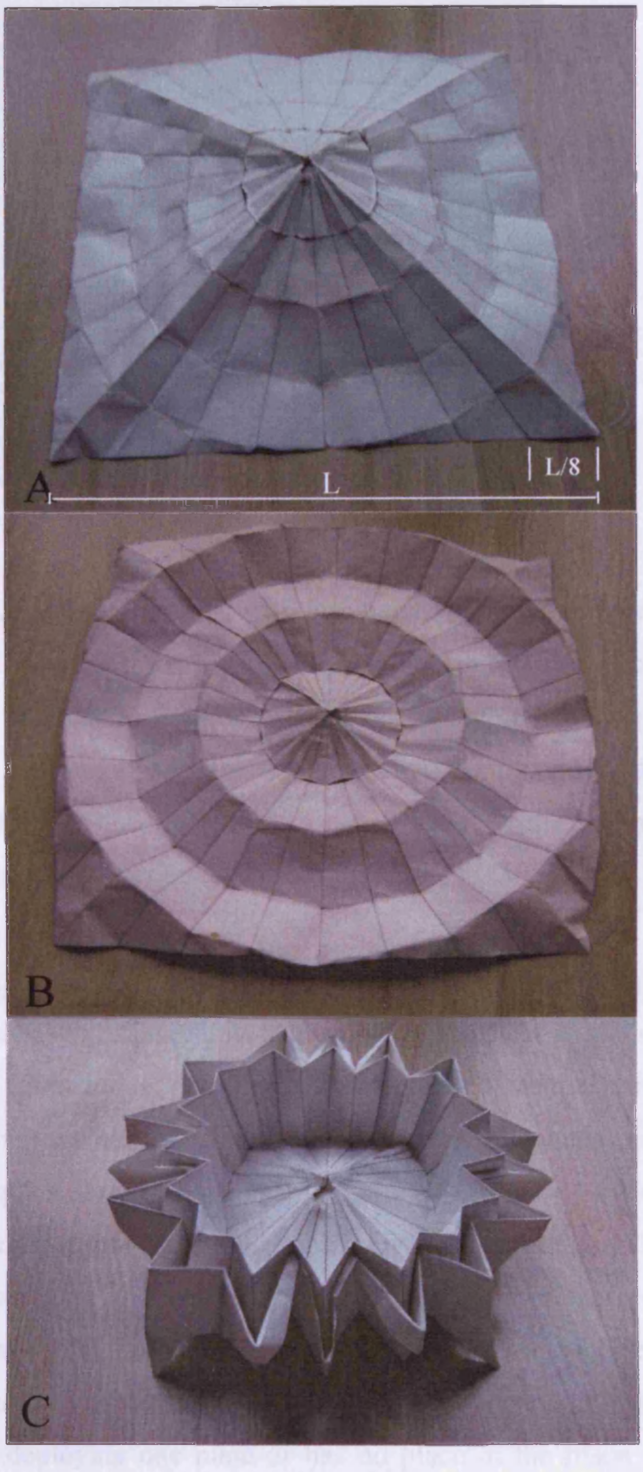

Figure 3.5 Model A4 (Folding stages)

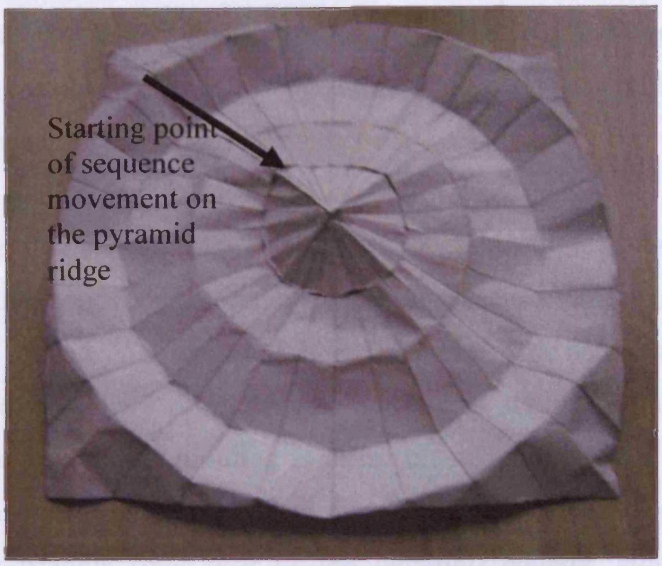

Figure 3.6 Model A4 (Sequence movement)

Although this trial is applied on a relatively low-height pyramid, and needs high strain to fold, the suggested solution for this problem is to detach the main faces of the pyramid in just one corner in order to provide flexible deploying and folding process. The basic problem was in deploying and folding plates on the pyramid ridge. This assumes that the main problem is the right angle situated between the pyramid faces which should be tackled so as to have a perfect shape of foldable pyramid.

From previous discussion, it is required now to change the base shape of the pyramid from square into octagonal shape, in order to change the right angle located in four sides of the pyramid. This model (Figure 3.7) is extended from the notion of dividing the four faces of the pyramid into small plates. Thus, deployment and folding is made according to consequent steps through changing the square- based pyramid into multiple shapes, in which each shape is formed separately. In this process, there is a replacement of small parts from one plane to another. In other words, changing coordinates of plates on plane X, Y, Z, whereas, the plate located in the enclosed area in each coordinate is to be shifted to another area in different plane. For instance, if difficulty is experienced in deploying one plate or has no place in the plane (X1, Y1, Z1), it can be shifted in later deploying stages to another plane (X2, Y2, Z2) until this step is complete, taking into account, connecting this part with other parts and its motional impact on the linked plates. If this technique is good for deploying, the problem of linking the four faces of the pyramid would disappear at the right angle as well as removing the strain problem of the structure.

In the process of changing the shape of the pyramid from square into octagonal shape, the symmetrical movement of the typical four faces of the pyramid should be taken into account. This means, cutting of faces should be made on the basis of multiples of four. In addition, symmetry of all lengths and angles should be maintained for all pyramid parts. For example, if dividing is based on shifting the base from the square shape into the octagonal shape, the vertical division would be based upon dividing the head angle of the triangle (one face of the pyramid) equally. Horizontal dividing determines the same lengths along the vertical division, i.e., each level in the horizontal division will form an octagonal shape. All these changes will be applied on the model, now referred to as Model A5.

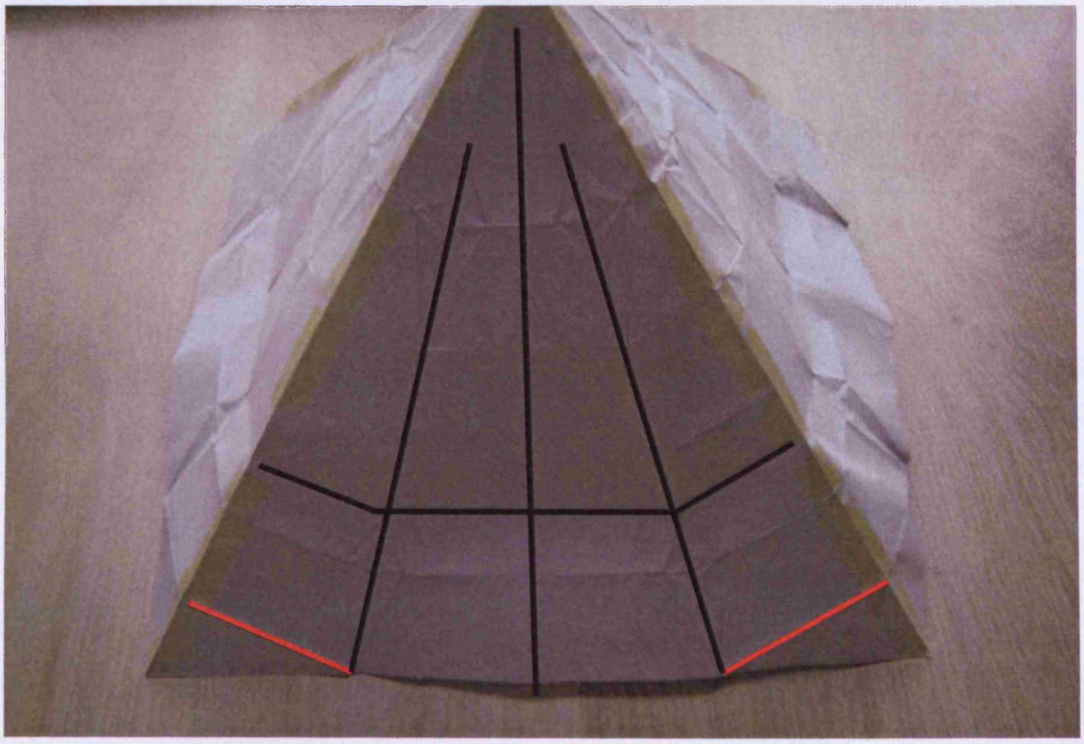

Figure 3.7. Model A5 showing additional levels on the pyramid ridges

This trial modelling is to be applied on the equilateral triangles. The head of each one will be divided into four equal parts, each one forming 15 degrees, thus maintaining the longitudinal division. The first division will be vertical on the triangle base from the top point. This will divide the triangle into two right angle triangles. The second division will be made on the two triangles that have thus yielded from the first division but with an angle 15 degrees. The horizontal division will be perpendicular to the vertical lines of the height in the four triangles, with 75 degrees angle on the second vertical division. The pyramid ridges would be regarded as highest lines of the original triangle and thus the horizontal division will be perpendicular to it which makes additional level only on the pyramid ridges that resulted from the variant of length between the highest line of the triangle and the triangle side (see Figure 3.7).

Deploying and folding in this trial will follow subsequent steps until reaching the complete folding. The complete deploying of the pyramid is regarded as stage A, while the next step B would be shifting the pyramid to an octagonal base pyramid. This step is done after changing the four angles located between the original four faces from 90° to 180° and then folding the four extra edges at the end of the pyramid corners to the top to form the octagonal base as (Figure 3.8) demonstrates.

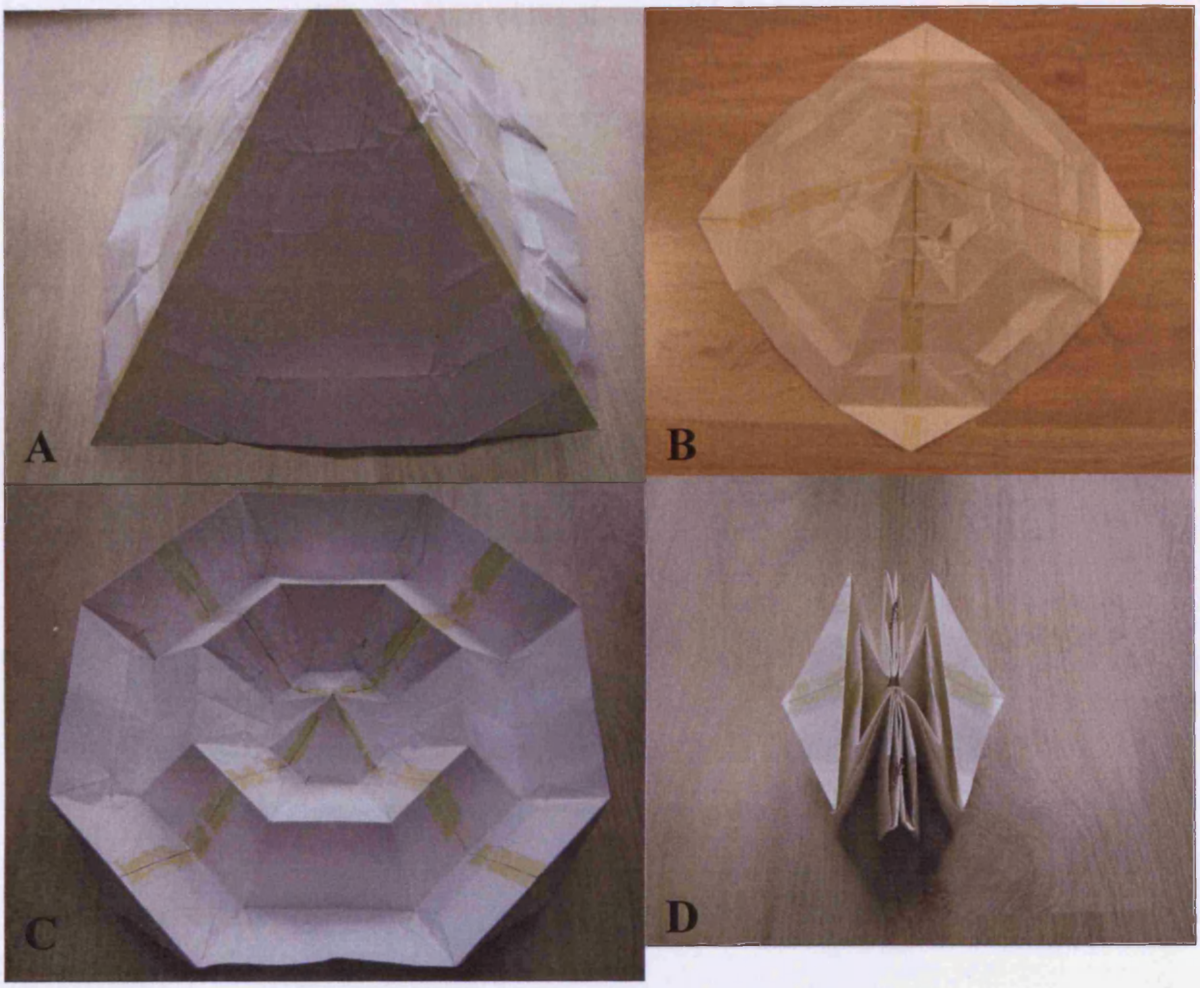

Figure 3.8. Model A5 – Folding steps.

To minimise the height of the pyramid we need to tuck the horizontal levels into each other. From the top view of the model a number of octagonal intermingled shapes can be seen, whereas the first smaller level will be inserted in the second level and second into the third and so on. The deployment process from B to C of Figure 3.8 requires force on all parts of the model because of the lack of adequate spaces between parts of the first and second level. As a result, there are curves and bending or defects in joints (Figure 3.9), thus presenting the same high strain problem. However, moving from stage (C) to stage (D), the force will be smaller compared with the fold between stages B and C. At the end of stage D, the model would turn into very small size compared to previous trials. This would support the notion of finding solution out of abandoning one of the conditions mentioned above, or by finding compromising solution without altering the structure or damaging part of the plates and joints.

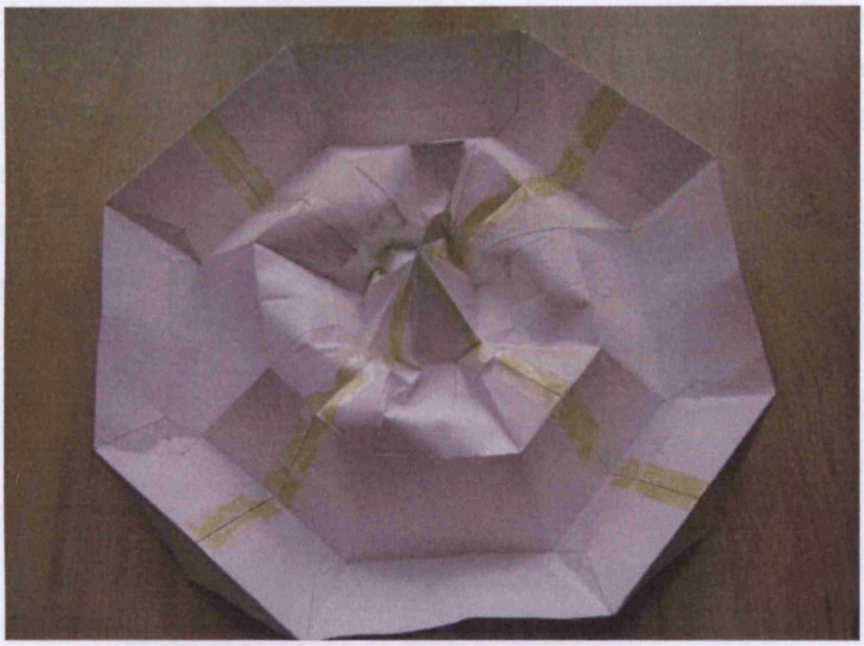

Figure 3.9. Damage on segments and joints caused by lack of spaces

3.3 Deploying Mechanism

The recurrence of the high strain problem in the previous trials might lead to a “deadlock point” during the deployment process or alternatively, the idea of providing some sort of more freedom to the main structure. It may be better to provide a freedom in certain deploying stages, for example, between B and C in Model A5, and thus a small size as well as easy control over it can be achieved after full deployment. This might suggest the eventual solution for the pyramid application.

3.3.1 Deploying Obstacles

In fact, there are two basic obstacles that prevent deployment without increasing strain. The first is illustrated in Figure 3.10 where the red configuration is the semi-deployed configuration. The structure should move from the red configuration to blue configuration in a strain-free manner to make the final pyramid shape. The problem is that the horizontal distance between *a* and *c* is fixed, because *c* is unable to move to the right or to the left, where *c* is the top point of the pyramid which only moves up and down. To get a pyramid shape *abc* should end up as *ab'c'*. Since *ab* is a fixed length, then a rotation of *ab* to *ab'* cannot be obtained first without some movement of *c* to the right, which is not allowed.

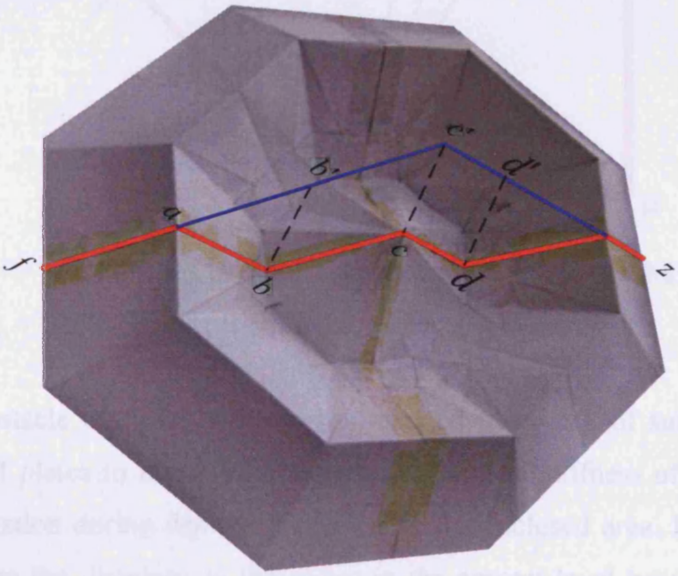

Figure 3.10 A cross section along a sector (semi-deployed configuration)

In the second obstacle, illustrated in Figure 3.11, the red shape is the fully deployed position while, the blue shape shows locations associated with high strain. The main obstacle here is the distance *e-b*, which is enough for two segments in that stage, which is required to move to *e'-b'* in the next blue stage. Since, *e'-b'* is shorter than *e-b*, then the corresponding segments are required to over-lap which cannot happen.

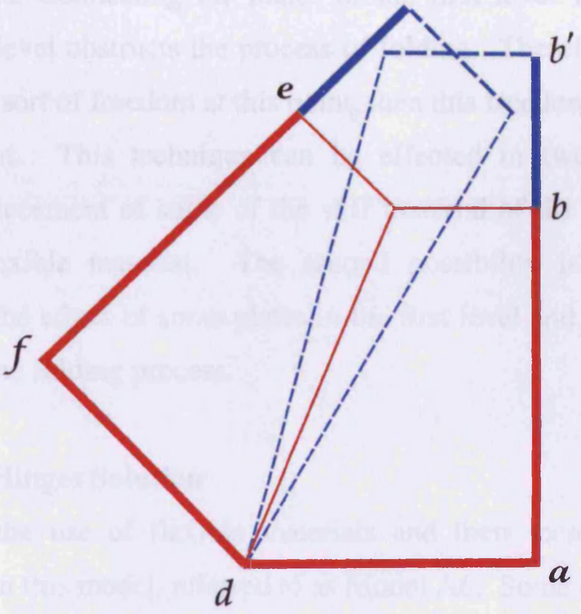

Figure 3.11 Over-lap of level two segments during fold

The obstacle of strain build-up has resulted from lack of sufficient spaces that permit the stiff plates to move from stage to stage. The stiffness of plates hinders the complete formation during deploying process in the enclosed area. It is thus necessary here to increase the divisions in the plates in the second level because their sizes are bigger than the available spaces. In addition, the plates in the first level can easily be deployed and folded without having any strain build-up, if some of them are not connected to some of the plates of the second level. Thus, the outcome of the greater division forms typical plates similar to those of the first level but in reverse manner, besides other plates that formulate other triangles of bigger sizes but not in contact with the plates of the first level. Although, adding further plate division is essential to solve the second problem, the deployment may still be not entirely strain free.

With reference to Figure 3.10, C can be moved vertically to C' provided that B can also move firstly to the right and then to the left, corresponding to the upward movement of C, so long as it remains in the space between A and C. The application of this motion on the three dimensional model means folding the plates of the first level is necessary in order to shrink their size while going through point of high strain before deployment continues. Connecting the plates of the first level with their counterpart plates in the second level obstructs the process of folding. Therefore, it is necessary to give the model some sort of freedom at this point, then this freedom should be controlled after full deployment. This technique can be effected in two aspects. The first possibility is the replacement of some of the stiff material of the parts that are in high strain with more flexible material. The second possibility is the removal of the connection between the edges of some plates in the first level and opposite plates in the second level during the folding process.

3.3.2 Soft Material Hinges Solution

Figure 3.12 shows the use of flexible materials and their locations as well as full deployment process in this model, referred to as Model A6. Some of the materials of the second level have been replaced by flexible ones. These materials were originally small triangles taken out of all plates of the second level.

With these modifications the model is capable of having a full deployment process without any strain build-up. Although this model is regarded as a step forward in the solution of deploying the pyramid, the connecting points between plates of the first and second levels are only eight contact points and these may be insufficient to endure the weight of the first level. In other words, it is possibly and easily affecting the rigidity of the final shape and its stiffness, whether through natural factors or sudden vibrations or even plates weight. In addition, the flexible material that has been used could easily tear during folding or deploying, compared to the plates made of stiff materials. Thus, this particular model should not be regarded as a full lasting solution for the foldable pyramid.

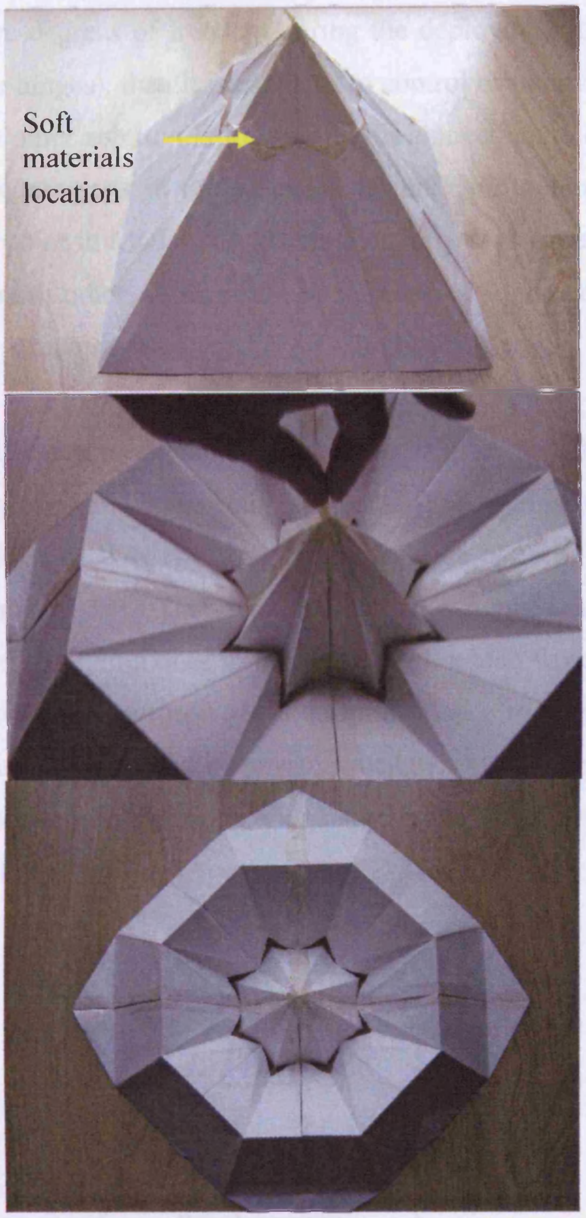

Figure 3.12. Model A6 with flexible materials

3.3.3 Free Connection Points Solution

From the discussion in previous sections, it can be seen that it is necessary to deal with the problem of high strain carefully. If the suggested solution of the high strain is to give the structure more degrees of freedom during the deploying process (for example, by inserting cuts in the hinges), then it is essential to control or remove the freedom after full deployment. The other solution is to initially disconnect some of the plates in the first level from the counterparts in the second level until the deployment process has passed the high strain point in Model A7. Then after fully deployment, these plates can then be connected to each other. This might be an acceptable temporary solution for a fully foldable pyramid structure.

The additional divisions of the plates on the second level in this model were made in half of the plates, and not in all the plates. As compared with Model A6, divisions were there made on only two parts on the left side of each face of the pyramid, shown in blue (see Figure 3.13). The resulting parts shown on Figure 3.13 in red were connected with the corresponding ones in the same level, which were disconnected with the parts of the first level. The purpose of the disconnection is to provide free movement on the edges. These parts were folded downward; meanwhile, the corresponding parts in the first level were folded upward which yield enough space that permits the structure to pass through a point of high strain without increasing the strain.

