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Composition Possibilities of Transformable Structures within an Islamic Architecture Context

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Abstract

This research aims to reveal the composition possibilities of transformable structures within an Islamic architectural context. Transformable structures are structural compositions with mechanical components (e.g., joints) that can achieve multiple form variations in order to fit functional, environmental, or aesthetical spatial requirements, such as retractable roof structures.

Despite the mechanical characteristics of these structures, they have been successfully utilized to achieve compositions that respond to their context and reflect their culture, such as the transformable tents of the Prophet's Mosque in the KSA, which is inspired by the Bedouin tents.

The research investigated five precedents in the Arab counties; The study found that the compositions of these structures were based exclusively on only two typologies: the foldable tensile fabric structures and movable spatial frame ones. So, why these only two typologies of such structures were commonly used, however, there are other typologies that can achieve Islamic compositions?

Therefore, the study investigated the typologies of transformable roof structures to explore the other forms of these structures that can possibly be utilized within an Islamic architecture context. The study found that pantographic, reciprocal and tensegrity structures can achieve the required compositions, however they were rarely used in architectural applications. Therefore, the study performed a critical review of these three typologies of structures in terms of their composition possibilities, applicability, and feasibility; then, the study revealed the advantages and disadvantages of each typology. Finally, this research presents the outcomes of the study and highlights the applicability of the other possible form variation of transformable structures to achieve spatial compositions within Islamic architecture context.

Keywords

Transformable Architecture – Deployable Structures – Islamic Perforations – Spatial-bar structures

1 Introduction

1-1 Transformable Structures in the Arab world

Transformable solutions in architecture have been utilized in various applications and building components such as moveable walls/partitions, kinetic facades, and retractable roof structures. The research focuses on transforming the roof structure that can be achieved either by moving or folding its components [1]. Transforming the roof structure is mainly utilized to convert an indoor space to an outdoor environment, and mostly employed to cover courtyards and stadiums.

In the Arab world, there are remarkable examples that employed the possibilities of transformable roof structures such as the umbrella-like structures of Prophet's Mosque in Madina, KSA (figure 1), which were designed by SL-Rasch and installed in the mosque's courtyard in 1992 and its outdoor piazza in 2011 [2]. Another example is the umbrella shades of the Al-hussein mosque, Cairo, Egypt (figure 3), which were also designed by SL-Rasch and installed in 2000 [2]. Both examples are considered umbrella-like foldable tensile fabric structure [3].

Other precedents employed retractable tent structures which are folded to their perimeter. For instance, the foldable tent of the Quba Mosque in Madina, KSA (figure 4), which is supported by cables and wires, also designed by SL-Rasch, and installed in 1987 [2]. Another instance, the foldable roof structure of Albayt Football Stadium in Al Khor, Qatar (figure 6), designed by Dar Al-handasah and opened in 2021. The outer fixed structure of the stadium looks like a tent supported by cables and space grid steel structure, and the retractable part is a foldable tent supported by moveable steel trusses supported by two steel girders on the perimeter of the roof opening [4]. All these examples are based on forms of tent structures and were claimed to reflect the Arab culture as they have the features of Bedouin tents [2].

The transformable roof precedents in the Arab world are not only limited to the forms of fabric structures, but there are also a number of precedents with rigid lightweight structures (e.g., steel). For instance, the moving domes of the Prophet's Mosque in Madina, KSA, designed by SL-Rasch and installed in 1992(figure 2) [2]. Each moveable dome is composed of a steel frame supported by four wheels on the beams of the mosque's structure; its exterior cladded with carbon and glass fibre laminated epoxy and ceramic tiles, and its interior cladding is wood and epoxy laminate [2]. the cladding has Islamic features and decorations with floral and geometric patterns.

Another instance, the roof of Hassan II Mosque in Casablanca, Morocco (figure 5) [5], which was designed by Michel Pinseau and opened in 1993. The roof covers a 3400 sqm prayer hall and it is made of cedar wood and covered by cast aluminium tiles. The roof interior has Islamic geometric patterns and follows the Moorish Andalusian style. Both examples can be considered a moveable space-frame structure with linear movement [3].