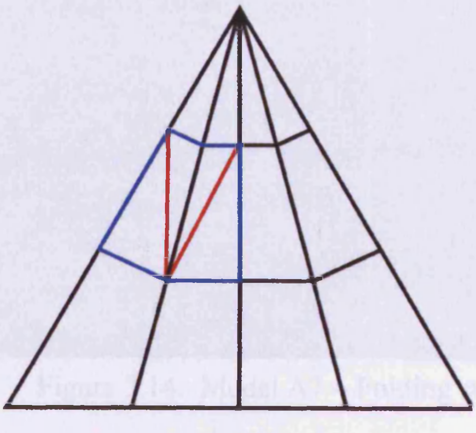

Figure 3.13 Additional divisions resulting in more parts in level two

Figure 3.14 illustrates various stages in the deployment process. In Stage A, the edges of all the plates in the first level form the first octagonal shape. Edges of the second level plates form the second octagonal shape. When the top point of the pyramid is pulled downward for folding the plates in the first level and those in the second level which are not connected start folding to form another octagonal pyramid with four protruding fins which is smaller than first one. This smaller octagonal pyramid is formed from only half of the first level plates. Since it is smaller, it provides additional spaces enough for lengths of the second level plates to move downward passing what would have been a point of high strain without actually increasing the high strain (Step C). A full foldable pyramid is in step D.

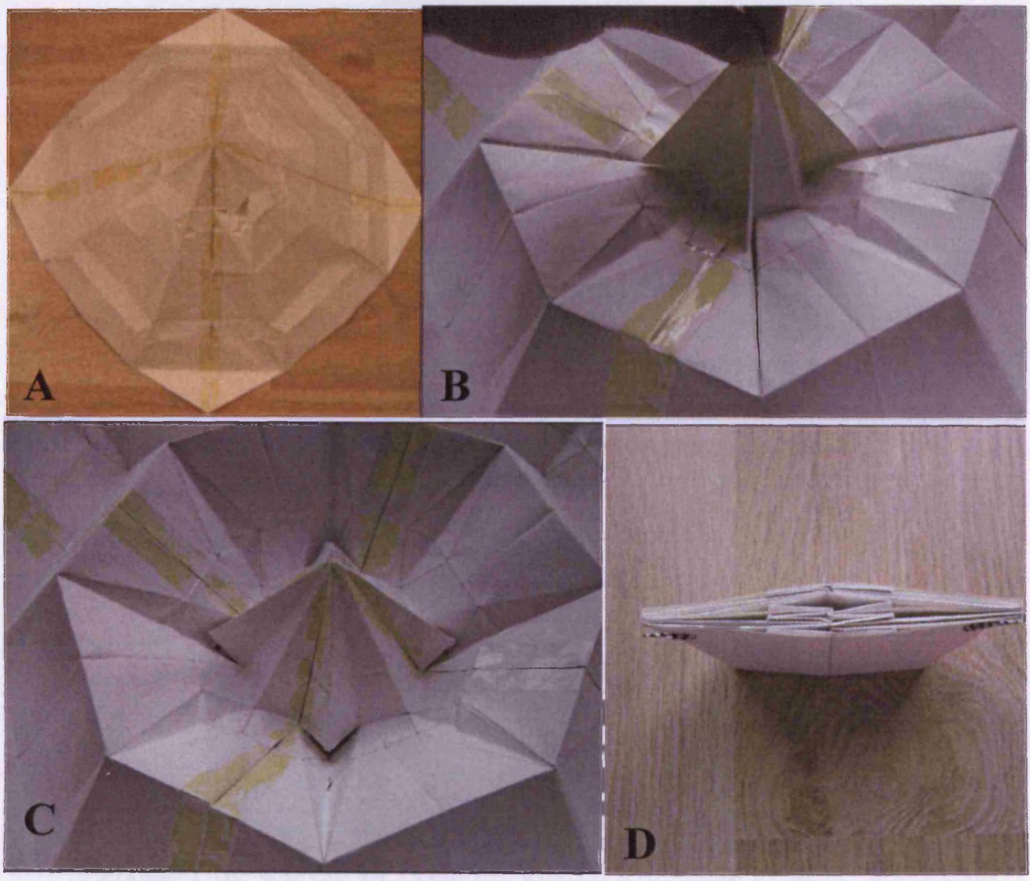

Figure 3.14. Model A7 – Folding steps

Model A8 with different divisions can give the same outcome. Figure 3.15 shows different locations for the additional divisions on the model as well as locations of connected points between the first level and second level. The different intermediate shape is shown in Fig 3.16 when the top point of the pyramid is pulled upwards. In this model, the plates in the first level and those in the second level which are not connected fold to form a small square-based pyramid and the protruding fins are this time fold as four upward fins in the second level (Figure 3.14-step B).

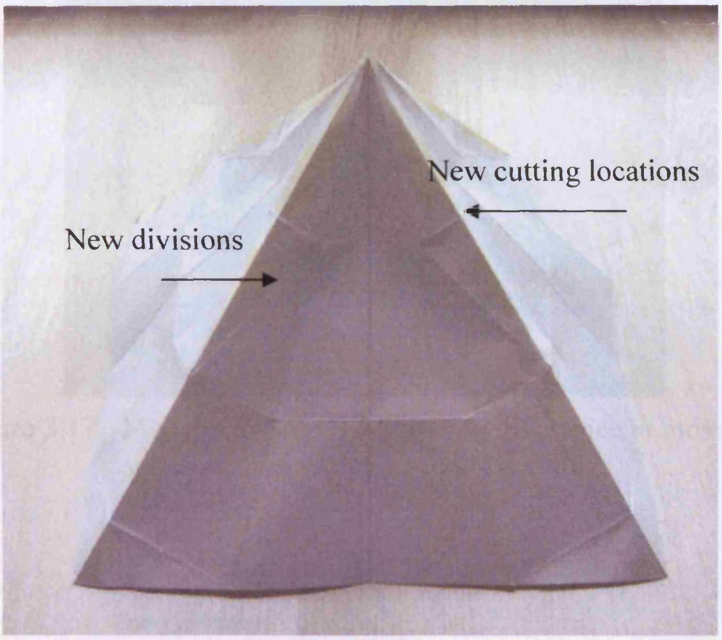

Figure 3.15. Model A8 –Showing differnet cuttings and divisions

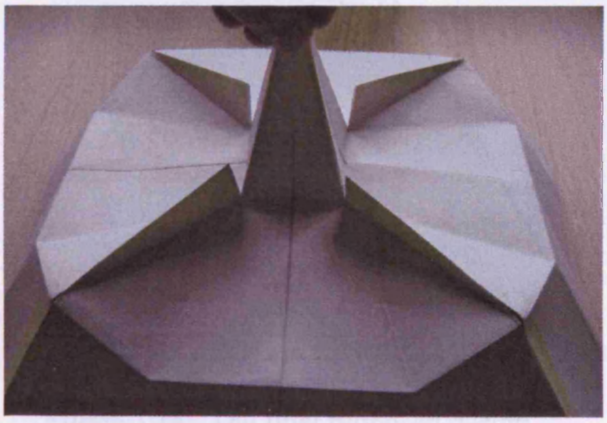

Figure 3.16. Model A8 –Step C - Showing different segment movement.

Both models have provided the required strain-free deployment. However, in Model A8 (Figure 3.16) additional divisions were on the plates of the main faces or at the pyramid ridges. To obtain a foldable pyramid, these folding divisions should be made inward folds, whereas they are actually outward folds to form the ridges of the final pyramid (Figure 3.17).

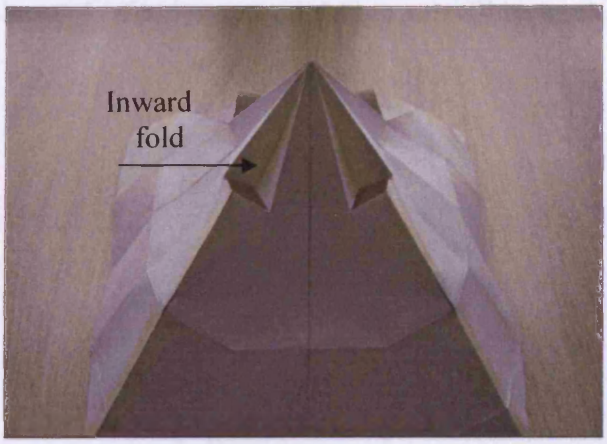

Figure 3.17. Model A8- Step B – Showing difference in movement

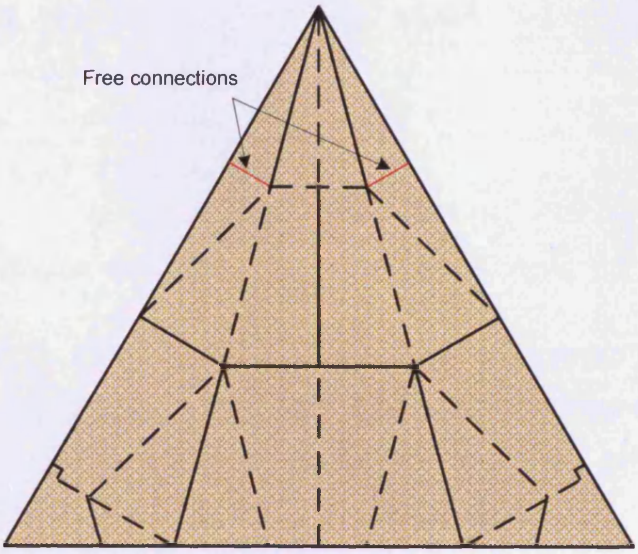

Figure 3.18. The final proposed design.

To avoid complication of joints design in Model A8, Model A7 Figure 3.14 would be used in the following design stages. This model meets most of the necessary conditions, especially the rigidity after deployment, as well as lacking any strain build-up during deploying and folding at all stages. Hence, Model A7 is considered the most appropriate folding solution for the pyramid shape. However, all trials, tests, and studies done so far were only on models that have "no thickness" or very thin material. Clearly, when thickness of the plates is taken into account, there will be some necessary adjustments to the fold lines and folding process. These adjustments are indicated in Figure 3.18 which shows the final proposed design, as will be explained in Chapter Five.

CHAPTER FOUR

THEORY AND CALCULATIONS

This chapter deals with the fundamental theories and main equations which determine the lengths and angles of the structure. The calculations will help to validate the reality of folding and deploying the pyramid shape, and will show whether the displacement mechanism (the concept designed in chapter 3) is valid or not.

4.1 Calculations of the pyramid with dependent height

This calculation is applied under the following assumptions:-

1. The pyramid base should be square (Figure 4.1).
2. The four triangular slanted faces of the pyramid (e.g., *abb'*) are four equilateral triangles.
3. Each slanted face contains four triangles (*abe, aed, ade', ae'b'*) and the total number of levels = *N*. (Figure 4.2).

4.1.1 General lengths equations

In Figure 4.1, *a* is the top point of the pyramid and *c* is the centre point of the pyramid base, directly beneath *a* and L is the length of any side of the square base. It is evident that the length of any side of the equilateral triangular slanted face (e.g., *ab* or *ab'*) is also L. From Figure 4.1, the height of the pyramid *ac* may be calculated as follows:

$$(ac)^2 = (ad)^2 - \left(\frac{L}{2}\right)^2 \qquad (1)$$

$$(ad)^2 = (ab)^2 - (bd)^2 \qquad (2)$$

$$(ad)^2 = L^2 - \left(\frac{L}{2}\right)^2 == \frac{3L^2}{4} \qquad (3)$$

Therefore, $ac = \sqrt{\frac{3L^2}{4} - \frac{L^2}{4}} = \sqrt{\frac{L^2}{2}} = \frac{L}{\sqrt{2}}$ (4)

And, $\sin \alpha = \frac{ac}{ad} = \frac{L}{\sqrt{2}} \text{ x } \frac{2}{L\sqrt{3}} = \frac{2}{\sqrt{6}}$

Therefore, $\alpha = 54.74°$.

Thus we see that the height *ac* is directly proportional to L, whereas α is not, and fixed angle for all the pyramids, which consists of four equilateral triangles.

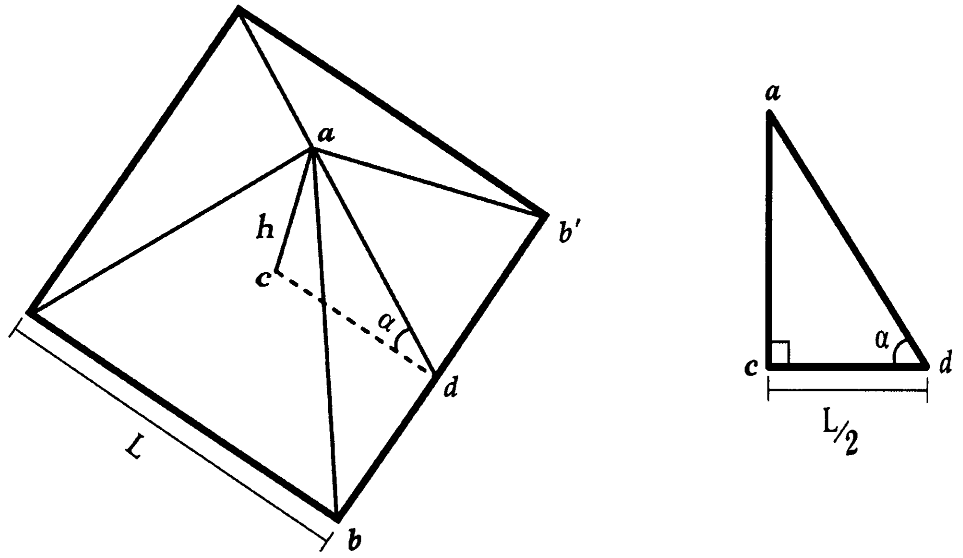

Figure 4.1 Pyramid of square base with equilateral triangular slanted faces (e.g., *abb'*).

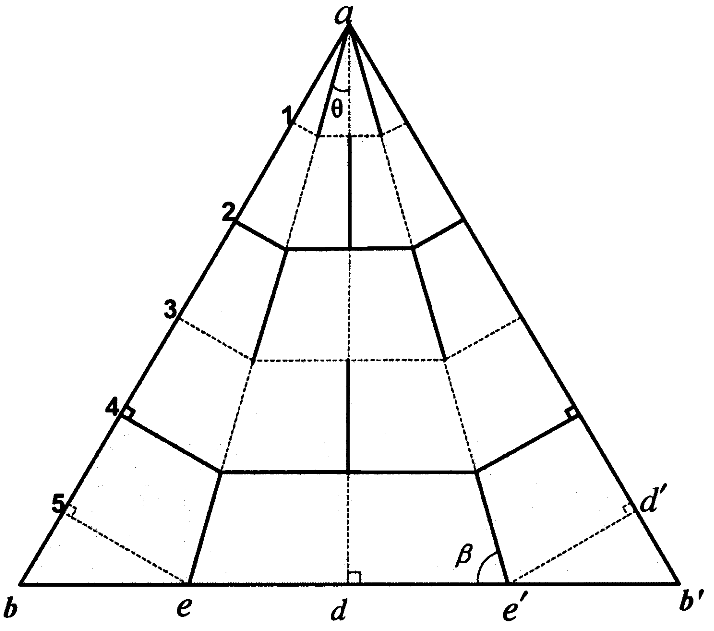

Figure 4.2 Detailed study of one slant face of the pyramid.
Where $N = 5$, $\theta = 60°/4$ and $\beta = 90° - \theta$

We shall now use length *ae* to find length *ed.*

By definition, $ad = ad'$, and

By symmetry, $ae = ae'$

$$\cos\theta = \frac{ad}{ae}, \qquad (5)$$

$$\text{thus } ae = \frac{\sqrt{3}}{2\cos 15} L \qquad (6)$$

$\tan\beta = \dfrac{ad}{de}$, which implies that

$$de = \frac{\sqrt{3}}{2\tan 75} L \qquad (7)$$

Furthermore,

$$ad_n = ad\frac{n}{N} \tag{8}$$

$$ae_n = ae\frac{n}{N} \tag{9}$$

$$de_n = \frac{\sqrt{3}}{2\tan 75}L \times \frac{n}{N}, \tag{10}$$

Where n denotes the nth level out of a maximum N levels, and the top most level. $n = 1$, then the length of segments along *ad* and *ae* are *ad/N* and *ae/N, respectively.*

4.1.2 Proof of the folding mechanism

The proposed model contains five levels and needs some steps to fold completely (see Figure 3.14). After step C the top view of the model will contain five octagons inside each other around the centre, where octagon 1 is the inner and octagon 5 is the outer (see Figure 4.3). The odd numbered fold lines are valleys and the even numbered ones are ridges. In steps two to three, the movement of the structure will be blocked between octagon two and the centre (the problem is illustrated in Section 3.3.1).

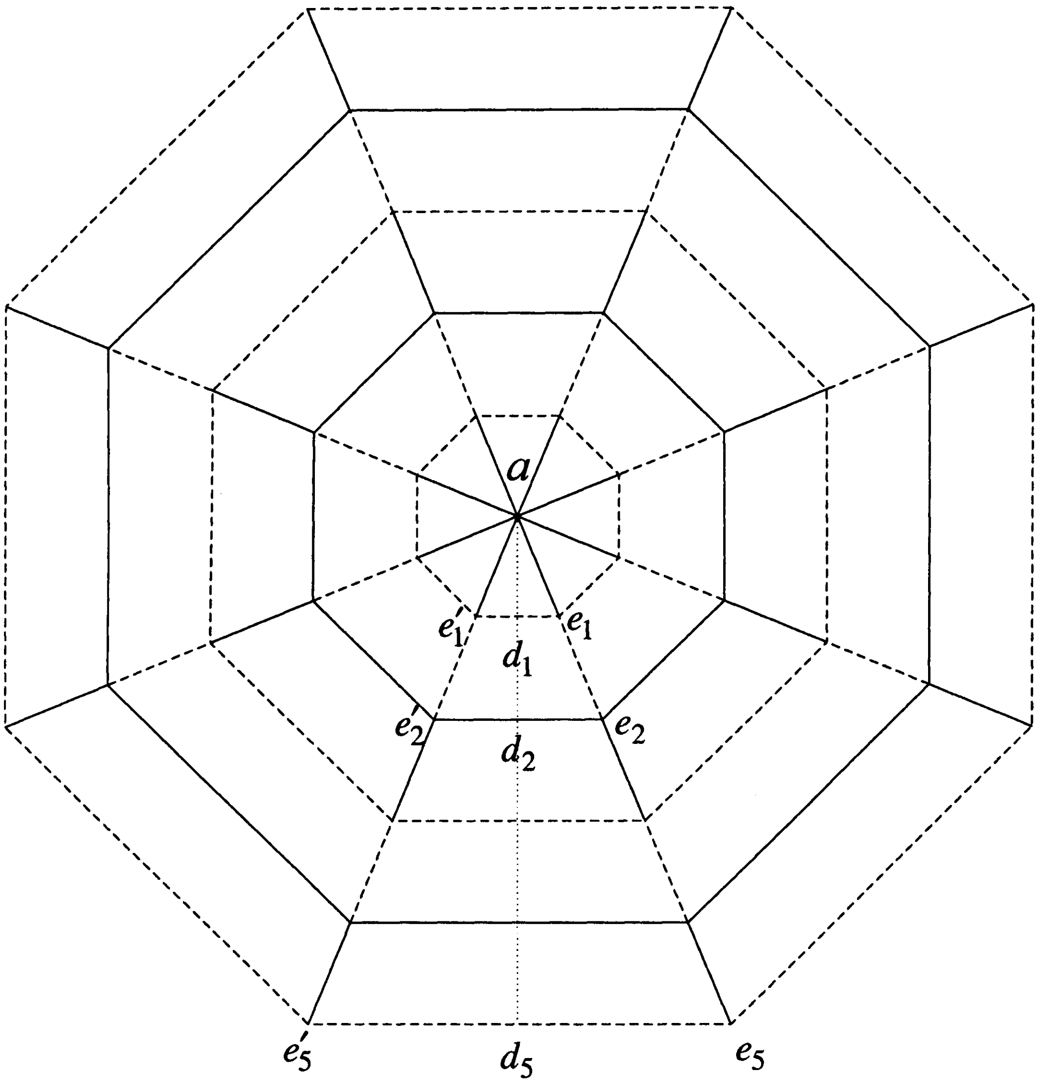

Figure 4.3 Top view of Model A7 during deploying from stage two to stage three.

Figure 4.4 shows a section is made along the line ae_2 in Figure 4.3. From Figure 4.4, it is found that the projection lengths, $e_2e_1' > \frac{ae_2}{2}$, and the proof of this is as follows.

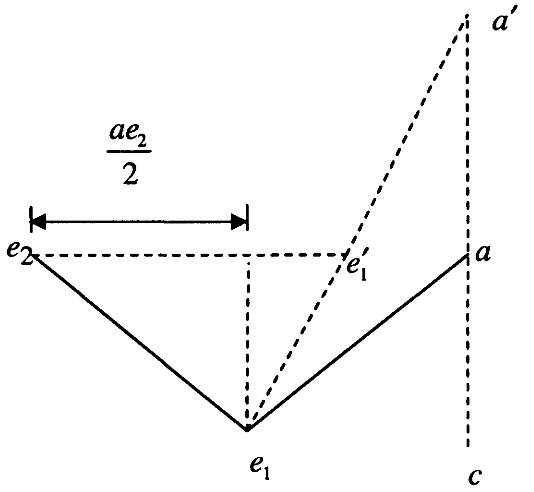

Figure 4.4 Section along line ae_2 in Figure 4.3

From Figure 4.3, the actual length $e_2' \; e_2$ of each side of octagon two is:

$$2d_2e_2 = \frac{2\sqrt{3}}{2\tan 75}L \times \frac{2}{5} = \frac{2\sqrt{3}}{5\tan 75}L \tag{11}$$

From the top view of Figure 4.3, the triangle ad_2e_2 has a 90° angle, and the projection angle between ae and $ae' = 360/8 = 45°$, so, the projection length:

$$ae_2 = \frac{d_2e_2}{\sin\frac{45}{2}} = \frac{\sqrt{3}L}{5\tan 75} \times \frac{1}{\sin\frac{45}{2}} \approx 0.2426L \tag{12}$$

hence, $\frac{ae_2}{2} \approx 0.1213L$ (13)

On the other hand, the projection length $e_2 \; e_1'$ in Figure 4.4 is equal to the actual lengths $e_1 \, e_2$ were: $e_1e_2 = \frac{ae}{5}$ (14)

since, $e_1e_2 = \dfrac{\sqrt{3}L}{2\cos 15}.\dfrac{1}{5} \approx 0.179L$. This shows that $e_2e_1' > \dfrac{ae_2}{2}$ which is the problem for a strain free deployment solved by applying the additional cuts and folds. The suggested solution is not to connect half the number of the segments in level one by those facing them in level two to allow them to fold up and those in level two fold down. This will reduce the length of the octagon one to the half to be de_1 instead of $2de_1$, so during deployment $d_1e_1 \Rightarrow d_1'e_1'$ where $d_1'e_1' = \dfrac{d_1e_1}{2}$ (see Figure 4.5).

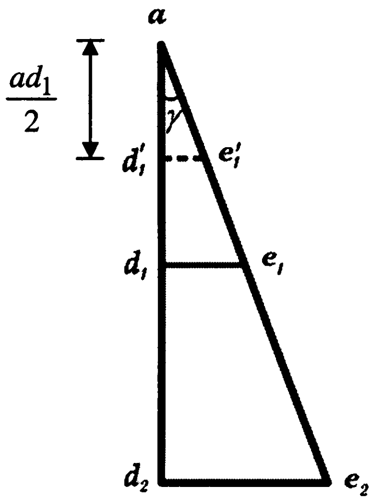

Figure 4.5 Showing the reduction of ad_1 length by half

$$ae_1' = \frac{d_1'e_1'}{\sin\frac{45}{2}} = \frac{\sqrt{3}L}{2\times 2\tan 75}\times\frac{1}{5}\times\frac{1}{\sin\frac{45}{2}} \approx 0.0606L \qquad (15)$$

Since, in this case we achieve the solution of Figure 4.4

$$ae_1' + e_2e_1' < ae_2$$
$$0.0606 + 0.179L < 0.2426L$$
$$0.2396L < 0.2426L$$

This shows that the length available after applying the displacement mechanism is more than enough than the length needed during deployment. Therefore, this would be a proof for the folding mechanisms designed in Chapter Three.

4.2 Calculations for the pyramid with an independent height

In this case the calculations would be applied on a pyramid with a predetermined fixed height *h* before design. These calculations may help to design a foldable pyramid with a particular height if needed. This means that the four equilateral triangular slanted faces as described before will be no longer equilateral. Now, each of the four triangular slanted faces will have two equal unknown sides with the base length of L (in Figure 4.2, *ab* and *ab'* are not equal to *bb'*). This implies that each of the four triangular slanted faces will be an isosceles triangular face but each has a base length of L.

However, the height *ac* will now not be equal to $\frac{L}{\sqrt{2}}$ because the pyramid has an independent height; in other words, the height *ac* is no longer proportional to L, where *ad*, *ab* and *ab'* are proportional to *h* and L.

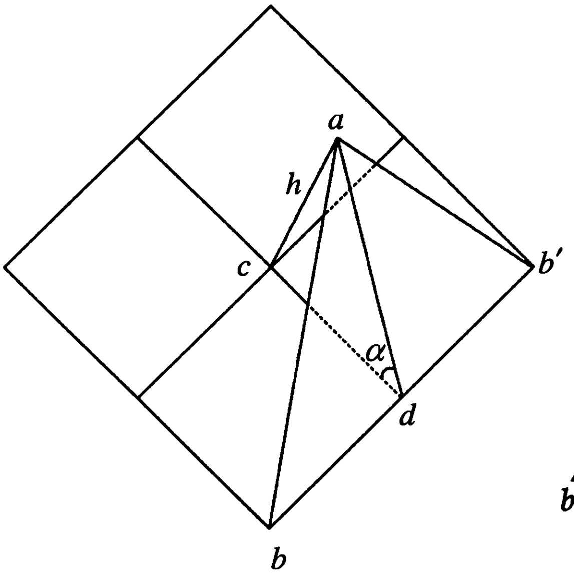

Figure 4.6a Pyramid with a predetermined fixed height, *h*.

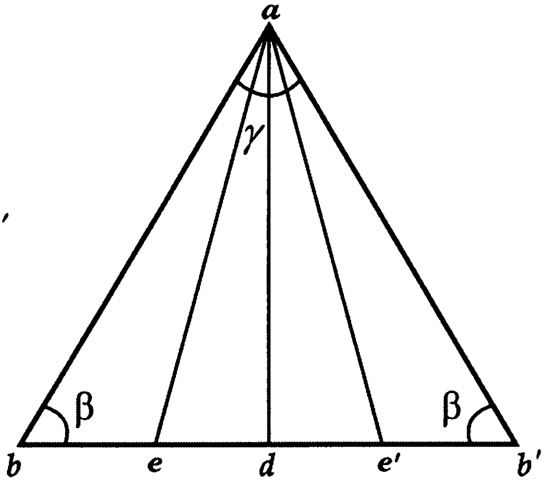

Figure 4.6b Triangle a b b′

From Figures 4.6a and 4.7b, the lengths *ad, ab, bd, ae* and *de* can be calculated as follows:

$ad^2 = h^2 + \frac{L^2}{4}$, which implies that

$$ad = \sqrt{h^2 + \frac{L^2}{4}} \qquad (16)$$

The slope angle α will be:

$$\alpha = \sin^{-1}\left(\frac{h}{\sqrt{h^2 + \frac{L^2}{4}}}\right)$$

$$ab = ab'$$

$$ab^2 = \left(\frac{L}{2}\right)^2 + ad^2 = \frac{L^2}{4} + h^2 + \frac{L^2}{4} = h^2 + \frac{L^2}{2}$$

Hence $ab = \sqrt{h^2 + \frac{L^2}{2}}$ (17)

Since, $\beta = \cos^{-1}\left(\frac{\frac{L}{2}}{\sqrt{h^2 + \frac{L^2}{2}}}\right)$, thus $\gamma = 180 - 2\beta$

$$ae = \frac{ad}{\cos\frac{\gamma}{4}}$$

$$(de)^2 = ae^2 - ad^2$$

$$de = \sqrt{ad^2\left(\frac{1}{\cos\frac{\gamma}{4}} - 1\right)}$$

Thus,

$$de = \sqrt{\left(h^2 + \frac{L^2}{4}\right)\left(\frac{1}{\cos\frac{\gamma}{4}} - 1\right)} \qquad (18)$$

$$ad_n = ad\frac{n}{N}$$

$$ae_n = ae\frac{n}{N}.$$

Where n denotes the nth level out of a maximum N levels.

If the foldable pyramid needs to be designed that consists of four isosceles triangles, the two sides of the triangle are shorter than the base; then it is possible for these calculations to be used in order to find the pyramid segments measurements; it is also possible to apply the folding mechanism proved in Section 4.1.2.

CHAPTER FIVE

CONSTRUCTION OF A MODEL WITH PANEL THICKNESS

The consideration of mechanisms so far has been with plates of zero thickness. However, a “real design” must consider plate thickness and weight. In order to build this final and real model for the foldable pyramid, two important factors must be investigated. Firstly, to investigate the effect of the thickness of materials used on the design in general and in particular on the hinges. Secondly, to make sure of the “cohesion” of the model plates during the process of deployment and folding, and the structural integrity and stability after full deployment. This leads to the asking of several key questions, the most important ones being the following:

- Is there any change in the design as concluded in Chapter Three?
- If there is change, then what is the required change?
- What are the causes of such change?
- What are the solutions suggested for this change?

This part of the study deals with answering these questions to uncover any necessary changes on the previous design. These models are referred to as **Model B** due to the consideration of material thickness used in manufacturing the model.

5.1 Design of Model with Thickness

5.1.1 Thickness Effect

When thickness is added to the structure panels, those panels will not meet in one point during folding. It was noted that when the design of Chapter Three was carried out using thick metal plates (Model B) there were two significant impacts of this thickness. The first is the inabilities of folding of some plates, which require reverse movement during the stage of deployment. For example, this becomes evident on the four pyramid corners during the process of full deployment to form the pyramid. This leads to difficult formation of the pyramid; and is sufficient to halt deployment before the final stage of full deployment, which establishes the full pyramid with an octagonal base (Figure 5.1a). The second is the absence of enough spaces inside the hinges to allow the interlocking of the model plates during the final stages of full folding. This results in the inability to fold the model completely (Figure 5.1b).

It was therefore important to find solutions for these two problems. Since both problems relate to plate thickness, this means that they are associated with the hinges. Accordingly, the change must start with the hinges; either concerning their types, sizes, or places of fixing them on the model plates, or by the materials used for manufacturing them, or some contributions of these solutions together.

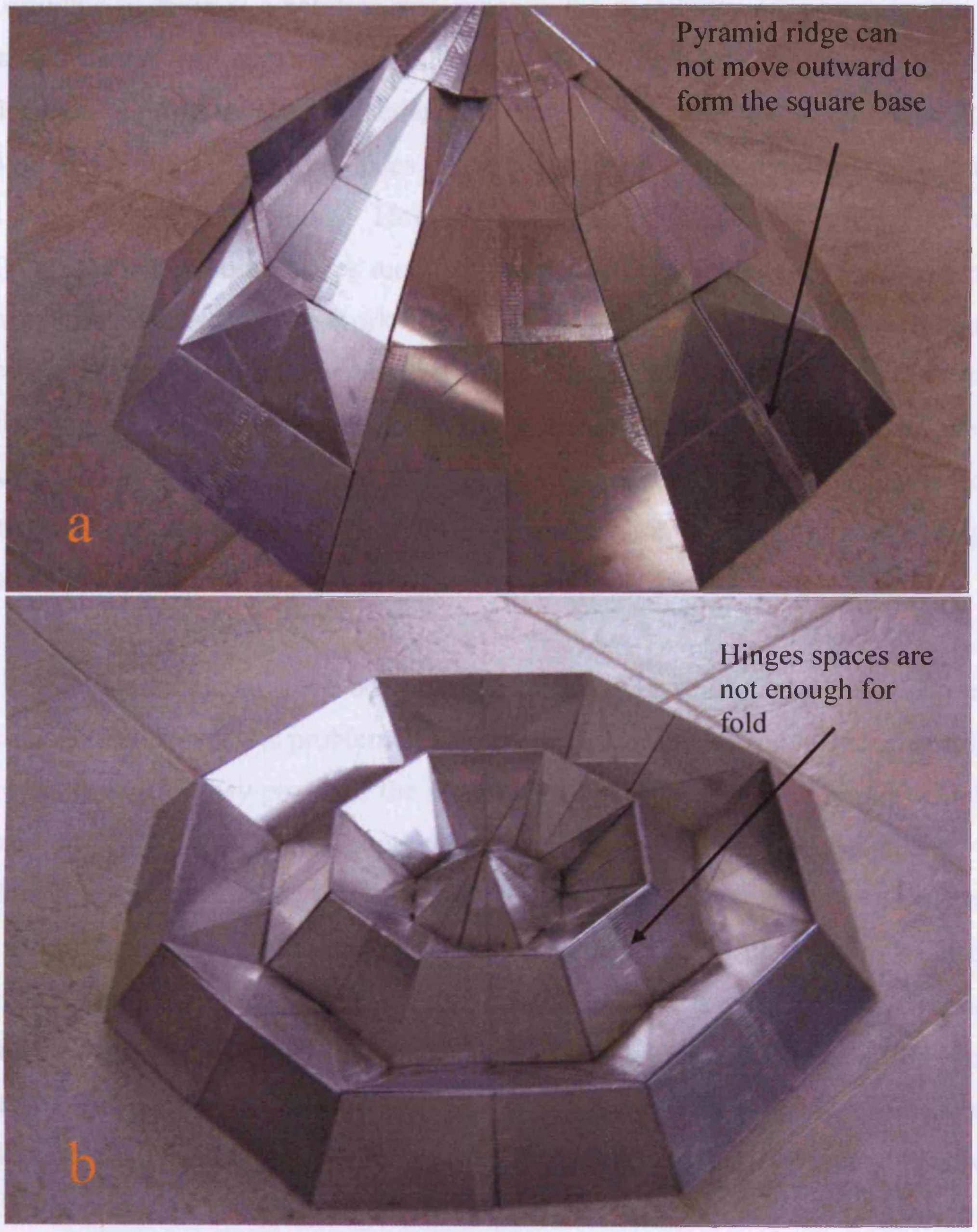

Figure 5.1 Model B1

a: Stuck stage before the full deployment. 1b: Stuck stage before fully folded model

5.1.2 Hinges Specifications

When dealing with the types, sizes, or locations of hinges on the model plates, the fitness of these hinges to the basic design of the model must be taken into consideration. For example, if there is a solution that suggests the possibility of increasing the hinge sizes such that it can accommodate all plates of the model during the process of full folding, the question raised is whether this increasing size of the hinges will fit after folding, given that the different sides of the plates need to touch each other before the final stages of the full folding. However, these hinges could be replaced by highly flexible materials in some places requiring this, such that the strength and deformation of these materials assume the work of hinges in connecting the model plates together. These are characterised by a larger size which can accommodate the thickness of the interlocking plates of the levels during the process of full folding. They are also characterised by the possibility of folding them in the reverse direction if needed. In addition to that, these materials would not pose problems concerning size; required spaces after the full folding process of Model (see Model B2 in Figure 5.2a).

Flexible materials have been chosen to adapt flexible hinges. These flexible materials have resolved the problem of full folding and also allowed full reverse folding. However, in return, they provided the model with more freedom than before which has affected its stability after full deployment to form the full pyramidal shape. This freedom has resulted in less resistance of the model to counteract physical factors or even its collapse, and the intermingling (loose rattling) of its plates with each other. This is attributable to the weight of the model itself, as well as to the plate thickness. As the thickness of the materials used in manufacturing the model increased, the sizes of hinges increased to accommodate this greater thickness. As a result, the amount of flexible materials for hinges also increased and hence freedom of movement increased (Fig 5.2b).

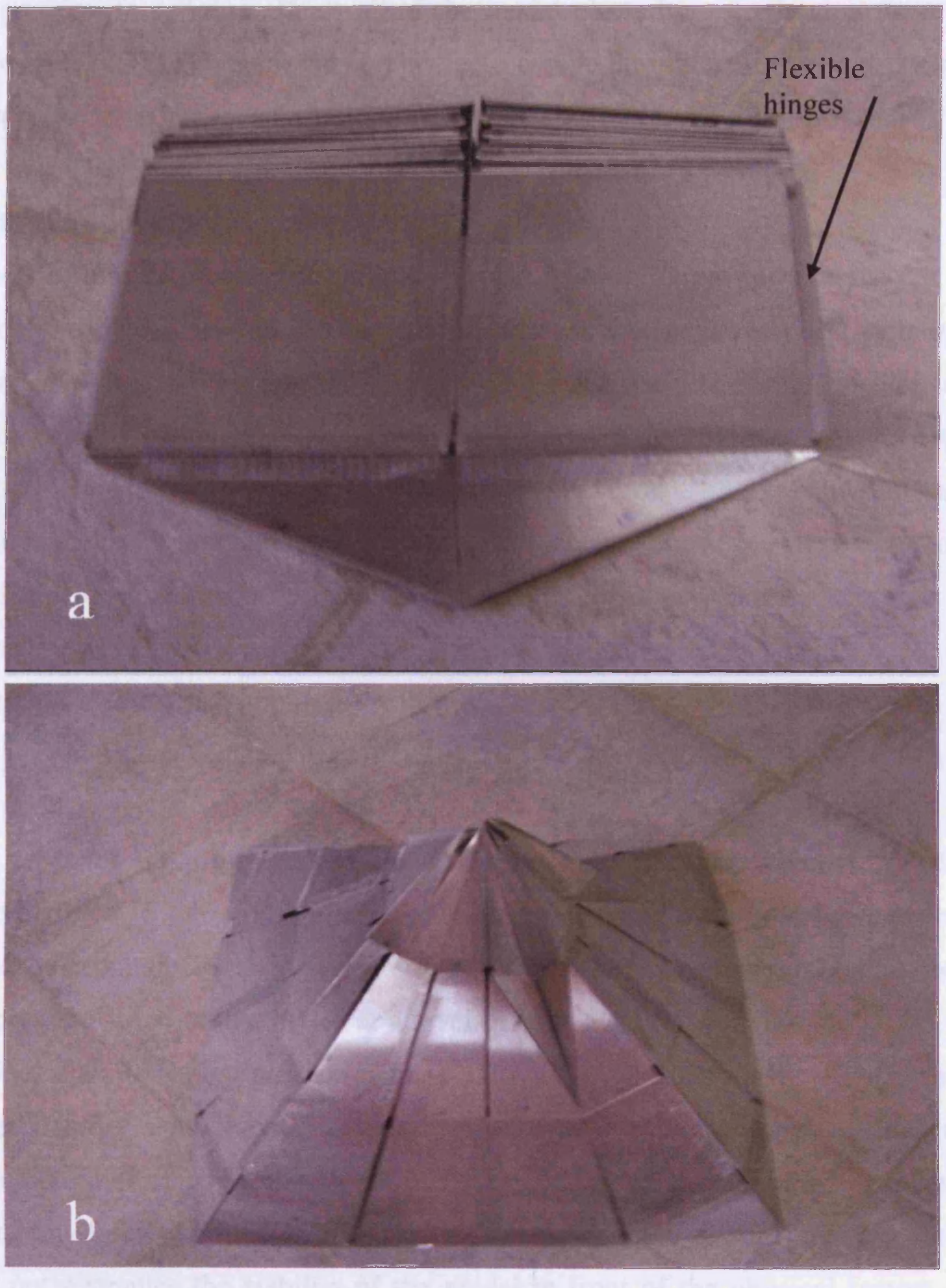

Figure 5.2 Model B2
a: Final fold with hinges made from flexible materials. b: Showing freedom of movement at stage of fully deployment

The problem of free movement only appears in the final stage after the full deployment; hence, it is possible to control the problem by giving the model a "post-compression force" that affects all of the model plates by not allowing these plates to move after full deployment only. This force can be introduced in several ways, and the appropriate form can be selected for the model.

5.1.3 "Post-compression Force"

If the freedom of movement by having loose flexible hinges is necessary to fold and deploy the model, and in return, this freedom affects negatively the stability of the model after full deployment, it is possible to deny the model this freedom after full deployment by adding a post-compression force on the model plates at the appropriate time. It is possible to add this force by adding an external "elastic band" for each plane of the model such that this cable is fixed on all plates of the level. It is essential to give this band the freedom of expansion to provide the model with the required freedom during the processes of deployment and folding. Nonetheless, this band should be under strict control after full deployment in order to establish the post-compression required after the final stage of deployment.

Model B3, illustrated in Figure 5.3, demonstrates the process of adding the external force to the model after deployment by adding an elastic band to the model plates on a single level. The elastic band exerts an external horizontal loop post-compression force on the plates at a level in such a way to provide the model with the required stability after full deployment. However, can this elastic band preserve the model stability against external loads? The force in the elastic band in this trial was adequate only to prevent the model plates separating from each other. However, after adding any force to pull all plates together, the elastic band expands quickly, though this does not guarantee the stability of the model in front of the physical factors. On the other hand, if the elastic band is stretched to its possible maximum limit such that it cannot stretch anymore, another problem emerges; that is, the folding of the model plates around the point of attachment in the direction of the pull. This happened on either the inner surfaces in some locations or the outer surfaces in the locations following them. This affects the model negatively which may cause the collapse of the model internally, hence leading to the total collapse of the model.

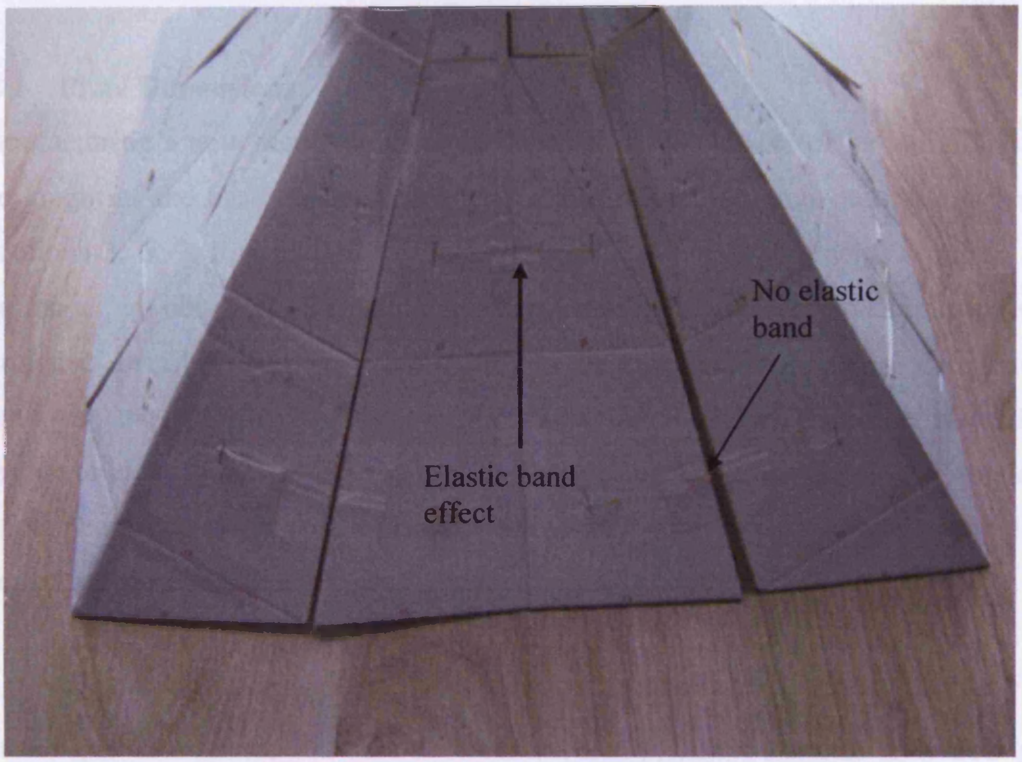

Figure 5.3. The effect of adding the elastic band.

The problem is that tension generates pressure on the plates locally at the contact points rather than evenly over large areas to resist this pressure. In addition, forces are not equal in direction and magnitude; hence, it is necessary that the elastic band passes through all plates of the individual level within paths especially designed for it, and appropriate to its thickness in all cases of expansion and shrinkage. It is also essential that all these paths are found in the middle of the thickness of all model plates and in a horizontal position so that incompatibility does not happen in the path of the elastic band.

Accordingly, it is necessary to manufacture a new model with thicker plates that can allow the making of paths necessary for drilling required to enable the elastic band to pass through. To manufacture this model it is necessary to calculate the plate lengths and also the angles of slope of these plates. The processes of manufacturing and assembly, and tests of processes of deployment and folding of this model are discussed below.

5.2 Manufacturing Process

5.2.1 Plate Dimensions

Manufacturing a new model requires the calculation of the size of its individual plates. The length of the base line of this model is one metre. By substituting this length in Equations 3, 6, 7, 8, 9 and 10 in Chapter Four all new measurements required for the new model are obtained. By taking into consideration the fixed slope angles previously mentioned in Chapter Four, cutting angles become known. This also results in identifying the slope angles for the pyramid's four surfaces. From this angle it is possible to identify the cutting angle of the three sides of each surface. This angle is the complementary angle of the slope angle of the four main triangles forming the external sides of the pyramid.

5.2.2 Machining Process

Wooden plates were used to manufacture this model, due to the ease in handling them and also their relatively light weight. The manufacturing process consisted of two main parts. The first was to cut the model plates as required, while the second was the drilling process inside these plates.

The machining process requires high precision in the plate angles because it affects the measurements of the model plates, which may cause some problems in the future when assembling these plates. It was also essential to take into account the thickness of the cutting saw in its effect on the plates' measurements. Therefore, it was necessary after the segmentation process to make sure of all of the plates measurements and to remove any surplus material from the sides of plates. The cuts were perpendicular to all plates, except the sides of the plates forming the three sides of each main triangle face of the pyramid. This machining process was undertaken in accordance with the angle complementing the slope angle of these faces, given that the slope angle was 54.7°. After the cutting process, the assembly of plates was necessary due to two reasons. The first reason was to make sure that the formation of the four main faces of the pyramid was identical in terms of their measurements, lengths and angles to confirm the calculation and manufacturing accuracy. The second was to facilitate drawing of the lines for the drilling process.

Undertaking the drilling process required drawing parallel horizontal lines. These lines were drawn on the pyramid's four outer faces. Each level of the pyramid plates contained two lines, one at the upper side of the level and the other at the lower side in order to prevent the plates of this level from rotating. The drilling process was highly precise to prevent any differences in the holes on the thickness of the plate so as to make these holes aligned with each other when the plates were assembled to form the pyramid. The thickness of the plates was 9 mm, and the diameter of the required path was 5 mm. The drilling process was made horizontally such that the drilling bit was in the middle of the plate thickness. A laser was used to match the previously drawn external lines in order to prevent any slanting in the drilling process. The drilling process was carried out for each plate individually due to the unavailability of a drilling bit matching the width of the whole model. Various difficulties were experienced during this process, including the method of stabilising the plates and controlling the drilling speed as well as the vibrations of the drill bit which necessitated some new replacement plates to be made. Accordingly, it would be preferable when manufacturing the real model to use moulds; in other words, the manufacturing process is undertaking using the casting procedure.

5.3 Assembly of the Model

The assembly process consists of several stages: firstly, connecting plates together; secondly, passing the elastic band; and finally, closing the model and marking the locking positions on the model faces.

The assembly process started with locating the hinges on the model plates. Folded plate structures consist of two sets of fold lines which can be described as "hill fold" or "valley folds." Hinges were placed on the internal surface at the 'hill' folds and on the outer surface at the 'valley' folds. As required, hinges were manufactured of flexible materials, as they were made of three layers of a strong material tape. Before the plates were connected, their surfaces were finely sanded and varnished such that contact of the adhesive tape would be better resulting in a stronger bond. The plates were connected at the first level internally at the 'hill' without having any spaces between the plates, and externally at the 'valley' with room for the thickness of four plates because they will later envelop the thickness of two plates of each of level two and level three. All connections between the plates at the second level were of the thickness of two plates whether in the 'hill' or in the 'valley', with differing places internally and externally. Connections at the third level were similar to that of the first level but with locations of 'hill' and 'valley' folds reversed. As stated in Chapters Three and Four, there are four levels, rather than three, at the corners of the four faces. So, connecting the edges of the faces with each other was made as follows: in the first level, the thickness of hinges was equal to the thickness of six plates; in the second, the thickness was that of four plates; in the third, the thickness of two plates; and finally, at the corners of the pyramid base there was not space for these hinges. However, it was noted that these four corners formed 'hill' folds, which means that these hinges are internal, and this leads to an important issue. They do not allow full folding externally more than 45° angle. However, one of the stages of deployment/folding requires that this plate of the pyramid should be flat, that is, at an angle of 90°. This led to two ideas; the first is that it is necessary to connect this part to the model together after the full deployment process; whereas the second idea is that this part could be considered as a part of the third level and should be treated in the same way of connection. However, this idea increases the size of the model after full folding. These four corners consist of eight plates forming an additional projection after final folding. This projection requires putting the model upside down, as illustrated in Figure 5.4. Accordingly, the first option was adopted. This problem will be fully explained in Chapter Six.

The discussion above related to the process of connecting the plates of one level on all sides of the pyramid. It is easier to connect the levels with each other horizontally.

These connections had no spaces at all, and were externally ('valley' fold) between the first and second levels and internally ('hill' fold) between the second and third levels

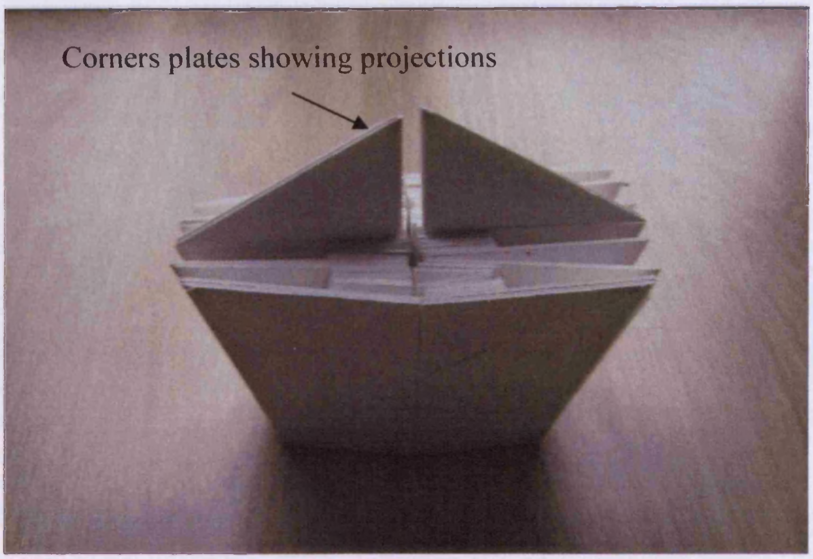

Figure 5.4. Projections of the plates necessitates upside down placement of the model.