Figure 1 : The foldable umbrella tents of Madina Mosque, KSA [2].

Figure 2 : The domes of Madina Mosque, KSA [2].

Figure 3 : Al-Hussain Mosque, Cairo, Egypt **[2]**.

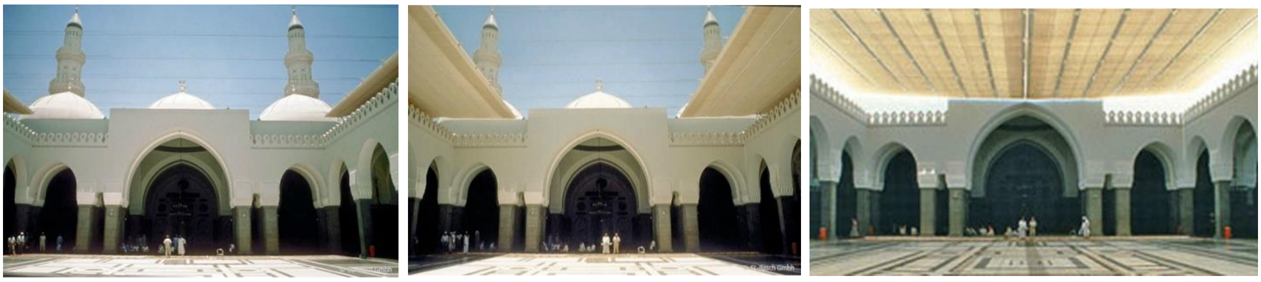
Figure 4 : Quba Mosque, Madina, KSA [2].


Figure 5 : Hassan II Mosque, Casablanca, Morocco [6, 5].

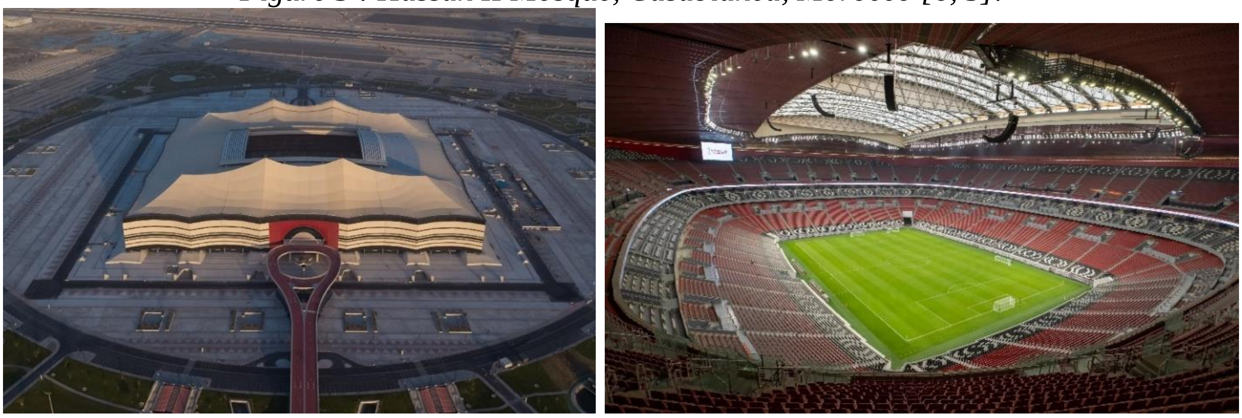
Figure 6 : Al Bayt Stadium, Al Khor, Qatar [4].

1-2 Research Problem

According to precedents examined in the previous section, it can be noticed that the precedents exclusively employed two common typologies of transformable structures, either foldable tent forms (e.g., Madina mosque) or moveable space structure (e.g., the roof of Hasan II Mosque). Despite the possibilities and capabilities of transformable solutions and their ability to achieve more flexible and creative solutions, the design options were limited to the mentioned two typologies.

1-3 Research Aim

The research aims to examine the possible forms of transformable structures and their features and determine their applicability within an Islamic architecture context. Moreover, the research seeks to investigate the advantages and drawbacks of each structural system and determine the cause of employing the common two solutions rather than the other investigated transformable solutions.