Figure 5.5 shows the paths through which the elastic bands pass. Four elastic bands have been passed through each path in the four faces, whereby the path was continuous throughout all plates of the model horizontally, forming a square similar to the pyramid base, though of different sizes according to its height above the base. In order to obtain precise closure after full deployment, certain locations had "locks" that do not allow further stretching of the elastic band. These locations were chosen to be between the plates connecting each other with no spaces required between them (Figure 5.6). Locks were placed on all faces of the pyramid and at the same place for each level. Each elastic band thus produces a horizontal loop force, and enforces a post-deployment horizontal compression ring force at each level. This model is referred to as Model C1.

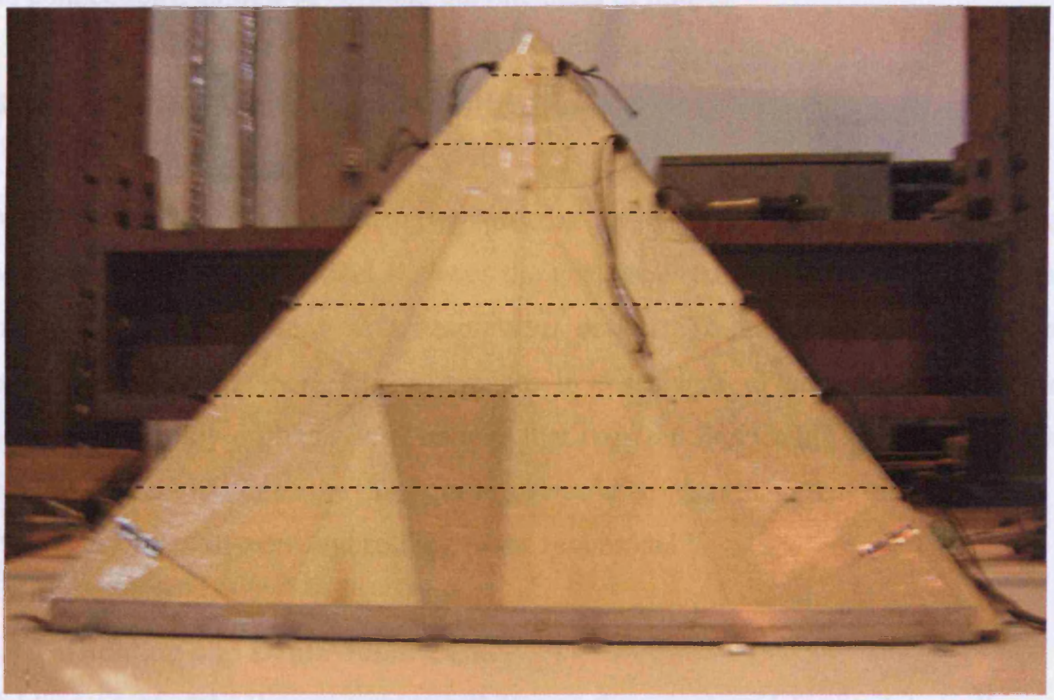

Figure 5.5. The paths through which the elastic band passes.

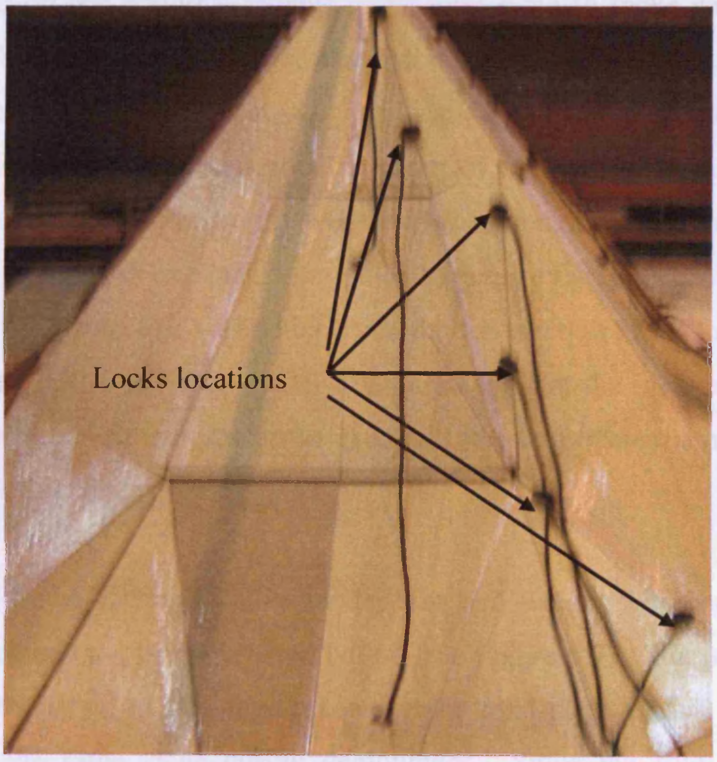

Figure 5.6. The locations of locks.

The assemblage process was the last stage of manufacturing, though the most difficult since it requires careful attention to connecting the plates and the locations of no connections, as well as defining the thickness of hinges.

5.4 Folding Mechanism Application

After completing the manufacturing process and assembly, the third step is to test whether or not that this model achieves the goal required, and also achieves full folding and full deployment, along with the previous design. To this effect, three questions are raised: Firstly, are there any differences in the stages of deployment and folding? Secondly, has any problem been noticed that requires fine tuning of, or changes in the design? If there has been the third question would be what the effect of the changes is on the stages of deployment and folding of the real model?

5.4.1 Folding and Deployment Tests

Folding of Model C1 was tested, and it was then deployed by applying all previous stages tested on the previous models. This was done to make sure that there are no differences between stages and also that the weight and thickness of the model has not hindered the deployment mechanism. The elastic band was loose during the deployment process which gave the model good freedom of movement during the process. The deployment stages must be continuous and when moving from one stage to another, deployment requires an external intervention to change the model shape and to prepare it for the following stage. It was noticed that the force required for that change was more powerful than in the previous models. This means that the increase in the model size and weight requires an increase in the external force to prepare the model for each stage, be it in folding or deployment.

Due to the increase in the model size and weight, another new problem was noticed which had not been observed before (see Figure 5.7). The problem is that of the increase in the strain in the stage preceding the final stage of full folding, which also emerged at the same stage during deployment. Since the folding process requires pressure from the outside on all plates of the model, whereas during the deployment process the same stage requires pull towards the outside, the problem was more evident during folding.

Preliminary studies in Chapter Three revealed that the problem of strain was due to two reasons; firstly, the absence of adequate areas for the model plates to move; and secondly, the difference of the planes of the model plates in levels two and three during the deployment. The second reason was more logical since the model enjoys freedom of movement during that stage. The problem lies at the junction or between the plates of the second and third levels; specifically, the point of contact forms a cross between two plates of the second level and two plates in the third level. This means the re-emergence of the problem of right angles once more (Figure 5.8)

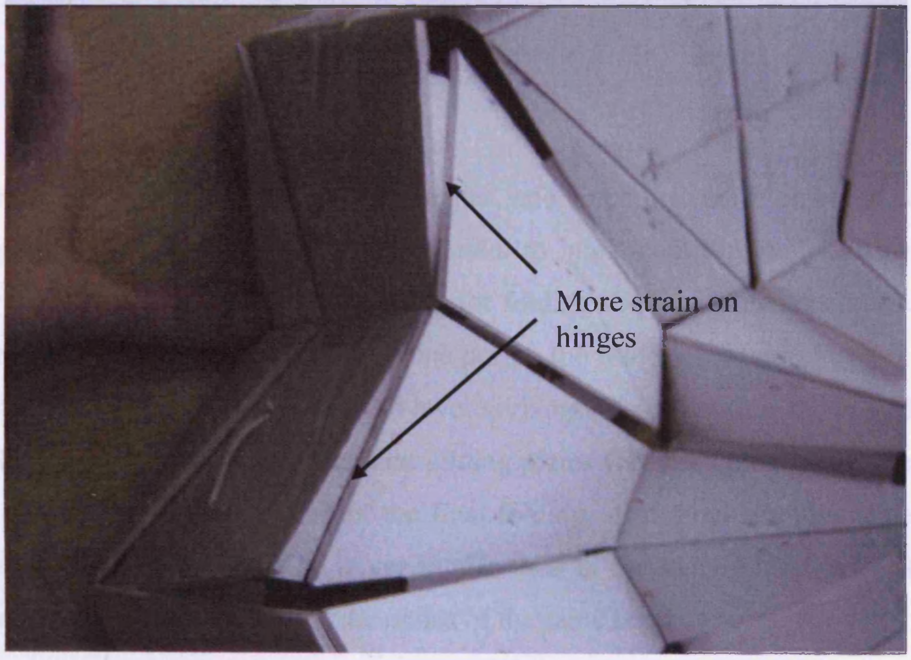

Figure 5.7. The effect of more strain on the hinges.

Figure 5.8. The location of right angles.

5.4.2 The Model Modifications

Since the problem is that of the right angles, and since it is not possible to change this design at this later stage, it is very important to implement the model as it stands. In order to avoid this problem, the solution for folding the four plates inside each other is the absence of any difference in the plane during the folding process. For this to happen requires folding the plates of the third level horizontally so that they touch perfectly with the plates in the second level, and then folding plates vertically in order to interlock with each other to solve the problem of the final folding. But, how can this achieved while the plates in the third level are larger in size than in the second level, as well as being connected in a closed form with the plates of the same level.

Accordingly, the solution is to increase the divisions of the plates in the third level such that all plates are then connected to the plates in the second level of the same size. This means that each plate in the third level is divided into two plates; one of the same size of the plates in the second level, and the other in the form of a triangle which is not connected with the second level, but its apex pointing upward and connected laterally with the other plates of the third level. These divisions lead to divisions in the other plates forming the corners of the pyramid, which can be regarded as a fourth leve. So, these plates are divided into two plates and with the same slope angle in the third level but in a reverse form so that they correspond with the plates of the third level after folding them. Hence, the number of plates in each face becomes 22 instead of 16 in the previous model.

Consequently, the name of the model is changed into Model C2 (Figure 5.9). In addition to this difference, there were two others: the first is that these divisions have been made on Model (A8) instead of Model (A7), on which Model C1 was based, given that the difference was only in specifying the plates in the first level connected with the plates in the second level. This difference has been explained earlier in Section 3.3.3. Due to solving the problem of reversing the hinges in this model by using flexible materials to construct the hinges, and because of the resistance of both designs to the laboratory tests, Model C2 was constructed according to the Model A8 design. The second difference was that of replacing the adhesive tape by metal hinges, only between the model plates that do not require thick hinges after full folding, and also replacing the elastic bands by a metal wire that does not stretch so easily as an elastic band. These variations were to provide the model with more rigidity and cohesion.

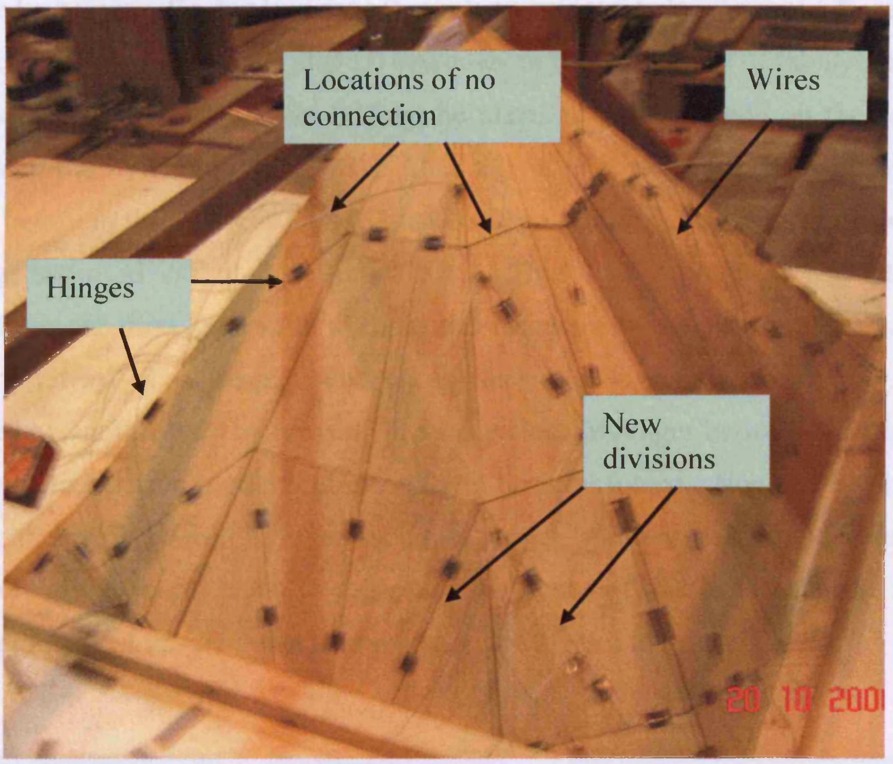

Figure 5.9. Pyramid Model C2 with added divisions, wires, metal hinges and locations of no connection.

5.4.3 Model C2 Folding Steps

The folding steps have been previously explained in Chapter Three. However, this section explains all folding steps regarding Model C2, especially that the new steps that have been added after making improvements to the design in Section 5.4.2. This section also explains the steps of folding, starting with the full deployment stage until the final folding stage, indicating the external interventions required before every step of these stages.

Figures 5.10 demonstrate the steps of folding, whereby the model changes from the square-base pyramid (Step A) to the octagonal-base pyramid (Step B). To change into the octagonal base, it must, first of all, be provided with more freedom by releasing the metal wire. It should be noted that it also requires the folding of the plates of level four upward or separating them from the model, as indicated previously. This step is not achieved automatically, but it is done through an external help. To move from this stage, in which the height of model (Step D) decreases to form one-third of the pyramid height, the model should be assisted in folding the plates in the first level on the edge of the pyramid inwardly (see Figure 10C). After this, a new stage is created which did not appear before in the previous models, that is, Stage E. This stage is an addition to avoid the large strain, as indicated in Section 5.4.2. This stage is accomplished after folding the plates in the third level so as to come into contact with the plates of the second level in a linear way. This stage is also accomplished through an external help, which is followed by another help by pressing in the locations of hinges between the plates of the third level to help the model fold inwardly to be fully folded. Nonetheless, before full folding, the model should be lifted such that enough space is created underneath to fold the plates of the fourth level, or separating the plates of this level from the model, or holding the model upside down in preparation for the full folding stage (F).

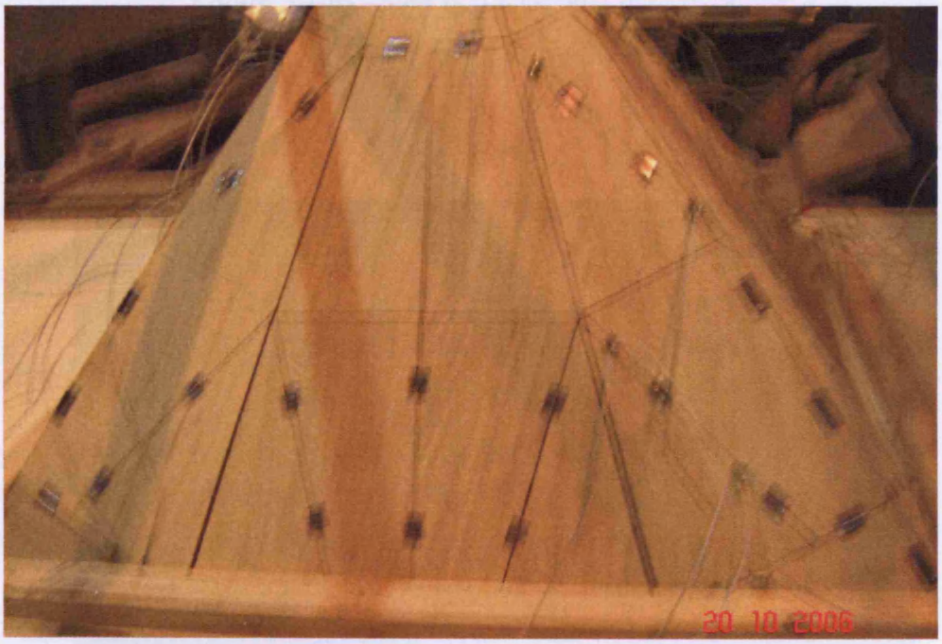

Figure 5.10A. Step A. Fully deployed pyramid

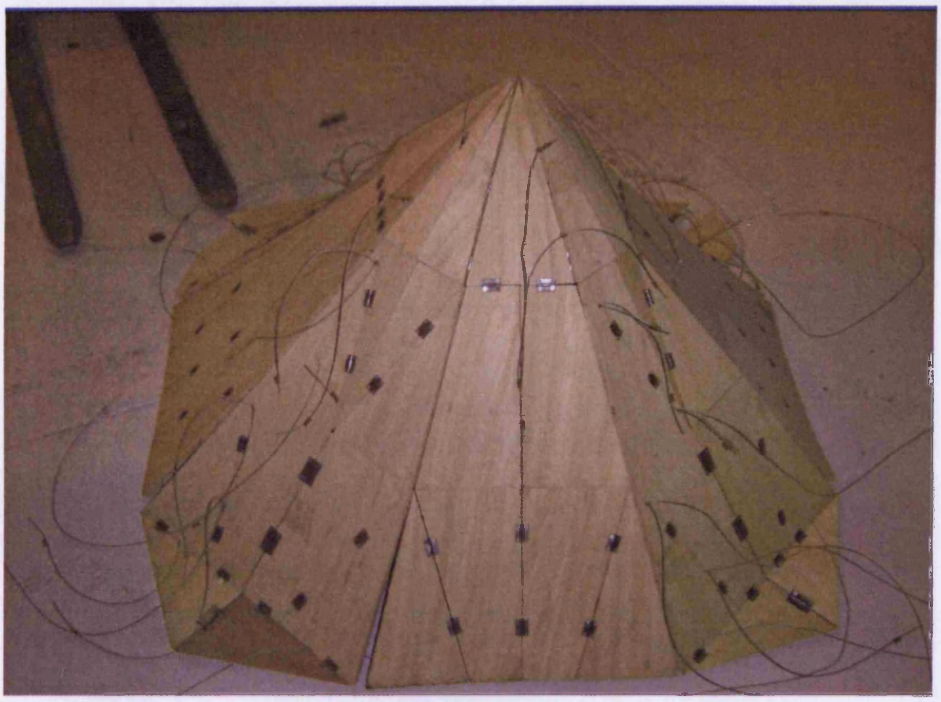

Figure 5.10B. Step B. Octagonal base pyramid

Figure 5.10C. Panels folding in first and second level

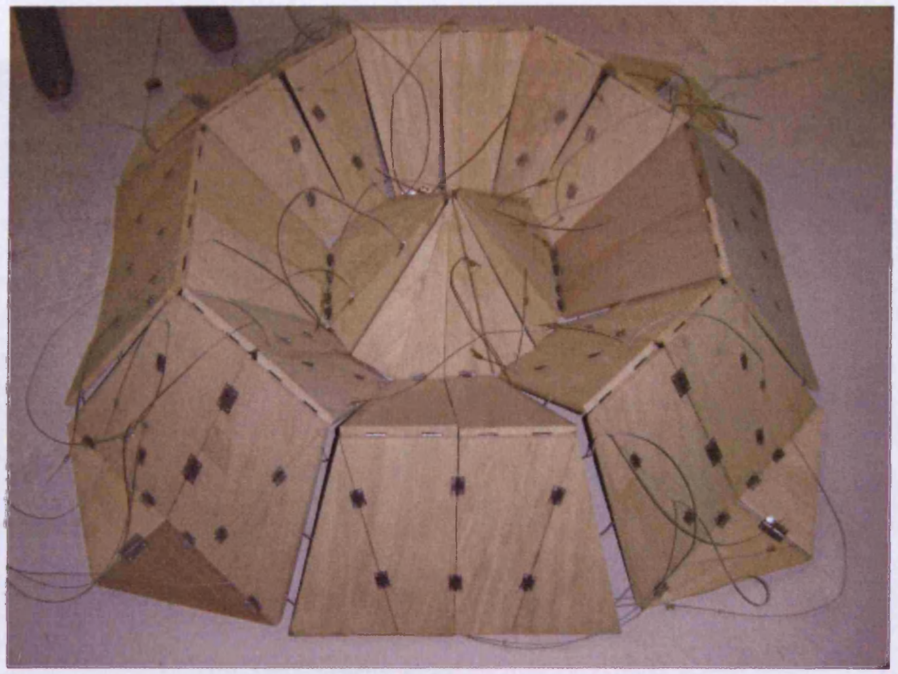

Figure 5.10D. Decreasing of the pyramid height to one-third

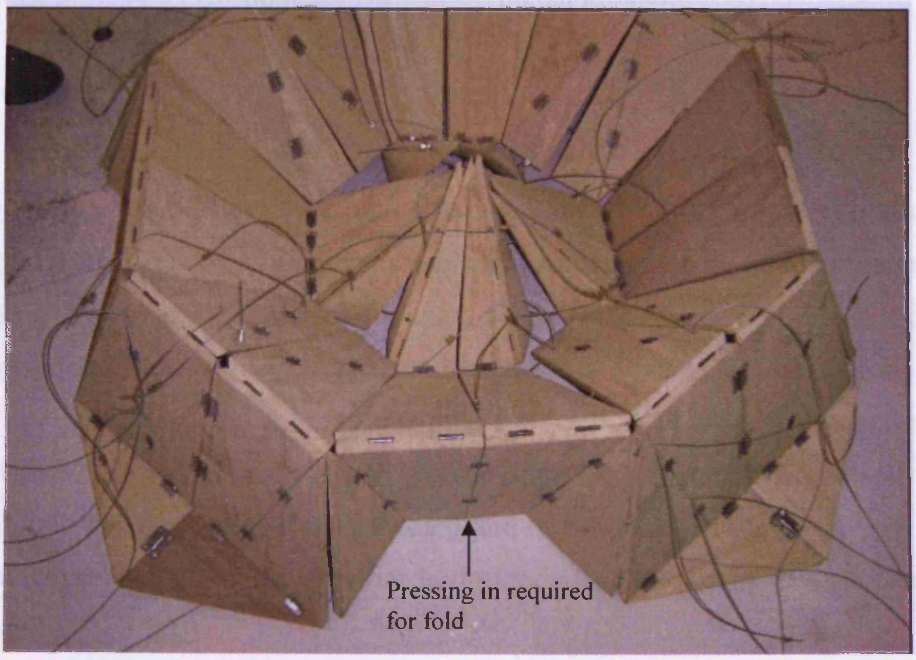

Figure 5.10E. New additional step.

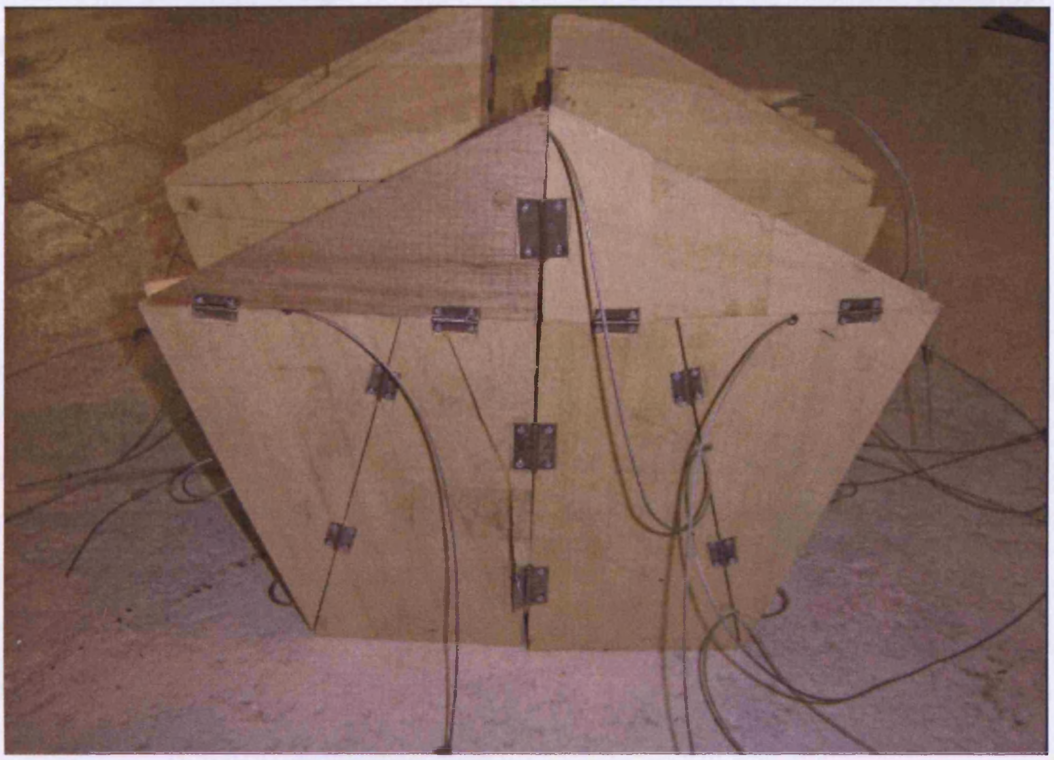

Figure 5.10F. Fully folded pyramid

5.5 Conclusions

Adding thickness to the model has obviously and noticeably affected the previous design in Chapter Three. This was obvious in replacing some hinges by flexible materials and also using a post-compression technique, and finally by adding some additional divisions on the plates. In fact, there had been some freedom in some of the folding stages, but in reality, the size of the model after full folding was smaller which facilitated the process of stacking and storage after use. The model certainly requires external help or intervention during folding and deployment, but this does not conflict with the parameters set previously prior to design. Hence, Model C2 is the final model in this study.

However, can the design of this model be applied without any endurance tests before the physical factors? Are there any weak points in this design? To answer these questions, the model should be subjected to laboratory tests in order to confirm and make sure that this design is regarded as the solution to fold the pyramidal shape manufactured by inflexible materials.

CHAPTER SIX

EXPERIMENTAL TESTS

6.1 Introduction

In Chapter Four of the present study, three methods have been described for the authentication of the credibility of the new design. This part of the study implements the second method; that is, laboratory tests of this design. Experiments were conducted using Models C1 and C2, in order to substantiate the extent of their effectiveness and the soundness of their design. These experiments were made concerning certain critical points that would possibly have an impact on the model's weakness and its stability, in order to identify the points of weaknesses in this design, if any, and then act to strengthen these points within the design. This, first of all, requires the identification of these points, and the methods of testing them; secondly, undertaking tests on both models, and then analysing the results of these tests, indicating whether these results are positive or negative; and thirdly, substantiating the negative points, if any, by suggesting solutions and adding improvements to the design.

6.2 Critical Points and Their Experimental Methods

After having dealt with the all of the previous models, two important critical points emerged in the pyramidal shape, and it is necessary to test them. The first point is an essential point in relation to the structure, in which all four faces converge at this point, that is, the apex of the pyramid. The second point is the point of the centre of mass of each of the four faces.

6.2.1 Load testing on Pyramid Apex

Choosing the apex point to run loading tests on is attributed to two reasons. The first reason is that the impact on this point affects all plates of the model since it is also the only point in the structure where all four main faces of the pyramid converge. The second reason for selecting this point is to make sure of the effectiveness of the post-compression technique used in the two models, Cl and C2. As known, the tension of the wire inside the model plates represents a compression ring on all plates of the model at that level. Since, all of the model plates are sloping to the interior from above and are not being perpendicular on the surface, this would affect the analysis of the compression force on these plates. The resultant of the compression force converges toward the central point in each level. From this resultant force, a force is created upward where the apex is. Accordingly, it is imperative to place a compression force opposing this force on the apex and to make sure of the extent of the force of the post-compression cable to maintain the model stability and to prevent its collapse.

The test method consisted of applying increasing weight on the apex, followed by taking readings of the dial gauge which measures the variation distances relative to the apex and also the aluminium angle sections which are added to the pyramid four edges forming the pyramid base in this test (Figure 6.1). Under these angle sections, roller bearings were placed in order to minimise friction between the pyramid base and the surface of the test table.

The weights were placed on a plate attached at the apex. The rate of increasing the weight for each reading was 5N. The starting point at the beginning of the test was 0 kg, and the dial gauges were set at 0 mm.

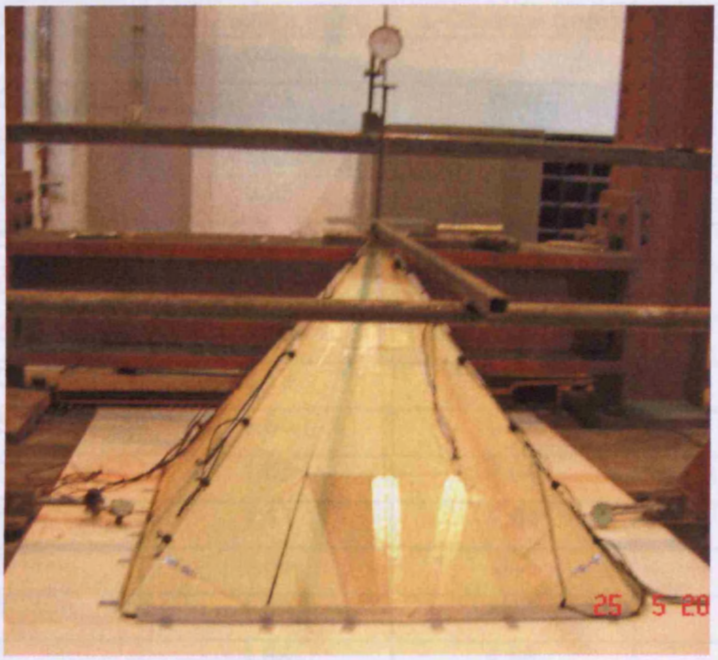

Figure 6.1 Apex point test

6.2.1.1 Test Results and Analysis

Table 6.1 shows the extent of variation of the top point site and also the edges of the pyramid base in the first test which involved Model C1 as well as the load. It is noticed that there was a direct relationship between increasing the weight, on the one hand, and the increase in the extent of variation of the top point position and the edges of the pyramid sides, on the other hand. This means that whenever pressure increased on the top point the pyramid height decreased and its base area increased.

Table 6.1

Effects of increasing load on changes on the right face, left face and pyramid height of Model C1

Load (N)	R-Change (mm)	L-Change (mm)	H-Change (mm)
5	0.03	0	0.05
10	0.08	0.04	0.13
15	0.17	0.08	0.25
20	0.25	0.1	0.34
25	0.38	0.2	0.52
30	0.48	0.24	0.6
35	0.60	0.39	0.86
40	0.73	0.8	1.02
45	0.80	0.85	1.14
50	1.05	1.84	1.67
55	1.18	1.94	1.81
60	1.55	3.7	2.72
65	1.62	3.76	2.78
70	1.88	4.88	3.36
75	2.05	5.17	3.55
80	2.36	6.62	4.27
85	2.64	6.66	4.64
90	3.56	7.08	4.95
95	3.66	7.43	5.18
100	4.22	7.45	5.4
110	7.68	7.46	7.76
120	11.0	7.46	8.24
Unload After test	9.04	5.6	5.65
Three hours later	4.18	4.27	2.88

It is logical that the pyramid height decreases when load is applied to its highest point, but not in an incremental way. In other words, it is logical to say that there is a reaction of the materials used in the cohesion of the pyramid plates. This also means that the materials used in linking the pyramid base, that is, the elastic bands in addition to the locks, have not any reversible action in controlling the cohesion of the pyramid plates against the external force impacting it, rather it is sufficient to keep the pyramid cohesion against the gravity force of the weights of its plates.

There are three observations that substantiate this conclusion. Figure 6.2 shows the first observation, that is, the difference in the extent of variation concerning the right side from the extent of variation on the opposite (left) side, given that the weight was placed during the experiment vertically on the top point. All these measures and measurements have been taken to make sure equal distribution of the weight on all pyramid sides. This means there is a difference in resistance provided by the elastic bands and the locks on one side compared to the other side. Furthermore, while the plates have been made to be the same, it is impossible to ensure that all the joints on each side have exactly the same contact and same amount of compression force and distribution.

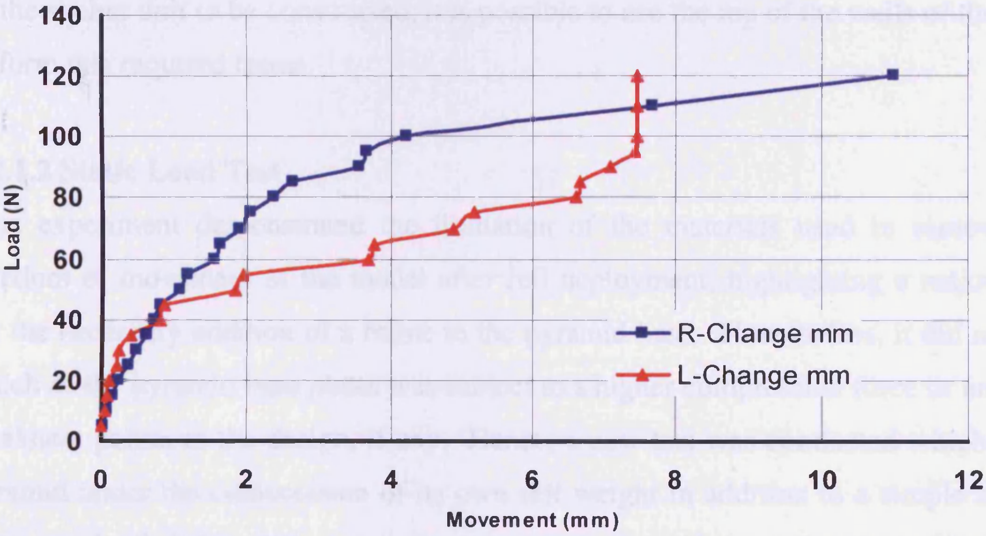

Figure 6.2. Different variations between the right and left side of the pyramid

The second observation concerns the measurements taken at the end of the test and the removal of all weights from the model, as illustrated in the last two rows of Table 6.1. These results indicate that the model plates did not regain their original shape after unloading, that is, the displacements did not return to zero. This confirms the ineffectiveness of the elastic bands, in that they expand but do not fully retract after the unloading process. The third observation is represented by the readings at the bottom of Table 6.1, taken three hours after unloading. Although the readings had decreased, they still did not attain the pre-loading readings. This confirms that locks have moved from their places and provided greater freedom for the model such that in this condition they could not adequately handle the model weight as before.

The above confirms the necessity for improvements of the materials used in maintaining the cohesion of Model C1. It is known that the elastic band in Model C1 has been replaced by a steel wire in Model C2 which is not liable to the same level of expansion. However, the locks used in Model C2 could still move from their places after the loading process. To provide for a better solution an external base in a square form and of the same lengths as the sides of the pyramid base was used. It is possible that this base is fabricated from the same materials used to fabricate the pyramid, but it can also simply be formed of four sides fixed with nuts and bolts to the loading frame after full deployment. Since the deployable pyramid is intended to form the upper part of the shelter unit to be constructed, it is possible to use the top of the walls of the shelter to form this required frame.

6.2.1.2 Static Load Test

This experiment demonstrated the limitation of the materials used in removing the freedom of movement of the model after full deployment, highlighting a major reason for the necessary addition of a frame to the pyramid base. Nonetheless, it did not show which of the pyramid base plates was subject to a higher compression force or any of the weakness points in the design, if any. Hence, a new test was conducted which left the pyramid under the compression of its own self weight in addition to a simple auxiliary static load of 2.7N, and under the same experimental conditions as the previous experiment in lowering the tension between the pyramid base and the surface of the experimental table. The pyramid was left for 48 hours under the same previous conditions. It was at least anticipated that the pyramid's four sides would separate from each other. Nonetheless, the result was better than anticipated despite the occurrence of damage to the plates of the third level forming the pyramid base; but the pyramid remained intact regarding its plates in the upper levels. Figure 6.3 illustrates the model at the end of the experiment and the damages sustained.

Figure 6.3. Showing static load effects on Model C1

It can be concluded from the previous test that the points in the structure subjected to the higher compression force were the points of contact between the pyramid's four sides, especially those in the fourth level. These points are the contact points which form the four corners of the pyramid base. The problem is in the internal hinges of this level which cannot bear the model weight. This means that the problem might be either at the places of fixing these hinges, the number of hinges, the method of fixing them, or due to all these factors. The problem in this level has been reported in Section 5.3 when all plates of the model were assembled. There were two suggestions; the first was to connect the plates of this level with the model after full deployment, that is, the hinges are internal. Due to what happened in this test and the doubt that connecting these corners internally might probably be the reason for weakening the pyramid base, the second solution is regarded as the better in this case.

The second solution was to consider these corners as extensions for the third level plates and treat them by the same way of connection in the third level; that is, they assume valley folds; hence, hinges are placed externally. Knowing that this solution would increase the volume of the model after complete folding, as previously illustrated in Figure 5.4, however, the cohesion of the pyramid plates is very important compared to the minor increase in its volume. This solution could solve the problem of the cohesion of pyramid corners, due to the following reasons. The first reasons is that when implementing the previous solution the hinges are placed externally, and the second is the increase in the areas of linking in the pyramid corners. Since if considering the plates of the fourth level as an extension to the plates of the third level, then there is no need to fold these plates within the plates of the third level. This means that the space between the plates of the third level which are at the edge of the pyramid will disappear. This is due to the fact that the linking areas at the pyramid corners would be as long as the plates of the fourth and third levels combined which means increasing the number of external hinges on the four edges of the pyramid forming the corners, which can stand larger compression force compared to the other plates of the model. This solution has been applied in the design of Model C2, and this test has been repeated and under the same conditions and the addition of a weight of 10N, which is heavier than the weight affecting Model C1. Model C2 has endured for 48 hours without any damages mentioned. This confirms the validity of this solution which has in the end helped the cohesion of the pyramid plates.

The benefit from the apex loading test was obvious from two main perspectives: firstly, adding the external frame for the pyramid base, and secondly, identifying weakness points in the design, as described earlier. The test above has realised what is required.

6.2.2 Centre of Mass Point Test

The centre of mass point in an equilateral triangle is located at the centre of this triangle, that is, the point of the intersection of the three perpendicular lines from the vertices to the opposite sides. If testing the extent of the pyramid side's endurance of the possible load, then this load must be directed to the most flexible point on the surface of this side. It is clear that the four sides of the pyramid support each other from two sides, whereas the third side of each face of the pyramid is supported by the base frame. Hence, the most flexible point for each surface is the centre point of each side of the pyramid surface. Hence, this point has been selected to test the extent of the pyramid surfaces' support to any external compression. In addition, this point is near to the areas at which the plates of the first level do not meet the corresponding plates of the second level, in accordance with the previous design of Models C1 and C2. Here lies the benefit of testing the extent of the efficacy of these two designs before the external factors, and also testing the extent of impact on the stability of the model as a whole of not directly connecting the model's plates with each other.

Figures 6.4 (a & b) illustrate the test method on the centre of mass point, whereby the model was placed on the test table and then the base frame used. Then necessary measurements were made to fix the weight arm perpendicularly onto the centre of mass point over one of the pyramid surfaces. Two dial gauges were fixed, one over the pyramid surface to be loaded in order to take readings of the extent of variation internally of the plates of the pyramid surface. The second was fixed on the pyramid apex in order to study the impact of loading on this point.

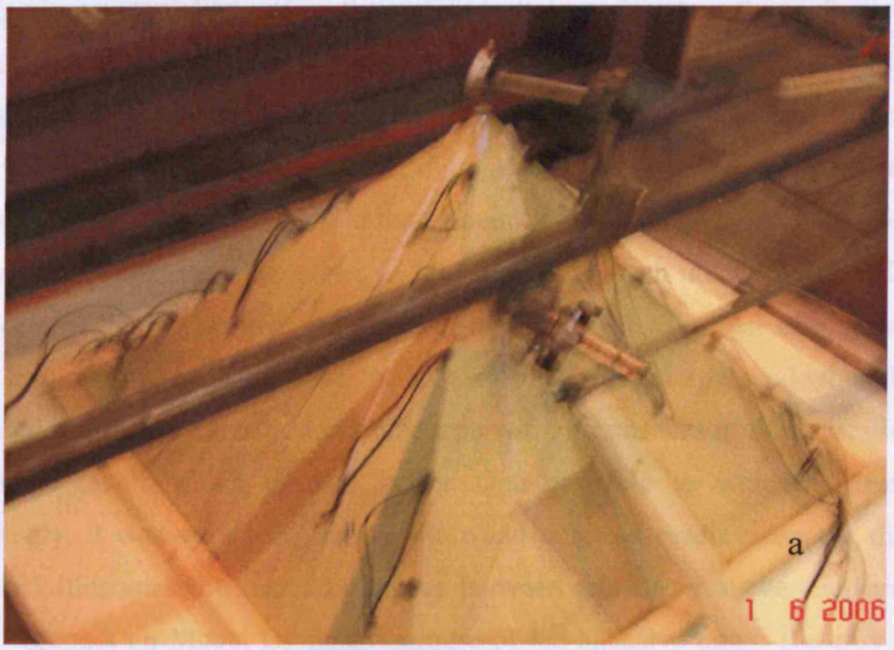

Figure 6.4a. The centre of mass point test

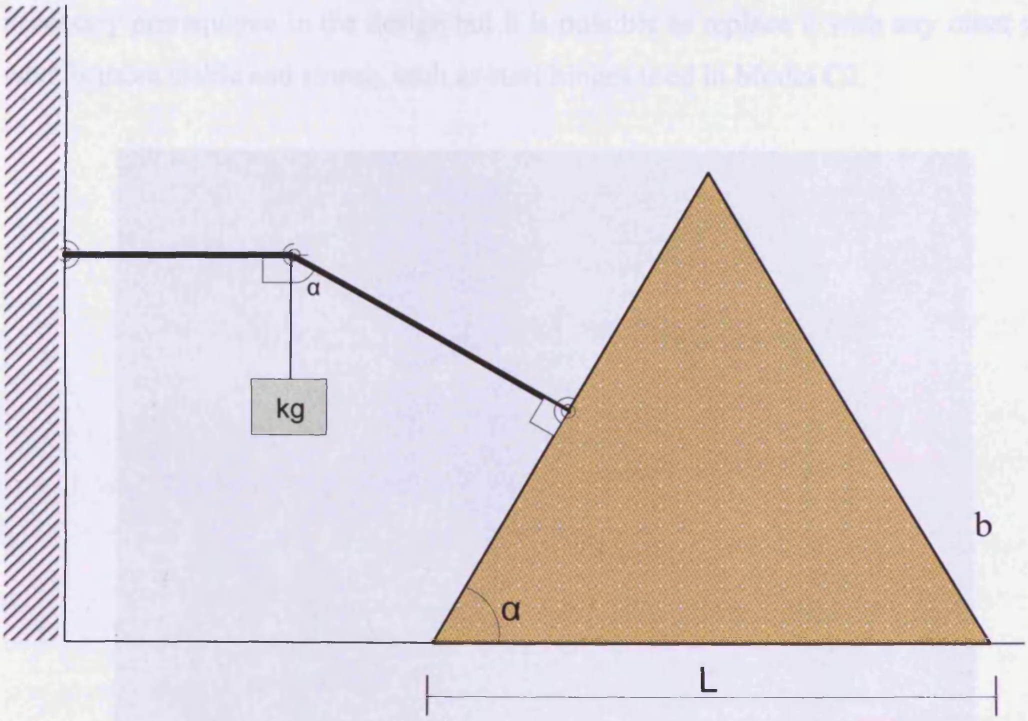

Figure 6.4b. The centre of mass point test.

6.2.2.1 Model C1 Tests

The experiment started by adding the weight to the arm fixed on the surface of the side of Model C1. The weight was added at a rate of 5N for each reading, but it was not possible to take a constant reading after the third weight addition, that is, loading the model with 15 N, as the reading of the dial gauge fixed onto the surface of the model was not constant, but accelerating in the amount of variation. The main reason was the adhesive tape which links the plates of Model C1 with each other. As already known, the process of linking between the plates of the first level with their counterparts in the second level formed the hill; hence, the adhesive tape was external, and when the weight was added it affected the adhesion of the tape with the surfaces of the plates in the first and second levels which resulted in the tape not able to withstand this weight. Accordingly, it was very hard to take clear and constant readings on the dial gauge. Figure 6.5 illustrates the increased spaces between the plates of the first and second levels. The test on Model C1 failed because of the adhesive tape. But this particular feature of adhesive tape does not exist in Model C2. Furthermore, this tape is not a necessary prerequisite in the design but it is possible to replace it with any other means what is more stable and strong, such as steel hinges used in Model C2.

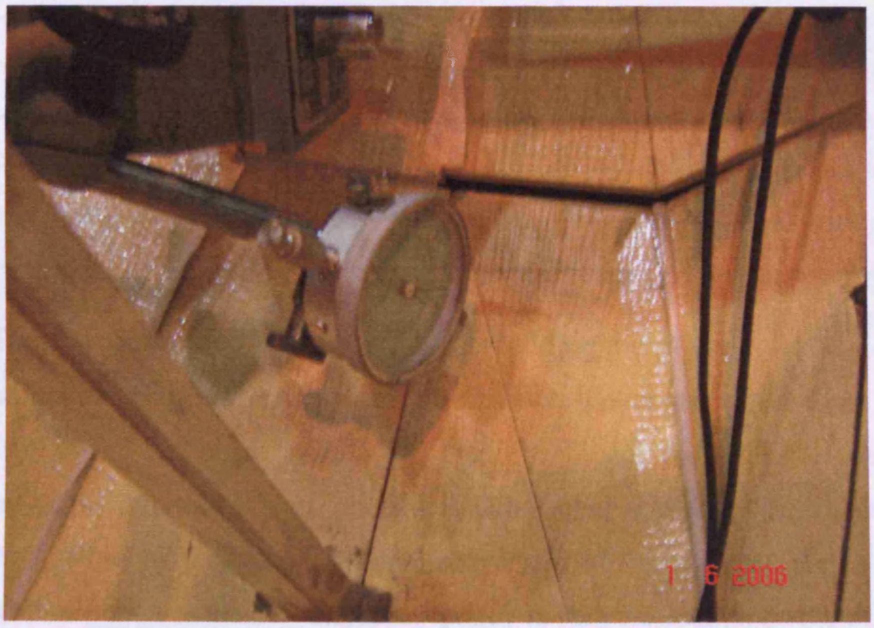
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Figure 6.5. Panels' separation due to load effect on Model C_1.

6.2.2.2 Model C2 Test

The same test was repeated on Model C2, and as usual readings were recorded after the addition of each weight. Table 6.2 illustrates the readings recorded from the dial gauges in terms of the variation in the pyramid height and also the amount of variation on the model's surface (site of loading).

Table 6.2.

Data variation of centre of mass test on Model C2

Load (N)	Apex Delta (mm)	Front Delta (mm)
0	0	0
5	0	0.9
10	0	2.4
15	0	4
20	0	5.4
25	0.02	7
30	0.02	8.3
35	0.08	10.3
40	0.13	11.5
45	0.19	12.8
50	0.25	14.2
55	0.31	15.7
60	0.36	16.95
65	0.41	18.25
70	0.45	19.3
75	0.5	20.5
80	0.55	21.7
85	0.6	23

These readings show that the process of loading the pyramid surface did not have a major effect on the pyramid height, where the overall decrease of the apex was 0.6 mm when a weight of 85N was loaded. On the other hand, the extent of change in the movement of the pyramid surface plates was substantial compared with that at the apex (Figure 6.6), whereby the overall internal movement of the pyramid plates was 23 mm when a load of 85N was added. The discrepancy is very normal since the effect is direct on the surface of the model sides and this surface is not supported internally. In fact, there was not any visible separation on the cohesion of the model plates during and after the loading process.

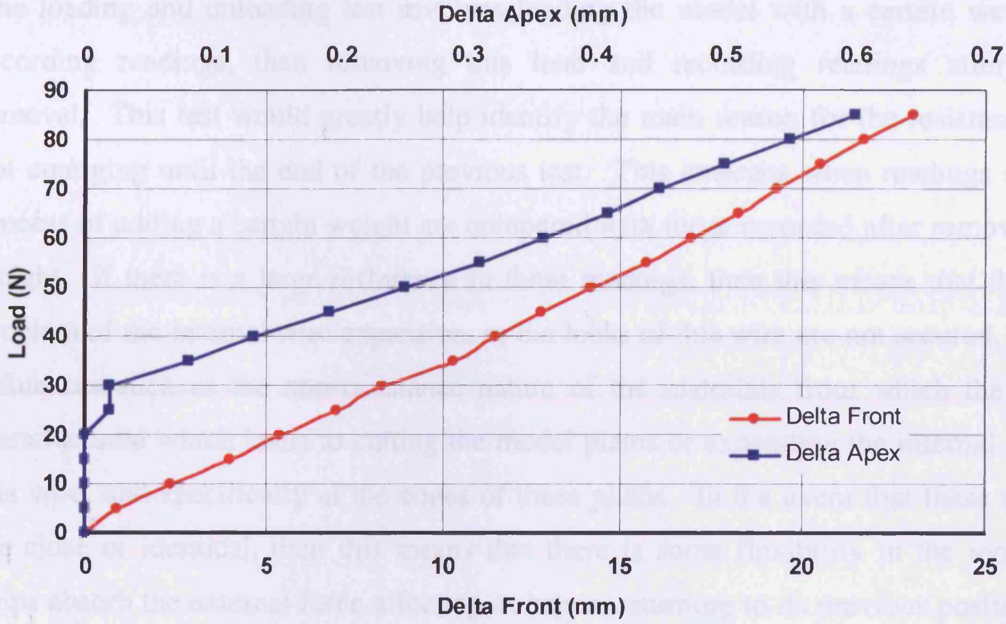

Figure 6.6. The substantial difference of movement between front face and apex of Model C2

However, from Table 6.2, it is obvious that the extent of change varied between one weight addition step and the one it followed, between 1.05 mm and 1.6 mm, except upon adding the 30N and 35N weights, when the difference was 2 mm. Also, during this stage and later on the difference diminished but did not stabilise or decrease, rather it changed during each stage. This means that there is an internal expansion below the point of stability and resistance. When assuming that the reason is due to the gaps found between the model plates and also between the internal wire which connect these plates and the path inside them, there must be a resistance point where the model has filled these gaps and starts to counteract the external compression force. However, such a point did not appear until the final weight was added, that is, the gaps were not filled until this stage, or that the gaps were increasing either due to the locking of the internal wire not being secured or due to large size of the path of this wire. To make sure of the actual reasons for the absence of a resistance point to the external compression on the model surface, another test should be carried out that illustrates this reason or reveals whether or not that is a fault in the model design.