1-4 Research Objectives

- Examine the typologies of transformable structures.
- Determine the possible forms and compositions of transformable structures that can be utilized within an Islamic architecture context.
- Evaluate the feasibility and applicability of each possible typology.

1-5 Research Methodology and Structure

The research started by a descriptive review for the transformable structures utilised within Islamic architectural contexts, by examining five precedents of transformable roof structures in the Arab world. Then the research in the following sections investigates the possible forms of transformable structures using an analytical descriptive approach, by studying the classification of moveable and foldable structures. After studying the classification, the typologies that were not employed in the precedents are revealed, then a detailed description with a critical review for these typologies is conducted, to reveal the possibility of each typology and their geometrical ability to achieve Islamic perforations and compositions. The review also reveals the advantages and drawbacks of each transformation typology and its feasibility and applicability.

2 Typologies of Transformable Structures

Transformable structures are considered a sort of kinetic architecture; they are defined as structural systems that can change their forms to achieve multiple spatial configurations for many purposes such as functional (e.g., space saving), or environmental (e.g., shading) purposes [7].

These structures have many typologies and were sorted in many different ways such as the classifications made by C.J. Gantes [8], Felix Escrig [9], Ariel Hanaor [10], Maziar Asefi [11], and Esther Adrover [12].

According to Asefi [11] and former research by the author [13] (figure 7), transformable roof structures can be sorted according to their structural behaviour into two major categories: bending and compression structures, and tensile structures. The first category has two sub-categories, ‘spatial bar’ and ‘spatial frame’ structures. The second category has also two sub-categories, ‘tensile membrane’ and ‘compressive tensile’ structures.

According to the investigation of the precedents, it is noticed that the structures of these precedents can be considered either spatial-frame or tensile membrane structures. The compressive tensile and spatial-bar structures categories are not commonly employed; however, they can have compositions that have the same characteristics of geometrical Islamic patterns.

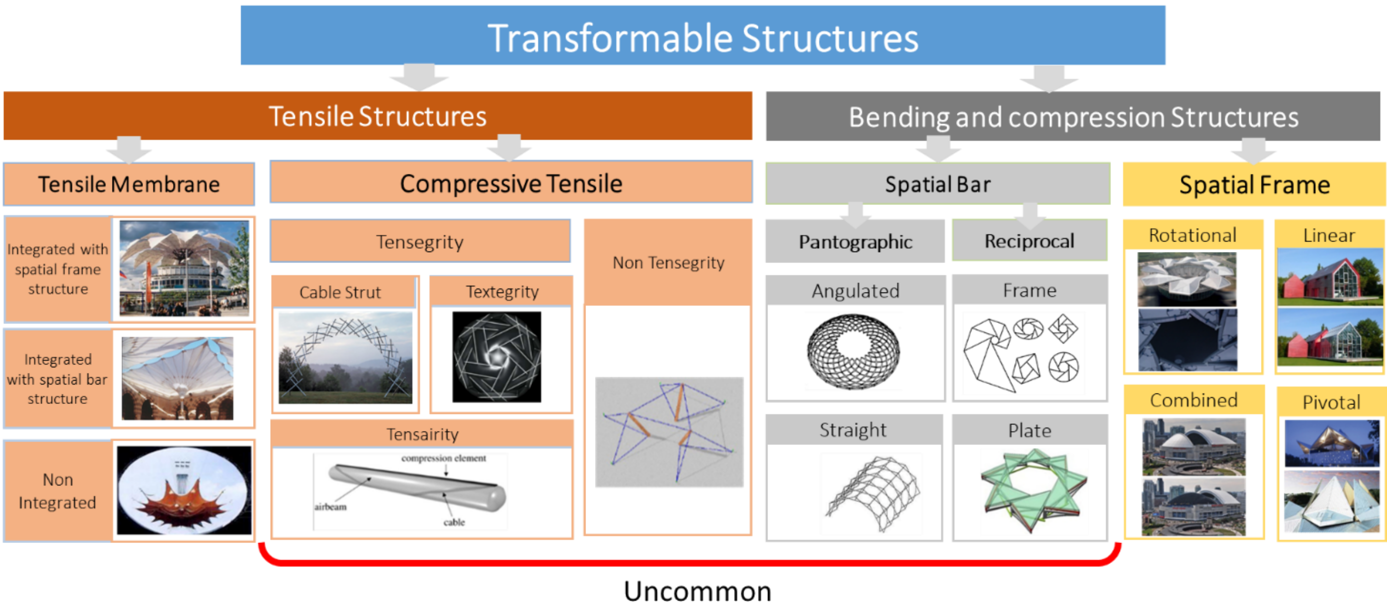

Figure 7 : Classification of transformable structures [13]