6.2.2.3 Loading and Unloading Test

The loading and unloading test involves loading the model with a certain weight and recording readings, then removing this load and recording readings after weight removal. This test would greatly help identify the main reason for the resistance point not emerging until the end of the previous test. This emerges when readings after the process of adding a certain weight are compared with those recorded after removing that weight. If there is a large difference in these readings, then this means that there is a problem of the internal wire expansion, or the locks of this wire are not secured, or other influences such as the non-resistance nature of the materials from which the wire is manufactured which leads to cutting the model plates or expanding the internal paths of this wire, and specifically at the edges of these plates. In the event that these readings are close or identical, then this means that there is some flexibility in the model that helps absorb the external force affecting it; hence, returning to its previous position after the removal of this force.

Prior to conducting this test the tension of the internal wire was confirmed and also the accuracy of the tension on the locks as much as possible. Table 6.3 illustrates the readings recorded from the dial gauges before adding the weight, after loading it, and once again after removing the weight. The first column specifies the weight of the load added; the second column represents the reading recorded from the top point after adding the weight; the third column gives the reading recorded from the centre of mass point also after adding the weight; the fourth column gives the reading recorded from the top point after removing the weight, designated as Apex′, and the fifth column represents the reading recorded for the centre of mass point after removing the weight, and designated as Front′.

Table 6.3.

Loading and unloading test data

Load N	Apex Delta (mm)	Front Delta (mm)	Apex′ Delta (mm)	Front′ Delta (mm)
0	0	0	0	0
5	0	0.8	0	0.8
10	0	2.3	0	2.4
15	0	3.8	0	3.85
20	0	5.3	0	5.4
25	0	6.8	0	6.85
30	0.01	8.1	0	8.1
35	0.06	9.5	0.07	9.6
40	0.11	11.1	0.11	11.15
45	0.17	12.3	0.18	12.4
50	0.24	13.8	0.24	13.9
55	0.28	15.1	0.25	15.15
60	0.32	16.3	0.31	16.3
65	0.36	17.55	0.36	17.6
70	0.4	18.7	0.4	18.7
75	0.44	19.95	0.45	20
80	0.48	21	0.49	21
85	0.51	22.05	0.51	22.1
90	0.54	23	0.54	23
95	0.57	23.9	0.58	24
100	0.59	24.85		

Readings recorded before and after adding the weights were compared as illustrated in Figures 6.7 and 6.8, where Figure 6.7 illustrates the readings of the Apex point and also the graph illustrating the readings of the Apex′. Figure 6.8 illustrates the graph representing the readings of the centre of mass point compared with the graph representing the Front′.

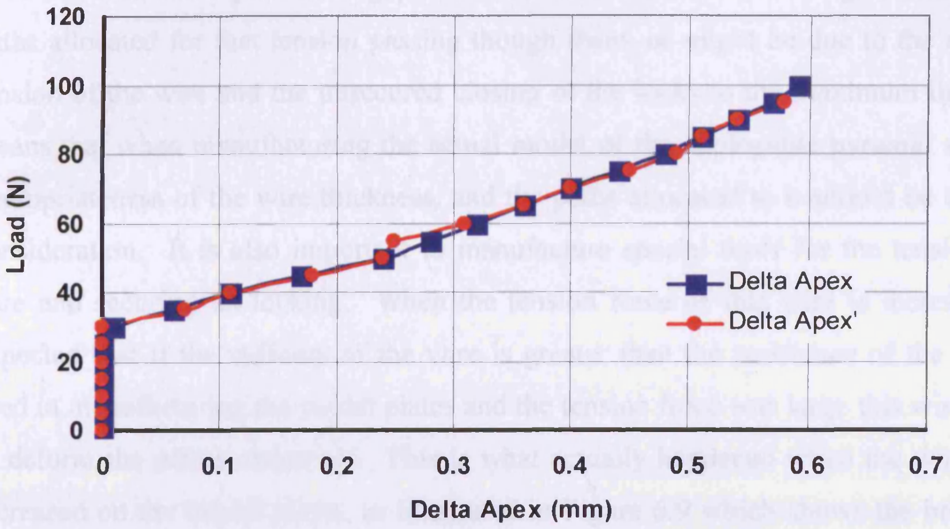

Figure 6.7. Slight changes before (Delta Apex) and after (Delta Apex') adding weights

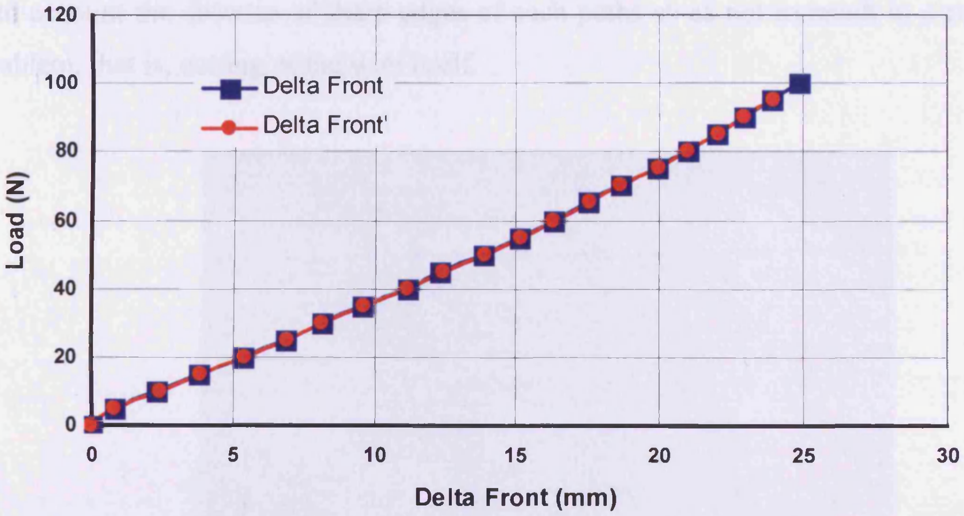

Figure 6.8. Slight changes before (Delta front) and after (Delta front') adding weights

From these two figures (Figures 6.7 and 6.8), there is close agreement between the two paths of adding the weight and then removing it, though there was no correspondence at one particular point. This confirms that the model returns to its previous state after the removal of the external force affecting it. Hence, the actual reason for the non-appearance of the resistance point was due to gaps still existing that have not been filled yet. Such gaps could have resulted from the large diameter of the paths allocated for that tension passing though them, or might be due to the unsecured tension of the wire and the unsecured closing of the locks to the maximum limit. This means that when manufacturing the actual model of the deployable pyramid shape, the appropriateness of the wire thickness, and the paths allocated to it should be taken into consideration. It is also important to manufacture special tools for the tension of the wire and securing its locking. When the tension force of this wire is increased, it is expected that if the stiffness of the wire is greater than the resistance of the materials used in manufacturing the model plates and the tension force was large this wire will cut or deform the plates' materials. This is what actually happened when the wire tension increased on the model plates, as illustrated in Figure 6.9 which shows the breaking of the wire due to the large tension force. Hence, it is recommended that the path should be sealed internally with the same material as the wire or an equivalent stiff material This is especially so at the edges of the plates which represent the pyramid corners, taking into account the absence of sharp edges of such paths so as not to result in a reversible problem, that is, cutting of the wire itself.

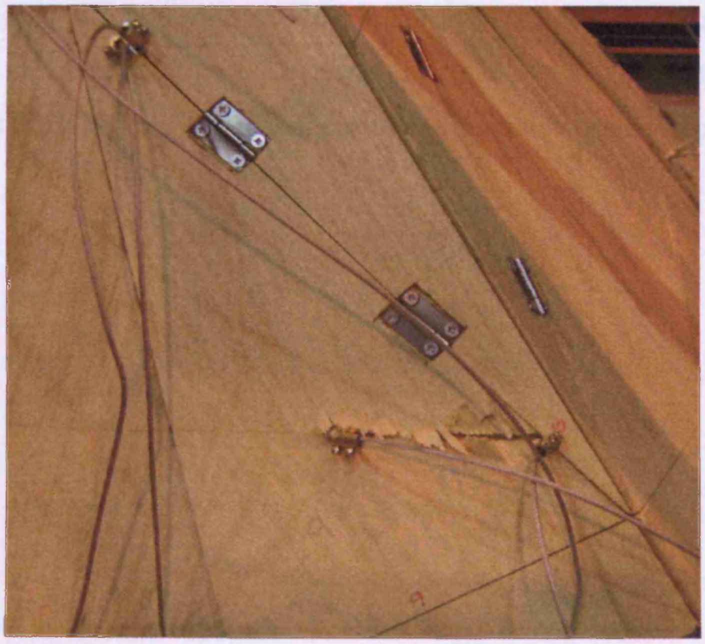

Figure 6.9. The effect of the immense tension force on the model panels.

6.3 Conclusions

The laboratory tests on the two models Cl and C2 have achieved their required purposes. One of the test results concerning the apex was the necessity of the presence of a frame embracing the pyramid base. Results also revealed that the points which are greatly affected by an external compression force on the model. This led to adopting the concept of treating the plates of the fourth level as if they were plates of the third level.

The test on the points of centre mass, on the other hand, revealed the inappropriateness of the materials used in linking the plates of Model Cl in counteracting the external force. The same test also revealed the extent of the absorption of the same force by the plates of Model C1, which confirmed the existence of a minor freedom of the model plates which can possibly be regarded as helping the model in case of the external force. The loading and unloading test revealed some points that should be taken into consideration when the manufacturing and production processes of this pyramid are assumed, such as the wire and its path edges stiffness.

Finally, there is no evidence of the presence of any fault in relation to the models' design with regard to the divisions on the pyramid's four surfaces, which confirms the accuracy of the design of Models Cl and C2. Hence, it can be concluded that both designs of Models Cl and C2 can be regarded as one of the logical solutions for the implementation of the pyramidal shape manufactured from rigid plates.

CHAPTER SEVEN

MODEL SIMULATION

7.1 Introduction

This chapter explains and discusses the third method used to verify the effectiveness of the foldable pyramid design. The MSC-ADAMS Software (2005) package was used to simulate the design resulting from the previous chapters. ADAMS is used in the construction and design of mechanical systems such as vehicles, the vehicle suspension, etc. The program helps identify the error and strain in the models to be designed.

This chapter shows the method of constructing the model with the tools and options available in ADAMS. It also discusses the results of the simulation process and elucidates the reasons for differences between these results and the experimentally determined results.

7.2 Building-up the Model

There are three main steps for the building of this model inside ADAMS. The first step is to mark the coordinates of model's panel corners for the three-dimensional plane. The second step is to create these panels in conformity with the coordinates marked in the first step. The third step is to connect these panels with each other.

7.2.1 Markers and Coordinate Calculations

The apex of this pyramid was chosen as the coordinate origin. Hence, all of the model coordinates on the Y-axis (vertical) were negative. The lengths of the side of each of the four main triangles which form the pyramid four faces were fixed at L = 500 mm. By substituting this length in the mathematical equations given in Chapter Four (pp. 56 and 57), the lengths of the panels were determined. It is also from these equations that the slope angle of the pyramid faces was calculated in Chapter Four ($\theta = 54.76°$). Figure 7.1 shows the main markers of one of the pyramid faces. With the lengths of panels and the slope angle calculated, trigonometry was used to find all coordinates of the panel corners to help create the triangular form within the program.

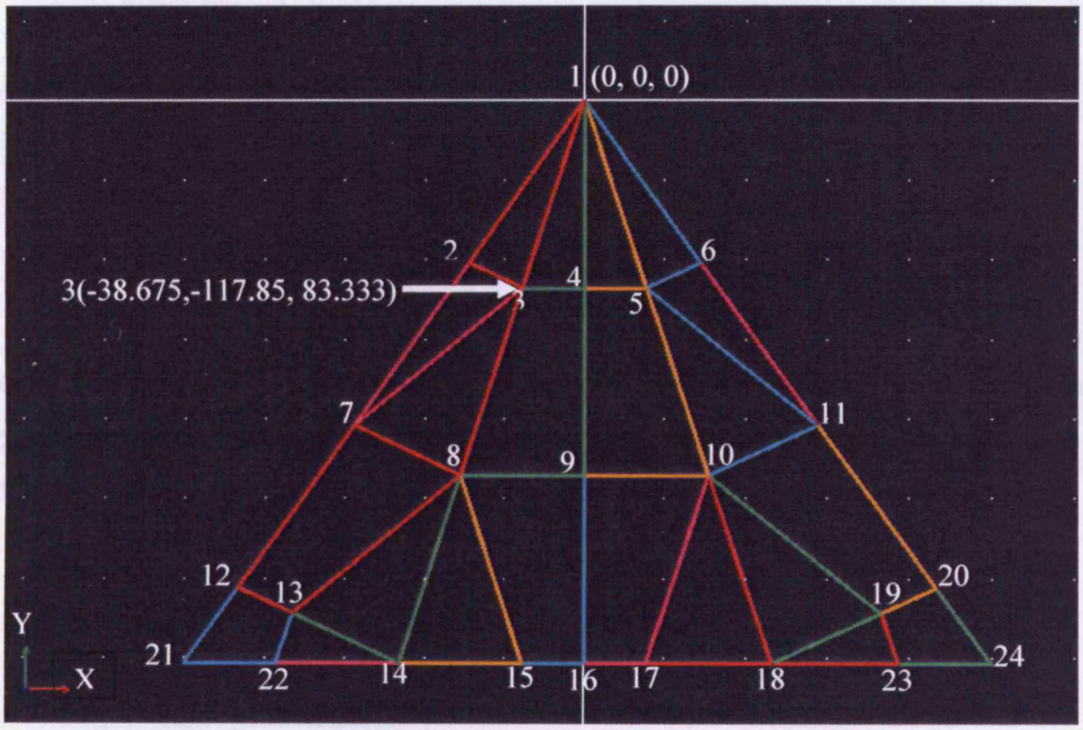

Figure 7.1. One face of the pyramid.

For example, finding the two coordinates of Marker 3 in Figure 7.1 was as follows. It is evident from comparing Figure 7.1 with Figure 4.2 that Marker 3 represents the interception point *ae* with level one, known as de_1, hence, first of all the coordinates of Marker 3 on the X-axis can be calculated by substituting L = 500 mm in Equation No. 10, Chapter Four:

$$de_1 = \frac{\sqrt{3}}{2\tan 75} \text{ x } 500 \text{ x } \frac{1}{3} = 38.675.$$

Since Marker 3 is located to the left of the apex, its coordinate is therefore negative; i.e., -38.765 mm.

Secondly, the Y-axis coordinate for this point can be calculated, using Equation 4 (Chapter Four) in which the Y-axis in Figure 7.1 represents the pyramid height *ac* in Figure 4.1.

$$ac_1 = \frac{500}{\sqrt{2}} \text{ x } \frac{1}{3} = 117.85$$

The Y-coordinate of Marker 3 is also negative, i.e., -117.85 mm.

The coordinates of 24 markers of the first face of the pyramid were determined in a similar way (see Table 7.1). The total number of points for the whole model was 77 points, since the four faces had a common point at the apex and each adjacent face had four common points at the edge of the pyramid which formed them.

Table 7.1.

Coordinates of the first face of the pyramid

Marker	face 1 (x, -y, z)		
No.	x	y	z
1	0	0	0
2	-72.167	-102.063	72.1646
3	-38.675	-117.850	83.333
4	0.000	-117.850	83.333
5	38.675	-117.850	83.333
6	72.167	-102.063	72.1646
7	-144.330	-204.125	144.330
8	-77.350	-235.700	166.660
9	0	-235.700	166.660
10	77.350	-235.700	166.660
11	144.330	-204.125	144.330
12	-216.500	-306.186	216.500
13	-183.009	-321.974	227.650
14	-116.025	-353.550	250.000
15	-38.675	-353.550	250.000
16	0	-353.550	250.000
17	38.675	-353.550	250.000
18	116.025	-353.550	250.000
19	183.009	-321.974	227.650
20	216.500	-306.186	216.500
21	-250.000	-353.550	250.000
22	-193.373	-353.550	250.000
23	193.373	-353.550	250.000
24	250.000	-353.550	250.000

7.2.2 Panel Creation and Connection

In order to create panels inside the model it was necessary to join these markers formed for each panel by selecting ADAMS's 'block' option. However, a problem emerged, that is, this option is only used to construct shapes with four sides, and since some of the model panels were triangles like those in the fist level, the 'Block' option was replaced by the 'cylinder' option. This option is actually a 'rod'. The triangle was made of three 'cylinders' and the rhomboids are formed of four cylinders. Each cylinder forms the sides of the panel, and in this form the panels resembled a framework which is empty on the inside but possesses the same required overall size according to the design.

After creating the panels the process of connecting these panels started. The panels were connected to each other by the ‘revolute joint’ option, taking into consideration the ‘hill’ and the ‘valley’ hinges. However, it was not possible to replace these hinges by flexible material for folding in the positions where the panels are attached to each other by such material. ADAMS did not have flexible hinges. The model was also connected to the ground by one fixed joint in order to fix the model base. The process of constructing the ADAMS model is complete when all the panels are connected together (Figure 7.2); hence, the model was ready for the simulation process.

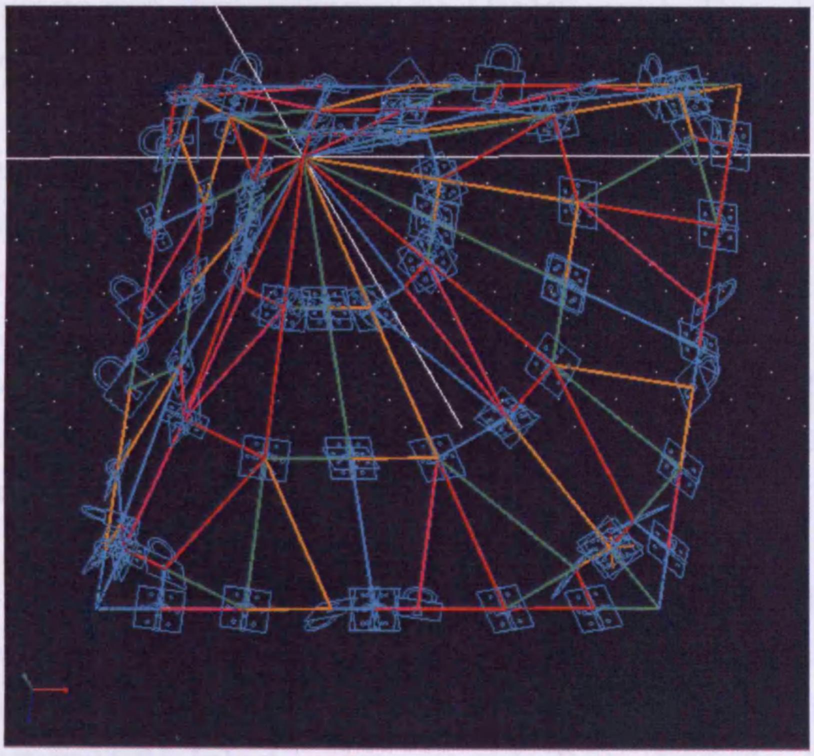

Figure 7.2 The Model before simulation

7.3 Model Simulation

When the 'Run' option of the program is activated the program checks all the panels and also the positions of the hinges direction. Initially some errors appeared in the directions of the hinges which were due to a mistake during the process of connecting the panels. However, despite the fact that the directions of the hinges and all such errors were corrected, the simulation results inside the computer still did not match to the movement of the model in reality.

After undertaking more than one attempt and making amendments in the connecting process between the panels and also between the model and the floor, the simulation results did not conform to the folding process of the real model. From these attempts and investigating their results, it was concluded that the main reason for this non-conformity was due to two main differences between the method of constructing the real model and the method of constructing the ADAMS model. These differences are given below:

Firstly, there was the absence of hinges in ADAMS that are made of the same flexible material as in real model and also the absence of the wire for the post-compression process.

Secondly, the actual model is designed to be folded in a series of consecutive stages manually with external help, whereas the program deals with the mechanical systems that were applied before simulation.

The absence of the hinges made of flexible materials necessitated linking of all the panels with each other by rigid hinges that cannot be folded reversibly. Hence, due to the requirement for folding some hinges reversibly, especially those found at the edges of the pyramid, this linkage has been not used. This is due to the absence of the option of internal wire which helps tie all the panels and provide them with some free movement; hence, the model parts during the simulation process moved in directions different to the directions required in reality (Figure 7.3). These differing movements appeared on the panels of the first and second levels only, which were on the edges of the pyramid, whereas the panels in the third level were fixed because they were not linked to each other.

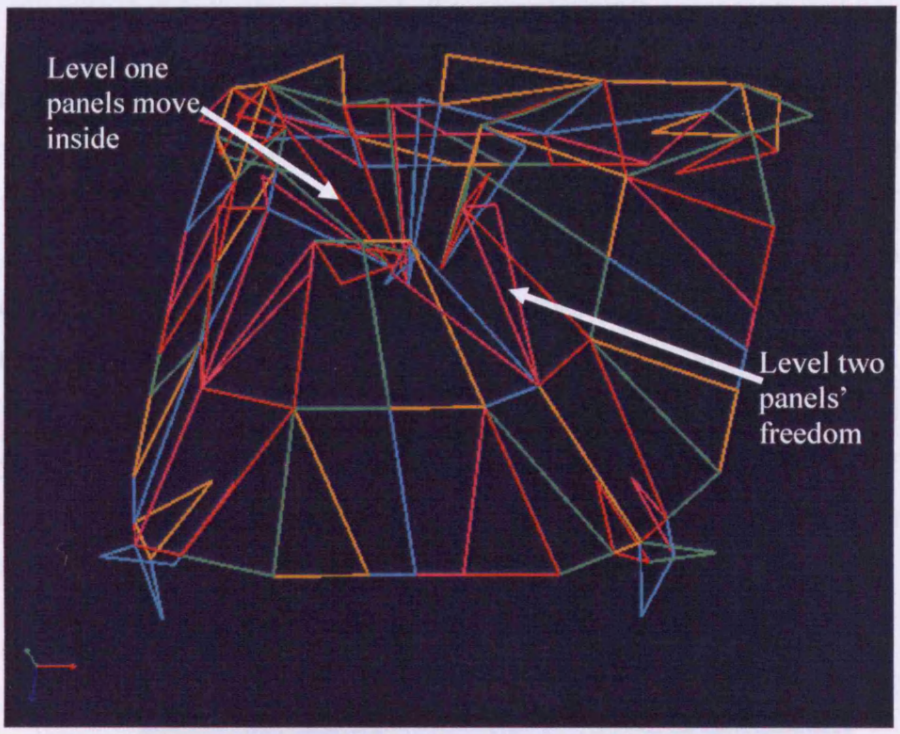

Figure 7.3. Different movements for panels of levels one and two.

The physical model was designed to fold manually and with external assistance. Section 5.4.2 showed the necessity for the succession of folding steps, in addition to the necessity of external intervention which prepares the model after each step for the following step. The folding model was not prepared to fold automatically, or self-deployed. This represents a major difference between the steps of folding the actual model and the simulation process within the program. It was therefore necessary to add a mechanical system to the design inside the program to act as the external agent required which, for the actual model is achieved by the operator who folds or deploys the model.

For example, the first folding step is changing the model from a pyramid with a four-sided base to an octagonal based pyramid (Figure 5.10b). Section 5.4.3 explains how this step cannot be done automatically, but required external intervention.

The model during the simulation process did not pass through this step but resorted to move involuntarily as available, depending on the hinges' direction. Instead of moving to form the octagonal base, it retracted inwardly to form a square base smaller than the original base (see Figure 7.4). Under gravity, the upper panels of the model form a compression force over the pyramid base which makes it move externally to form the octagonal base. Nonetheless, these weights were not effective as required. In this case this hypothesis is rejected and the only alternative option is the process of pulling panels in the middle sides of the square base to form the octagonal base. This process in reality is done manually such that it does not exist during the construction of the model inside the programme. Since ADAMS handles the data entered in advance during construction, this process is not available during simulation.