3 Possibilities of Transformable Bar Structures.

According to the previous section, it is noticed that the configurations of spatial-bar structures and tension integrated structures can achieve compositions with Islamic features. This section examines the characteristics, features, advantages, and drawbacks of pantographic, reciprocal and tensegrity structures.

3-1 Pantographic Structures

These structures are composed of bars linked by scissor like mechanism, or so-called scissor-like elements (SLE). There are two main typologies of these structures according to the forms of their bars/struts: straight and angulated bars (figure 8).

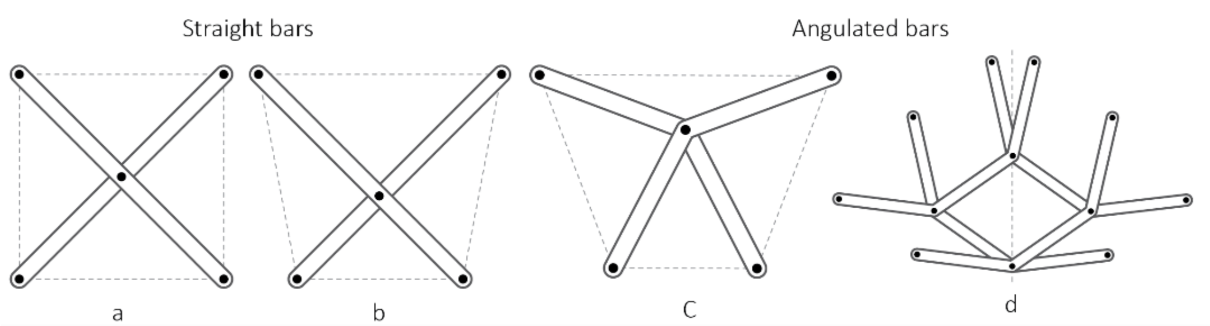

Figure 8 : Typologies of pantographic structures

The SLE units with straight bars have two typologies according to the position of their intermediate joints; the first type has an intermediate joint exactly at the middle point of the bars (figure 8- a), which is mostly employed in linear, flat, or straight surfaces with double layer grids (DLG) (figure 9). The second type's joint is shifted from the mid points (figure 8-b), which is mostly employed in curved surfaces, such as domes and vaults (figure 10 & 11).

INTERNATIONAL JOURNAL OF
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VOLUME 5, ISSUE 2, 2022, 344 – 359.

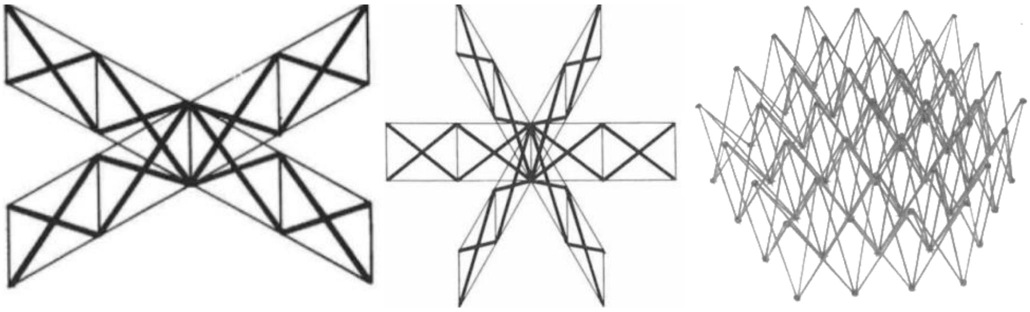

Figure 9 : Linear pantographic structures [14].