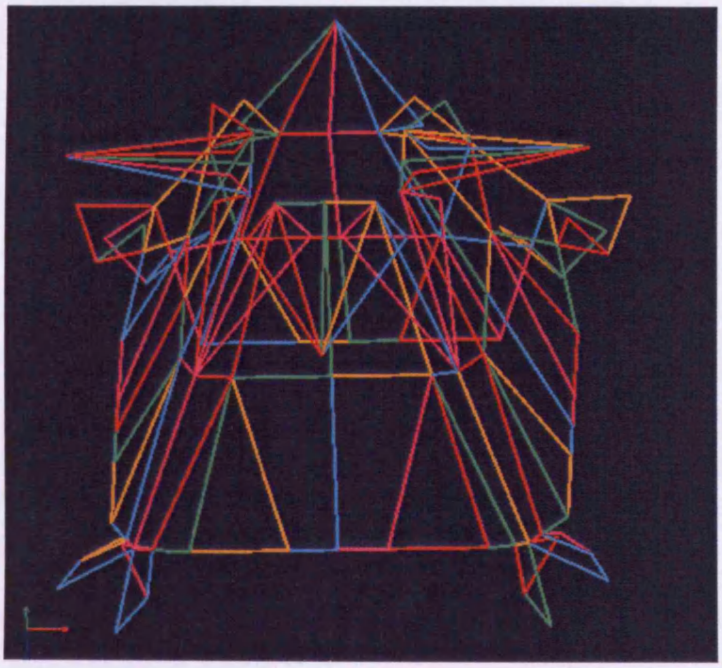

Figure 7.4. Model panels retracted inward to form a smaller square base

From the discussion above, it was not possible to obtain Step B using ADAMS, and this step is considered as one of the first prerequisite steps of folding the model. Since the model depends on the succession of folding steps, and it was not possible to obtain Step B, the subsequent steps and full folding were not obtained in ADAMS.

CHAPTER EIGHT

CONCLUSIONS

This chapter summarises the main findings of the present study, focusing on the important issues raised in each chapter separately. It also presents the conclusions and recommendations concerning certain issues that can be re-developed or investigated in a different way based on knowledge gained in the present study.

Chapter Two of this thesis classified foldable structure types, principally following Hanaor and Levy's (2001) classification where applicable. Previous studies relating to these types were also reviewed, in addition to the implementations undertaken in practical applications, and the use of the applications. Despite this, the researcher believes that there are many aspects that could have solutions and applications of foldable structures that have not been discussed by researchers.

In Chapter Three several attempts have been made to fold a pyramidal shape, using the concertina zigzag method to divide plated surfaces and also to present a method of not connecting some of the structure panels in order to give the structure more freedom during the deployment process and to avoid increasing the strain of the panels inside the enclosure areas. Several designs have been produced in this chapter, from which only one design was selected in consideration of a number of issues, the most important of which was that the deployment needed to be strain-free. Accordingly, it is possible to undertake future studies on the designs excluded and resolve some of their aspects, especially the sequence configuration on Model A4 (Section 3.2.3) which reduces the increase in divisions on the structure panels.

Chapter Four explained the mathematical equations relating to the lengths and angles of the panels of the structure previously designed in Chapter Three. It also proved theoretically the possibility of implementing the displacement mechanisms recommended in Chapter Three.

Chapter Five illustrates the actual applications of the previous two chapters, using models manufactured from several solid materials with different thicknesses. It is revealed through these applications that the thickness does not affect the effectiveness of the design and the validity of the suggested mechanisms in relation to all stages of folding and deployment. The effect was only on the thickness of the hinges used to accommodate the model panels which required the use of a post-compression technique. Despite the fact that the final model represents a good solution for the concept of folding the pyramidal shape, it is not a self-deployed structure but requires external assistance in the folding and deployment stages. However, this does not contradict the specifications previously required, since it is possible to construct this structure using this external assistance in each step. Here are revealed good areas for future investigation such as adding a manual or electrical mechanism for the deployment or folding the structure.

Laboratory tests in Chapter Six showed that the model weight affects some of its points of weakness. The most important of these points were the contact points at the corners of the model base. This led to addition of a frame for this base in order to secure the stability of the model after complete deployment. Tests also indicated the necessity of making sure that materials used in the process of connecting and tension of the structure panels must be compatible with the material from which the structure is manufactured. In addition, this chapter also revealed the presence of good and simple freedom in the design in order to absorb sudden shocks on the structure.

Chapter Seven illustrates the method of building the model using the computer programme ADAMS and the subsequent deployment simulation. This chapter also revealed the main factors that led to the non-conformity of the deployment and folding steps in the actual structure with their counterparts in the simulation model. These factors are, firstly, the design of the foldable pyramid is neither self-folded nor self-deployed, that is, it needs an external assistance in some steps that it was not possible to apply inside the programme; and secondly, the post-compression technique applied to the actual model was not applied to the ADAMS model due to the absence of such features in the software. A good point emerged from this that could be investigated in the future, that is, designing a special simulation programme concerning this design.

Finally, the design resulting from this study is one of the preliminary solutions to fold the pyramidal shape and manufactured from stiff material. The proposed design cannot be considered as the final solution for the problem of accommodating pilgrims at Menna and Arafat; rather it is considered as a concept for the final solution. In other words, at the time of manufacturing the final product of this design, research must be undertaken by manufacturing and production engineers specifically with regard to the hinges and tension and linkage materials. This thesis has been written with special emphasis on the research topic of pyramidal shape, but it is possible to benefit other forms of the foldable structures.

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APPENDIX

FIELD STUDY

Introduction

The purpose of my study is to provide a descriptive and analytical profile of the factors influencing the general issues of the pilgrims' accommodation structures. It aims at discovering the pilgrims' needs motives, expectations and gratifications. The study focused on the pilgrims and the motawefs (who are responsible for all the pilgrims' needs) and the patterns of their interaction with the accommodation specifications.

On February 2003 the researcher conducted a focus group study and self administered questionnaire during his visit to Saudi Arabia. The study took place in Menna.

Part one (Focus Group)

Eight focus groups were conducted. Each group consists of 5-8 pilgrims or motawefs. The researcher as a moderator led a discussion of approximately 45 minutes.

Focus groups are employed extensively among many social researchers. They are used as a preliminary study leading to quantitative research. In any case, focus groups involve persons specially selected owing to their particular interest, expertise or position in the community in an attempt to collect information on a number of issues, as well as to brainstorm a variety of solutions, and ultimately facilitate group discussion as a tool of data collection and possibly policy construction. This method is therefore often referred to as group discussion particularly among European researchers.

The objective is to form the groups with pilgrims and motawefs who are capable of providing the highest-quality discussion about the topic being researched.

All of the eight groups were audio taped to preserve a permanent record of the proceedings and allowed the moderator to lead the discussion effectively.

The purposes of focus group

In social research, focus groups can serve several purposes. The following are thought by many researchers to be the most significant:

- As a pre-research method it can help to prepare the main study by providing sufficient information about the study object, about operationalisation by defining indicators and about preventing possible errors.
- In another form, group discussion allows access to valuable information about group processes, attitude changes and manipulation, attitudes and opinions of group members, the group or the public, the effectiveness of certain methods and so on.

Thus, focus groups are usually used as a form of exploration rather than as an independent and autonomous study.

Methods

An outline covering all aspects of the topic to be discussed during the focus group session was distributed to all group members. The outline included information hoped to cover and list the specific external stimuli, which were used during the group to elicit information from the participants.

The researcher introduced him to the participants briefly explaining the purpose of the session and alerted them to the microphone recording the session and then let participants introduce themselves by filling in the sheet.

As a warm up, the participants were asked to discuss very general issues about their satisfaction of the accommodation, in order to learn some basic information about the topic. Different authors see the conduct of group discussion in different ways. While some (Sarantakos, 1998) suggest that there are three major steps in group discussion *warm-up, confrontation and relaxation.* A detailed discussion was carried out to identify important information about the topic under investigation.

Discussion was developed so that inputs were gained from the participants about the research topic itself. During this, the participants were exposed to several concepts and questions of the topic to be investigated.

Finally, a summary section was determined to give the participants an opportunity to share any information about the topic that they may have forgotten or they wanted to add.

The Focus Groups

As mentioned earlier eight focus groups were formed as follows:
Group one: consists of 8 pilgrims.
Group two: consists of 8 pilgrims.
Group three: consists of 8 pilgrims.
Group four: consists of 8 pilgrims.
Group five: consists of 5 Motawefs.
Group six: consists of 7 Motawefs.
Group seven: consists of 6 Motawefs.
Group eight: consists of 8 Motawefs.

After a group was selected for investigation, the moderator introduced a goal-directed discussion. The moderator intervened as required, directing the discussion to the research goals and keeping its course interesting and balanced. The following questions were used as interview schedules:

For pilgrims

1. What are your first impressions when you get in the tent?

2. How did you find the space availability in terms of size and privacy? And why?
3. Do you think that double layers bed system will be a good idea?
4. If your Hajj journey is during the summer, do you think the air conditioning is necessary?
5. How do you assess the current air-conditioning system?
6. Are you satisfied with the safety within the camp? If not why?
7. What did you not find, which you were expecting before you came here?
8. If you had a chance to give advice to the director of this project, what advice would you give?
9. Finally, is there anything that you came wanting to say that you did not get a chance to say?

For Motawefs

1. Are you satisfied with these kinds of structures? If not why?
2. What do you think the problems, which are caused by the size of the unit and the area available, are.
3. How can the construction influence your job in terms of the time and ability?
4. During the Hajj time do you feel it is easy to offer the pilgrims all the services? If not why?
5. Do the materials of the tents cause any problems? If so what are they?
6. If you have a chance to change any component of this structure, what are you going to change? And why?
7. If you got a new unit suitable for 20 pilgrims, how long do you expect you need to build it up? And what do you think is the minimum numbers of workers that it needs to be built?
8. Finally, is there anything that you came wanting to say that you did not get a chance to say?

Sessions were conducted with the mentioned groups respectively. Each session was held separately and lasted approximately 45 minutes.

Focus group discussion results

The results of this focus group study will be divided into two parts. Part one deals with pilgrims, and part two deals with Motawefs.

Part I (pilgrims)

General impressions:-

The study showed that most pilgrims accept the tents in Menna due to three reasons: First, Pilgrims are persuaded of the existence of some troubles during pilgrimage. Second, comparing the pilgrim's tents in Menna to the traditional tents in Arafat which are made of cloth, made pilgrims satisfied with the level of housing which is much improved in Menna than in Arafat. Third, the difficulty of reaching Menna after the troubles of moving from Arafat to Mozdalifa, then to Menna, forced the pilgrims to accept the situation in Menna, knowing that all of them are looking forward for the better.

More serious problems:

From the pilgrims' point of view there are two great problems, the first of which is that the space available inside the tent is not enough for sleeping and for the private belongings. The second is concerned with the public areas like the difficulty of praying due to non availability of mosques in the camps. Also the medical points are small and toilets and bathrooms are few.

Accepting the suggested solution:

There was almost complete consensus on the suggested solution, i.e., the existence of a two layers bed to avoid the problem of the small space given to the pilgrim, giving places for prayers inside the tent, and giving shelves for storing, taking into account the conditions related to some sick and aged people who can not get to the second layer of the bed.

Impossible:

"It is so impossible of performing the rites of pilgrimage in summer without air-conditioning" said one Lebanese pilgrim during the second interview with pilgrims. In all interviews all pilgrims emphasised the necessity of air-conditioning in both summer and winter. Some of them considered the existing air conditioning in current February as very good at night but needs to be cooler by day. Thus it becomes clear the importance of the air-conditioning and improving its level during the coming years in particular in which pilgrimage will be in summer.

Others denied the mal-ventilation inside the tent, attributing that to the bad sticking material used to fix the side walls of the tent which makes it open from all sides, which in turn causes variation of the tent temperature and the penetration of noise to the tent.

Complete satisfaction:

The pilgrims felt complete satisfaction as regards the safety procedures including the existence of fire extinguishers and the automatic extinguishing system inside the tents. On the other hand, many of them complained about the easy opening of the side walls of the tents, and that they can not be closed tightly, which causes losing some belongings, and increasing their feeling of lacking of safety, that a pilgrim could take the sleeping place of another because of the problem of the crowd and gathering. All participants in the discussion preferred the small size tents to the big ones which take over thirty pilgrims.

Demands:

Most pilgrims emphasised substituting the method of cooling the drinking water using ice to using the electric coolers. Also, some emphasised the existence of a fridge to keep food inside the tent. Also, some pilgrims complained about the difficult system of numbering tents, the narrow passages and the few means of clarification inside the camp which could cause difficulty of movement and lost in sometimes.

Conclusions:

According to the discussions made with pilgrims and their comments, the research concluded some important points which should be put into consideration when designing new pilgrim's accommodation. They are as follows:

- Supporting the idea of two-layer bed as a solution to the problem of space, while taking into consideration the possibility of folding the bed at times of prayers.
- Providing shelves for storing the pilgrim's luggage inside the tents.
- Availability of some spaces at the stage of design for putting drinking water coolers and wastes baskets inside the tent.
- Improving the level of the air-conditioning or changing it if possible.
- Fixing tight the side walls of the tent.
- Designing easy installed bathrooms.
- Taking into consideration the small size of the new units at the stage of design.

Part II (Motawefs)

General impression:-

Although all participants agreed that the new tents project in Menna which is made of fibre glass is better than the old one of Menna which is currently used at Arafat, but they also mentioned that the design lacks some points.

Privileges of the new project in Menna:

The most important reasons made by the developers of the new project are: First, the tents are fire-proof, as many pilgrims suffered much from being subject to death and physical loss. Also the new tents are re-constructed in a very short time causing great physical loss and the camp lacking most services proposed to exist. Second, designing the new tents half-fixed saves the time and efforts of Motawefs when preparing the camp as required and no need for warehouses for keeping the tents and their fittings over the year.

The weak points of the design:

The points which the new design lacks are: first, not solving the main problem which is the crowd and gathering, as the new spaces are not proportionate to the number of pilgrims. The second is the difficulty of controlling the distribution due to unavailability of entries and exits for the tents. Third, no tight closure of tents as the partitions or the side walls of the tents are easily-broken, which makes it easy to anyone to go into any tent, which is not his, and taking the place of another pilgrim. Fourth, the design is too open which causes difficulty of separating the camps, which in turn causes confusion among the groups of pilgrims in one place. Fifth, the passages are narrow in some camps which cause confusion during the distribution of services to pilgrims and the difficult movement inside the tent. Sixth, the small size of the few kitchens and lacking water and sources of power for cooking affect the pilgrim's satisfaction. Finally, there are no special stores for keeping the light meals and the like.

The conclusions of the study coincide with the suggestions of the Motawefs:-

As some participants of the discussions have long experience of not less than ten years on the service of pilgrims and for some of them it exceeds thirty years, the researcher found that it is very necessary to mention their suggestions which coincide to a large extent with the results of the study. They are as follows:

- Doubling the available spaces either by using two layers beds or multi-level tents.
- Preferring the same foldable system to other systems to solve two problems, the first of which is the economic view, i.e. reconstructing the infrastructure such as extensions of water, electricity and air-conditioning each year, besides storing during the year. The second is to keep the manufactured materials of the tents from natural factors in case of folding them , as well as easiness of monitoring the project over the year. This also means fixing the skeleton of the project and the easiness to fold the upper cover and the side partitions.
- Developing the current air-conditioning system or replacing it if possible as they are fully persuaded by experience that it is not efficient during summer season.

- It is necessary to move the side walls of the tents easily and close them tightly, by special locks to be available with the person in charge of the tents only.
- Providing fixed places for the administration, storing and medical clinic in each tent.
- Increasing the number of the bathrooms threefold in each camp, maybe by making multi-level bathrooms.
- The unit size had better be small for easy control and housing the pilgrims. Also it is preferable that each camp to be prepared for 3500 pilgrims.
- The suggested period of constructing a tent for the service of 3500 pilgrims is 10 working days of two 8-hour shifts, 20 workers in each.

General Discussion:-

The main objective of these focus groups is to provide a descriptive and analytical profile of the factors influencing the general issues of the pilgrims' accommodation structures. It aims at discovering the pilgrims' needs, expectations, and satisfaction. Discussion of previous results with the two groups, pilgrims and Motawefs are fruitful and very beneficial.

Both groups of pilgrims and Motawefs agreed that the new tents project in Menna is better than the position in Arafat from the general point of view, but severely criticised the failure to solve the problem of the small spaces. In addition the data of the study gave an indicator that the two groups agreed that the number of bathrooms is too few. Both groups preferred the small-size unit while taking into consideration the tight closure of the side partitions. Pilgrims did not emphasize as strongly as the Motawefs on improving the level of the air-conditioning. All agreed that the passages are narrow.

Pilgrims had additional requests like providing storing shelves. They complained about the method of cooling the drinking water and the few means of clarification. Also Motawefs requested specifying fixed places for the administration and the warehouses. They complained of the multiple exits and entries that are not tightly closed in each camp.

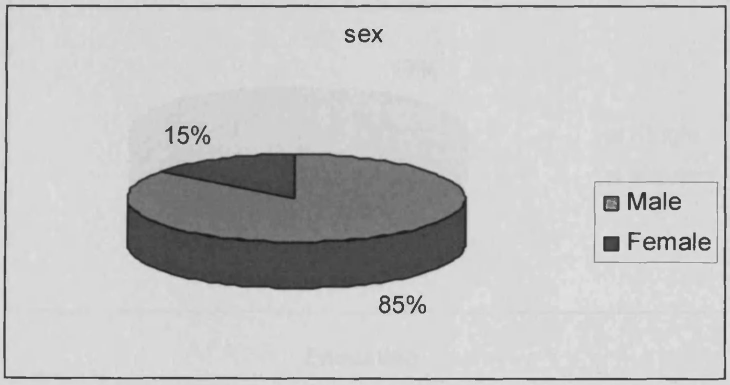
It is important to note that the overall key findings indicated clearly the factors influencing the pilgrim's accommodation structures and solutions mentioned by the two groups under investigation. In other words the suggestion provided by the two groups would serve as solution.

Part two (Self Administered Questionnaire)

Statistical Report

sex

	Frequency	Percent
Male	1109	85.3
Female	191	14.7
Total	1300	100.0



age

	Frequency	Percent
Less than 30 years	198	15.2
30 to less than 40	518	39.8
40 to less than 50	227	17.5
50 to less than 60	207	15.9
60 or more	150	11.5
Total	1300	100.0

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Conclusions:

According to the discussions made with pilgrims and their comments, the research concluded some important points which should be put into consideration when designing new pilgrim's accommodation. They are as follows:

- Supporting the idea of two-layer bed as a solution to the problem of space, while taking into consideration the possibility of folding the bed at times of prayers.
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- Designing easy installed bathrooms.
- Taking into consideration the small size of the new units at the stage of design.

Part II (Motawefs)

General impression:-

Although all participants agreed that the new tents project in Menna which is made of fibre glass is better than the old one of Menna which is currently used at Arafat, but they also mentioned that the design lacks some points.

Privileges of the new project in Menna:

The most important reasons made by the developers of the new project are: First, the tents are fire-proof, as many pilgrims suffered much from being subject to death and physical loss. Also the new tents are re-constructed in a very short time causing great physical loss and the camp lacking most services proposed to exist. Second, designing the new tents half-fixed saves the time and efforts of Motawefs when preparing the camp as required and no need for warehouses for keeping the tents and their fittings over the year.

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General Discussion:-

The main objective of these focus groups is to provide a descriptive and analytical profile of the factors influencing the general issues of the pilgrims' accommodation structures. It aims at discovering the pilgrims' needs, expectations, and satisfaction. Discussion of previous results with the two groups, pilgrims and Motawefs are fruitful and very beneficial.

Both groups of pilgrims and Motawefs agreed that the new tents project in Menna is better than the position in Arafat from the general point of view, but severely criticised the failure to solve the problem of the small spaces. In addition the data of the study gave an indicator that the two groups agreed that the number of bathrooms is too few. Both groups preferred the small-size unit while taking into consideration the tight closure of the side partitions. Pilgrims did not emphasize as strongly as the Motawefs on improving the level of the air-conditioning. All agreed that the passages are narrow.

Pilgrims had additional requests like providing storing shelves. They complained about the method of cooling the drinking water and the few means of clarification. Also Motawefs requested specifying fixed places for the administration and the warehouses. They complained of the multiple exits and entries that are not tightly closed in each camp.

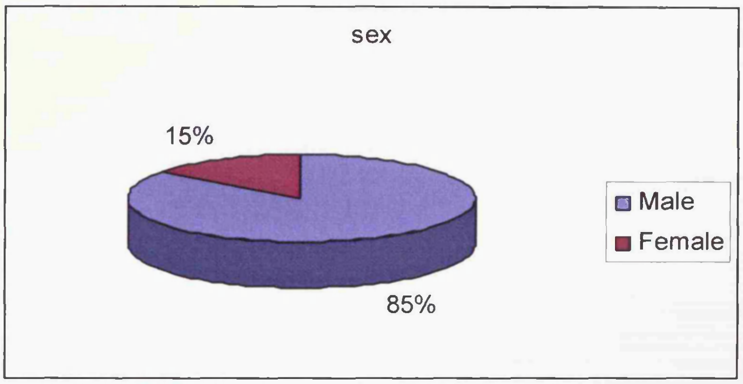
It is important to note that the overall key findings indicated clearly the factors influencing the pilgrim's accommodation structures and solutions mentioned by the two groups under investigation. In other words the suggestion provided by the two groups would serve as solution.

Part two (Self Administered Questionnaire)

Statistical Report

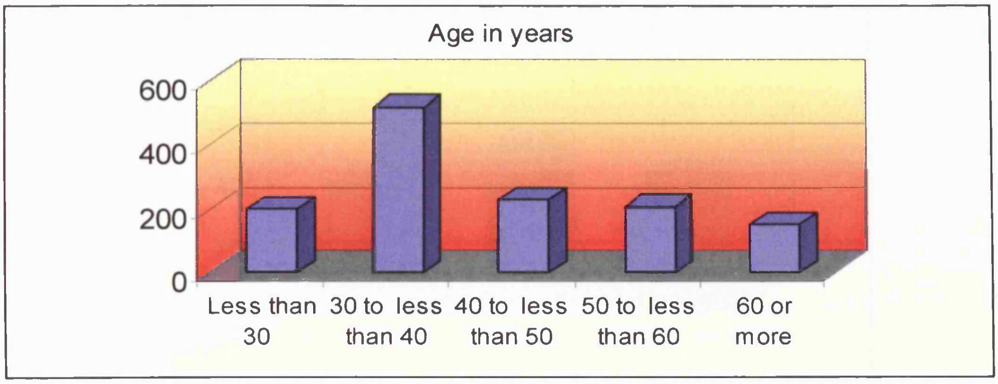
sex

	Frequency	Percent
Male	1109	85.3
Female	191	14.7
Total	1300	100.0



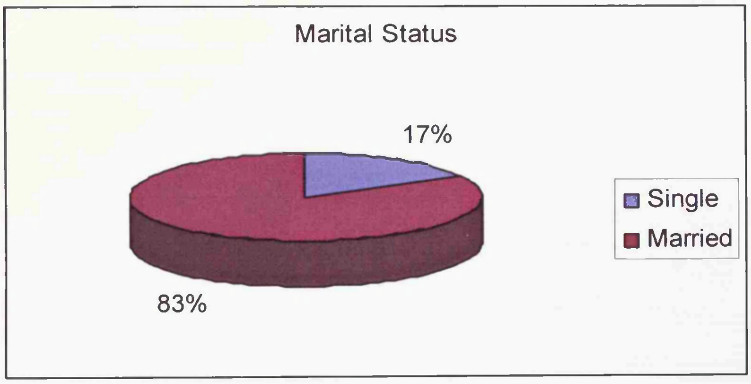
age

	Frequency	Percent
Less than 30 years	198	15.2
30 to less than 40	518	39.8
40 to less than 50	227	17.5
50 to less than 60	207	15.9
60 or more	150	11.5
Total	1300	100.0



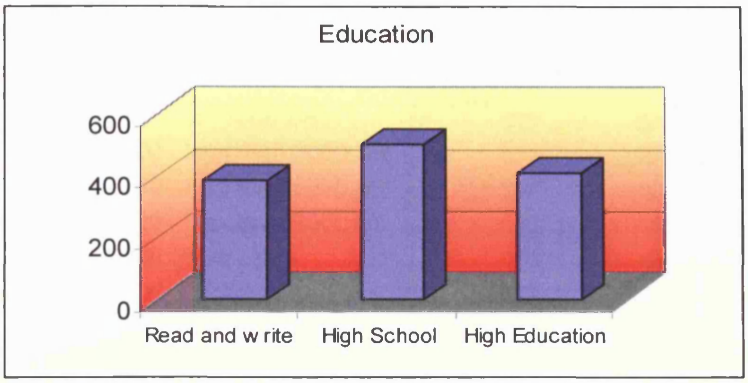
Marital status

	Frequency	Percent
Single	222	17.1
Married	1078	82.9
Total	1300	100.0



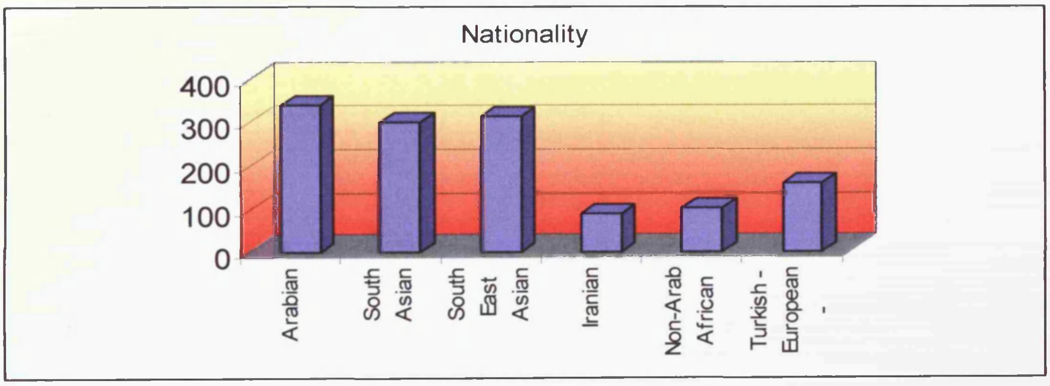
Education

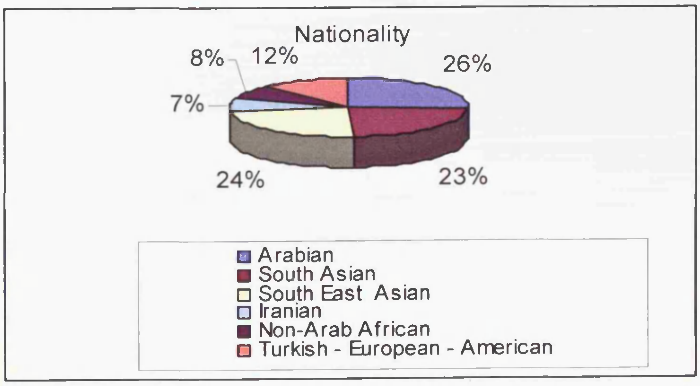
	Frequency	Percent
Read and write	385	29.6
High School	505	38.8
High Education	410	31.5
Total	1300	100.0



Nationality

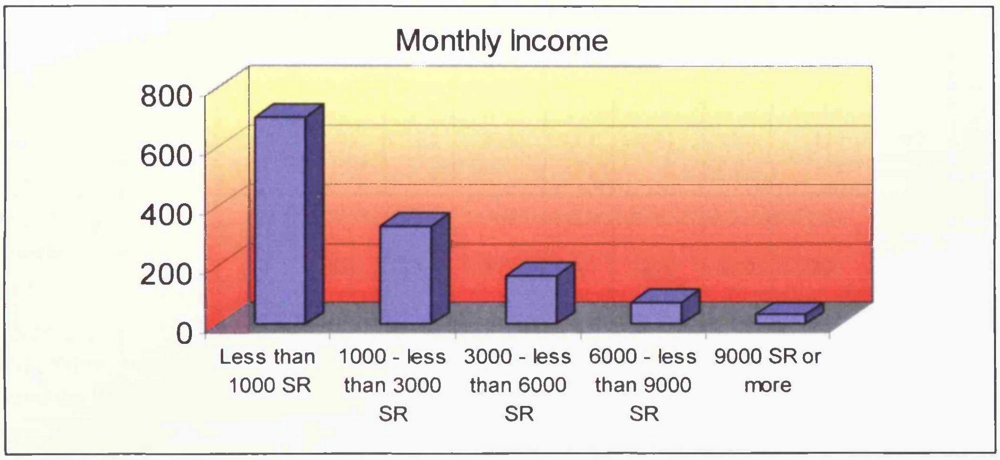
	Frequency	Percent
Arabian	340	26.2
South Asian	299	23.0
South East Asian	312	24.0
Iranian	89	6.8
Non-Arab African	100	7.7
Turkish - European - American	160	12.3
Total	1300	100.0





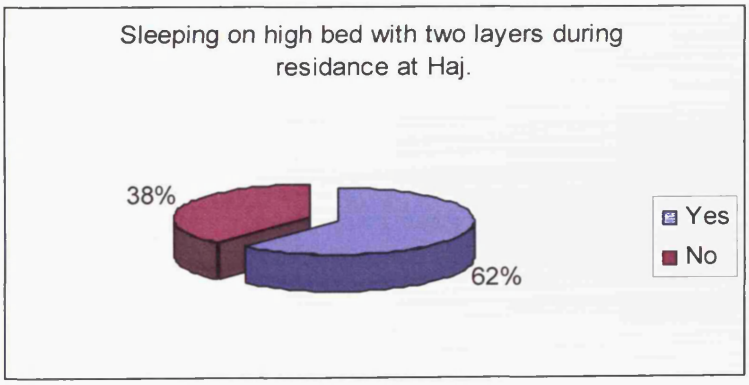
Monthly Income

	Frequency	Percent
Less than 1000 SR	699	53.8
1000 - less than 3000 SR	331	25.5
3000 - less than 6000 SR	164	12.6
6000 - less than 9000 SR	73	5.6
9000 SR or more	33	2.5
Total	1300	100.0



Sleeping on high bed with two layers during residance at Haj.

	Frequency	Percent
Yes	802	61.7
No	498	38.3
Total	1300	100.0



	Absolutely Disagree	Disagree	Neutral	Agree	Completely Agree	Mean	Interval	Ra

	Absolutely Disagree		Disagree		Neutral		Agree		Completely Agree		Mean	Interval	Ra
	Freq	%	Freq	%	Freq	%	Freq	%	Freq	%			
Comfortable tent	242	18.6	416	32.0	210	16.2	382	29.4	50	3.8	2.68	Neutral	
Crowded tent	53	4.1	346	26.6	270	20.8	406	31.2	225	17.3	3.31	Neutral	1
Own enough privacy in the tent	87	6.7	348	26.8	562	43.2	272	20.9	31	2.4	2.86	Neutral	
Bad ventilation in the tent	149	11.5	368	28.3	456	35.1	286	22.0	41	3.2	2.77	Neutral	
Feeling very hot inside the tent during day	109	8.4	300	23.1	573	44.1	276	21.2	42	3.2	2.88	Neutral	
Feeling very cold inside the tent during night	121	9.3	307	23.6	560	43.1	258	19.8	54	4.2	2.86	Neutral	

Comfortable tent

	Absolutely Disagree		Disagree		Neutral		Agree		Completely Agree		Mean	Interval	F
	Freq	%	Freq	%	Freq	%	Freq	%	Freq	%			
Arabian	71	20.9	173	50.9	50	14.7	29	8.5	17	5.0	2.26	Disagree	
South Asian	15	5.0	38	12.7	31	10.4	203	76.9	12	4.0	3.53	Agree	
South East Asian	51	16.3	95	30.4	80	25.6	84	26.9	2	0.6	2.65	Neutral	
Iranian	1	1.1	3	3.4	28	31.5	41	46.1	16	18.0	3.76	Agree	
Non-Arab African	66	66.0	30	30.0	2	2.0	2	2.0	0	0.0	1.4	Completely Disagree	
Turkish-European-American	38	23.8	77	48.1	19	11.9	23	14.4	3	1.9	2.23	Disagree	

Crowded tent

	Absolutely Disagree		Disagree		Neutral		Agree		Completely Agree		Mean	Interval	R
	Freq	%	Freq	%	Freq	%	Freq	%	Freq	%			
Arabian	15	4.4	301	9.1	73	21.5	132	38.8	89	26.2	3.73	Agree	
South Asian	13	4.3	213	71.2	18	6.0	46	15.4	9	3.0	2.41	Disagree	
South East Asian	21	6.7	87	27.9	107	34.3	88	28.2	9	2.9	2.93	Neutral	
Iranian	0	0	5	5.6	7	7.9	28	31.5	49	55.1	4.36	Completely Agree	
Non-Arab African	0	0	0	0	10	10.0	56	56.0	34	34.0	4.24	Completely Agree	
Turkish-European-American	4	2.5	10	6.3	55	34.4	56	35.0	35	21.9	3.68	Agree	

Own enough privacy in the tent

	Absolutely Disagree		Disagree		Neutral		Agree		Completely Agree		Mean	Interval	Rar
	Freq	%	Freq	%	Freq	%	Freq	%	Freq	%			
Arabian	37	10.9	112	32.9	169	49.7	16	4.7	6	1.8	2.54	Disagree	4
South Asian	16	5.4	76	25.4	97	32.4	102	34.1	8	2.7	3.03	Neutral	3
South East Asian	9	2.9	59	18.9	139	44.6	94	30.1	11	3.5	3.13	Neutral	2
Iranian	14	15.7	23	25.8	49	55.1	3	3.4	0	0	2.46	Disagree	5
Non-Arab African	0	0	61	61.0	33	33.0	6	6.0	0	0	2.45	Disagree	6
Turkish-European-American	11	6.9	17	10.6	75	46.9	51	31.9	6	3.8	3.15	Neutral	1

Bad ventilation in the tent

	Absolutely Disagree		Disagree		Neutral		Agree		Completely Agree		Mean	Interval	Rank
	Freq	%	Freq	%	Freq	%	Freq	%	Freq	%			
Arabian	15	4.4	31	9.1	73	21.5	132	38.8	89	26.2	3.73	Agree	3
South Asian	13	4.3	213	71.2	18	6.0	46	15.4	9	3.0	2.41	Disagree	6
South East Asian	21	6.7	87	27.9	107	34.3	88	28.2	9	2.9	2.93	Neutral	5
Iranian	0	0	5	5.6	7	7.9	28	31.5	49	55.1	4.36	Completely Agree	1
Non-Arab African	0	0	0	0	10	10.0	56	56	34	340	4.24	Completely Agree	2
Turkish-European-American	4	2.5	10	6.3	55	34.4	56	35.0	35	21.9	3.68	Agree	4

Feeling very hot inside the tent during day

	Absolutely Disagree		Disagree		Neutral		Agree		Completely Agree		Mean	Interval	Rar
	Freq	%	Freq	%	Freq	%	Freq	%	Freq	%			
Arabian	49	14.4	45	13.2	203	59.7	28	8.2	15	4.4	2.75	Neutral	4
South Asian	8	2.7	173	57.9	32	10.7	78	26.1	8	2.7	2.68	Neutral	5
South East Asian	15	4.8	55	17.6	113	36.2	114	36.5	15	4.8	3.19	Neutral	1
Iranian	28	31.5	3	3.4	58	65.2	-	-	-	-	2.34	Disagree	6
Non-Arab African	0	0	7	7.0	93	93.0	0	0	0	0	2.93	Neutral	3
Turkish-European-American	9	5.6	17	10.6	74	46.3	56	35.0	4	2.5	3.18	Neutral	2

Feeling very cold inside the tent during night

	Absolutely Disagree		Disagree		Neutral		Agree		Completely Agree		Mean	Interval	Ra
	Freq	%	Freq	%	Freq	%	Freq	%	Freq	%			
Arabian	64	18.8	72	21.2	170	50.0	27	7.9	7	2.1	2.53	Disagree	
South Asian	5	1.7	163	54.5	45	15.1	79	26.4	7	2.3	2.73	Neutral	
South East Asian	22	7.1	53	17.0	114	36.5	91	29.2	32	10.3	3.19	Neutral	
Iranian	25	28.1	4	4.5	59	66.3	1	1.11	-	-	2.40	Disagree	
Non-Arab African	0	0	3	3.0	95	95.0	2	2.0	0	0	2.99	Neutral	
Turkish-European-American	5	3.1	12	7.5	77	48.1	58	36.3	8	5.0	3.33	Neutral	

The t -test for Independent Samples

The t -test is the most commonly used method to evaluate the differences in means between two groups. This test was done to compare the opinions according to the sex and the marital status.

Analysis of Variance (ANOVA)

Analysis of variance, or ANOVA, is a method of testing the null hypothesis that several group means are equal in the population, by comparing the sample variance estimated from the group means to that estimated within the groups.

We assume that the data are a random sample from a normal population; in the population, all cell variances are the same.

The One-Way ANOVA procedure produces a one-way analysis of variance for a quantitative dependent variable by a single factor (independent) variable. Analysis of variance is used to test the hypothesis that several means are equal. This technique is an extension of the two-sample t test.

In addition to determining that differences exist among the means, we may want to know which means differ. There are two types of tests for comparing means: a priori contrasts and **post hoc tests**. Contrasts are tests set up before running the experiment and post hoc tests are run after the experiment has been conducted.

The post hoc tests are done only when the null hypotheses of equal means is rejected (that is when the test is significant).

One of the post hoc tests used in our study is the method known as the LSD (Least Significance Difference). This test was done to compare the opinions according to the age, Education, Nationality and Monthly income.

Pearson Chi-square

The Pearson Chi-square is the most common test for significance of the relationship between categorical variables. This measure is based on the fact that we can compute the expected frequencies in a two-way table (i.e., frequencies that we would expect if there was no relationship between the variables).

The value of the Chi-square and its significance level depends on the overall number of observations and the number of cells in the table.

The only assumption underlying the use of the Chi-square (other than random selection of the sample) is that the expected frequencies are not very small. The reason for this is that, actually, the Chi-square inherently tests the underlying probabilities in each cell; and when the expected cell frequencies fall, for example, below 5, those probabilities cannot be estimated with sufficient precision. This test was done to compare the opinions according to sleeping on high bed with two layers during residence at Hajj and all of the demographic variables taken.

Comparing opinions according to the sex

	T	Sig.	Significance
Comfortable tent	.632	.527	Not Significant
Crowded tent	5.363	.000	Significant
Own enough privacy in the tent	-3.092	.002	Significant
Bad ventilation in the tent	-3.774	.000	Significant
Feeling very hot inside the tent during day	-4.272	.000	Significant
Feeling very cold inside the tent during night	-3.698	.000	Significant

Comparing opinions according to the Age

	F	Sig.	Significance
Comfortable tent	2.695	.030	Significant
Crowded tent	8.792	.000	Significant
Own enough privacy in the tent	3.721	.005	Significant
Bad ventilation in the tent	2.094	.079	Not Significant
Feeling very hot inside the tent during day	1.891	.110	Not Significant
Feeling very cold inside the tent during night	2.351	.052	Not Significant

The LSD tests explain the differences for the comfortable tent as follow:

1) age less than 30 years and age from 50 to less than 60
2) age 30 to less than 40 years and age from 50 to less than 60

The LSD tests explain the differences for the crowded tent as follow:

1) age less than 30 years and both age from 40 to less than 50 and age from 50 to less than 60
2) age 30 to less than 40 years and both age from 50 to less than 60 and 60 years or more
3) age 40 to less than 50 years and 60 years or more

The LSD tests explain the differences for the Own enough privacy in the tent as follow:

1) age 30 to less than 40 years and age from 40 to less than 50
2) age 40 to less than 50 years and both age from 50 to less than 60 and 60 years or more

Comparing opinions according to the Marital Status

	t	Sig.	Significance
Comfortable tent	-3.404	.001	Significant
Crowded tent	1.020	.308	Not Significant
Owen enough privacy in the tent	-.561	.575	Not Significant
Bad ventilation in the tent	1.949	.051	Not Significant
Feeling very hot inside the tent during day	-.391	.696	Not Significant
Feeling very cold inside the tent during night	-.207	.836	Not Significant

Comparing opinions according to the Education

	F	Sig.	Significance
Comfortable tent	3.692	.025	Significant
Crowded tent	3.611	.027	Significant
Owen enough privacy in the tent	3.666	.026	Significant
Bad ventilation in the tent	2.264	.104	Not Significant
Feeling very hot inside the tent during day	3.929	.020	Significant
Feeling very cold inside the tent during night	2.474	.085	Not Significant

The LSD tests explain the difference for the comfortable tent as follow:
read and write and high school

The LSD tests explain the difference for the crowded tent as follow:
high school and high education

The LSD tests explain the differences for the Own enough privacy in the tent as follow:

1) read and write and high school
2) high school and high education

The LSD tests explain the difference for the feeling very hot inside the tent during day as follow:
read and write and high school

Comparing opinions according to the Nationality

	F	Sig.	Significance
Comfortable tent	119.646	.000	Significant
Crowded tent	120.437	.000	Significant
Owen enough privacy in the tent	30.173	.000	Significant
Bad ventilation in the tent	67.054	.000	Significant
Feeling very hot inside the tent during day	21.293	.000	Significant
Feeling very cold inside the tent during night	30.136	.000	Significant

The LSD tests explain the differences for the Comfortable tent as follow:

1) Arabian with south Asian, south east Asian, Iranian and non-Arab African
2) South Asian with south east Asian, non-Arab African and Turkish – European and American
3) South East Asian with Iranian, non-Arab African and Turkish – European and American
4) Iranian with non-Arab African and Turkish – European and American
5) non-Arab African and Turkish – European and American

The LSD tests explain the differences for the crowded tent as follow:

1) Arabian with south Asian, south east Asian, Iranian and non-Arab African
2) South Asian with south east Asian, Iranian, non-Arab African and Turkish – European and American
3) South East Asian with Iranian, non-Arab African and Turkish – European and American
4) Iranian with Turkish – European and American
5) non-Arab African and Turkish – European and American

The LSD tests explain the differences for the own enough privacy in the tent as follow:

1) Arabian with south Asian, south east Asian, with Turkish – European and American
2) South Asian with Iranian and non-Arab African
3) South East Asian with Iranian, non-Arab African
4) Iranian with Turkish – European and American
5) non-Arab African and Turkish – European and American

The LSD tests explain the differences for bad ventilation in the tent as follow:

1) Arabian with South Asian, South east Asian, Iranian, non-Arab African and Turkish – European and American

2) South Asian with south east Asian, Iranian, non-Arab African and Turkish – European and American
3) South East Asian with Iranian
4) Iranian with non-Arab African and Turkish – European and American

The LSD tests explain the differences for the feeling very hot inside the tent during day as follow:

1) Arabian with south east Asian, Iranian and Turkish – European and American
2) South Asian with south east Asian, Iranian, non-Arab African and Turkish – European and American
3) South East Asian with Iranian and non-Arab African
4) Iranian with non-Arab African and Turkish – European and American
5) non-Arab African and Turkish – European and American

The LSD tests explain the differences for the feeling very cold inside the tent during night as follow:

5) Arabian with south Asian, South east Asian, non-Arab African and Turkish – European and American
6) South Asian with south east Asian, Iranian, non-Arab African and Turkish – European and American
7) South East Asian with Iranian
8) Iranian with non-Arab African and Turkish – European and American
9) non-Arab African and Turkish – European and American

Comparing opinions according to the Monthly Income

	F	Sig.	Significance
Comfortable tent	2.101	.078	Not Significant
Crowded tent	3.284	.011	Significant
Owen enough privacy in the tent	9.540	.000	Significant
Bad ventilation in the tent	4.243	.002	Significant
Feeling very hot inside the tent during day	6.590	.000	Significant
Feeling very cold inside the tent during night	3.523	.007	Significant

The LSD tests explain the differences for the crowded tent as follow:

1) The monthly income less than 1000 SR with the monthly income form 6000 to less than 9000 SR
2) The monthly income form 3000 to less than 6000 SR with the monthly income form 6000 to less than 9000 SR

The LSD tests explain the differences for the own privacy in the tent as follow:

1) The monthly income less than 1000 SR with the monthly income form 1000 to less than 3000 SR, from 3000 to less than 6000 SR and from 6000 to less than 9000 SR
2) The monthly income form 1000 to less than 3000 SR with the monthly income from 3000 to less than 6000 SR and from 6000 to less than 9000 SR

The LSD tests explain the differences for the bad ventilation in the tent as follow:

1) The monthly income less than 1000 SR with the monthly income from 3000 to less than 6000 SR
2) The monthly income form 1000 to less than 3000 SR with the monthly income from 3000 to less than 6000 SR

The LSD tests explain the differences for feeling very hot inside the tent during day as follow:

1) The monthly income less than 1000 SR with the monthly income from 3000 to less than 6000 SR
2) The monthly income form 1000 to less than 3000 SR with the monthly income from 3000 to less than 6000 SR

The LSD tests explain the differences for feeling very cold inside the tent during night as follow:

1) The monthly income less than 1000 SR with the monthly income from 3000 to less than 6000 SR
2) The monthly income form 1000 to less than 3000 SR with the monthly income from 3000 to less than 6000 SR
3) The monthly income form 3000 to less than 6000 SR with the monthly income 9000 SR or more

Sleeping on high bed with two layers during residence at Hajj

1) Sex

Crosstab

Count

		Sleeping on high bed with two layers during residance at Haj.		
		Yes	No	Total
sex	Male	696	413	1109
	Female	106	85	191
Total		802	498	1300

The Fisher Exact test show that the p-value (sig.) = 0.035 which means there is a significant difference between male and female according to Sleeping on high bed with two layers during residence at Hajj.

2) Age

Crosstab

Count

		Sleeping on high bed with two layers during residance at Haj.		
		Yes	No	Total
age	Less than 30 years	135	63	198
	30 to less than 40	320	198	518
	40 to less than 50	134	93	227
	50 to less than 60	123	84	207
	60 or more	90	60	150
Total		802	498	1300

The Chi square test show that the p-value (sig.) = 0.304 which means there is no significant difference between age categories according to Sleeping on high bed with two layers during residence at Hajj.

3) Marital status

Crosstab

Count

		Sleeping on high bed with two layers during residance at Haj.		Total
		Yes	No	
Marital status	Single	151	71	222
	Married	651	427	1078
Total		802	498	1300

The Fisher Exact test show that the p-value (sig.) = 0.019 which means there is a significant difference between single and married according to Sleeping on high bed with two layers during residence at Hajj.

4) Education

Crosstab

Count

		Sleeping on high bed with two layers during residance at Haj.		Total
		Yes	No	
Education	Read and write	237	148	385
	High School	303	202	505
	High Education	262	148	410
Total		802	498	1300

The Chi square test show that the p-value (sig.) = 0.481 which means there is no significant difference between education categories according to Sleeping on high bed with two layers during residence at Hajj.

5) Nationality

Crosstab

Count

		Sleeping on high bed with two layers during residance at Haj.		Total
		Yes	No	
Nationality	Arabian	182	158	340
	South Asian	215	84	299
	South East Asian	183	129	312
	Iranian	65	24	89
	Non-Arab African	70	30	100
	Turkish - European - American	87	73	160
Total		802	498	1300

The Chi square test show that the p-value (sig.) = 0.000 which means there is a significant difference between nationalities according to Sleeping on high bed with two layers during residence at Hajj.

6) Monthly Income

Crosstab

Count

		Sleeping on high bed with two layers during residance at Haj.		Total
		Yes	No	
Monthly Income	Less than 1000 SR	441	258	699
	1000 - less than 3000 SR	206	125	331
	3000 - less than 6000 SR	95	69	164
	6000 - less than 9000 SR	38	35	73
	9000 SR or more	22	11	33
Total		802	498	1300

The Chi square test show that the p-value (sig.) = 0.307 which means there is no significant difference between nationalities according to Sleeping on high bed with two layers during residence at Hajj.

Moderator Guides for Pilgrims

1. **Gender**

   Male ☐ Female ☐

2. **Age:** .... Years.

3. **Marital Status:**

   Single ☐ Married ☐ Divorced ☐

4. **Education:**

   Read and write ☐ High school ☐
   Diploma ☐ Higher Education ☐

5. **Nationality:** ....

6. **Monthly Income:**

   Less than SR1,000 ☐ SR1,001-3,000 ☐
   SR3,001-6,000 ☐ SR6,001-9,000 ☐
   Over SR9,000 ☐

Shall we start our discussion now? It will take about an hour.

1. What are your first impressions when you get into the tent?
2. How did you find the space availability in terms of size and privacy: and Why?
3. Do you think that double layer bed system is a good idea?
4. If you Hajj journey were during the summer, do you think air conditioning is necessary?
5. How do you assess the current air conditioning system?
6. Are you satisfied with the safety within the camp? If not, why?
7. What did you not find, what did you expect before coming here?
8. If you have the chance to give an advice to the director of this project, what advice would you give?
9. Finally, if there anything that you came across which you wanted to say that you did not have the chance to say?

Thank you for your co-operation.

Moderator Guides for Motawefs

Shall we start our discussion now? It will take about an hour.

1. Are you satisfied with these kinds of structures? If not, why?
2. What do you think are the problems which are caused by the size of the unit and the area available?
3. How can the construction influence your job in terms of the time and ability?
4. During the Hajj time, do you feel it is easy to offer the pilgrims all the services? If not, why?
5. Do the materials of the tents cause any problems? If so, what are they?
6. If you have a change to change any component of this structure, what are you going to change? And why?
7. If you got a new unit suitable for 20 pilgrims, how long do you expect you need to build it up? And what do you think the minimum numbers of workers that it needs to be built?
8. Finally, is there anything that you came wanting to say that you did not get a chance to say?

Thank you for your co-operation.

Pilgrims' Accommodation Structures Questionnaire

I. Please, state your group

1. Gender:

Male ☐ Female ☐

2. Age:

Less than 30 years ☐ 31-40 years ☐ 41-50 years ☐
51-60 years ☐ Over 60 Years ☐

3. Marital Status:

Single ☐ Married ☐

4. Education:

Read and write ☐ High school ☐ Higher Education ☐

5. Nationality

Arab ☐ South Asia ☐ South east Asia ☐
Non-Arab African ☐ Turkey/Europe/America ☐

6. Monthly Income:

Less than SR1,000 ☐ SR1,001-3,000 ☐
SR3,001-6,000 ☐ SR6,001-9,000 ☐
Over SR9,000 ☐

II. Please, indicate your feeling by ticking the relevant box:

	Not at all	A little bit	Moderately	Quite a lot	Very Much
1. The tent is comfortable	☐	☐	☐	☐	☐
2. The tent is crowded	☐	☐	☐	☐	☐
3. In the tent, I have enough privacy	☐	☐	☐	☐	☐
4. In the tent, the ventilation is bad	☐	☐	☐	☐	☐
5. I feel the tent is too hot during the day	☐	☐	☐	☐	☐
6. I feel the tent is too cold at night	☐	☐	☐	☐	☐

III. Please, tick one of the boxes below:

Do you accept to sleep on a double layer bed during your stay at Menna?
Yes ☐ No ☐