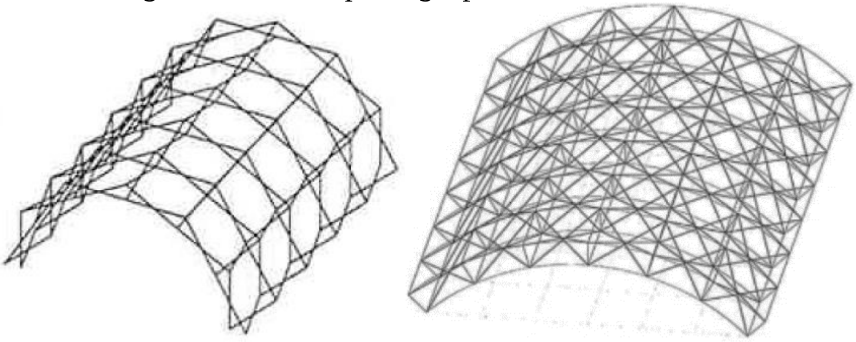

Figure 10 : Cylindrical linear pantographic structures. [3, p. 19].

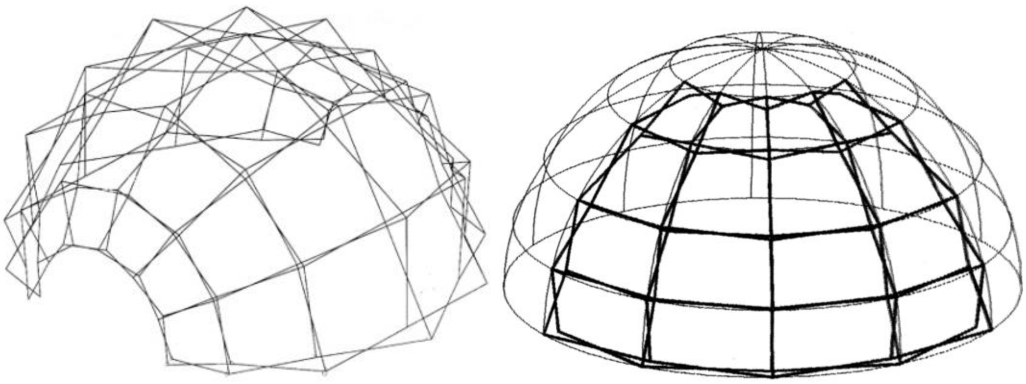

Figure 11 : Two configurations of the linear pantographic structures for hemispherical geometries. [3, p. 22].

According to Pellegrino [15], pantographic structures with straight bars cannot transform if its bars they were placed in a closed loop (e.g., closed flat circle). Additionally, the curved surfaces made by straight bars cannot maintain their original form while they are transformed (i.e., from expanded to compacted). Therefore, pantographic structures with angulated bars were invented to solve these issues, as they can achieve a smooth movement and maintain their forms throughout the transformation process (figure 12).

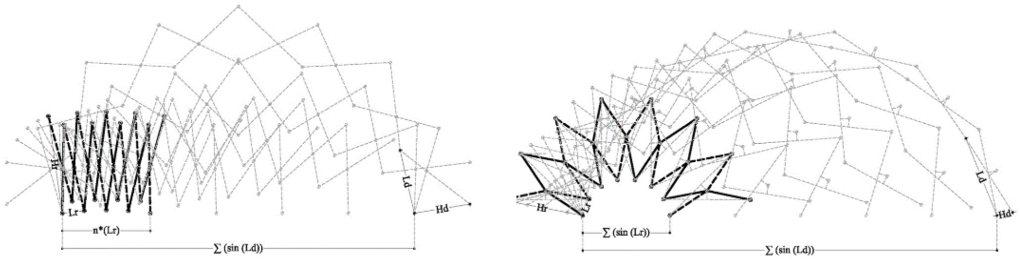

Figure 12 : The transformation behaviour of straight and angulated bar structures. [16]

The pantographic structures with angulated bars have two typologies: First, scissor mechanisms with single-angulated bars and a single intermediate joint (figure 8-c), which can have multiple forms of structures such as hyperbolic or polyhedral surfaces (e.g., Hoberman sphere) (figure 16). Second, multi-angulated bars with multiple intermediate joints (figure 8-d), which can be employed to make single-layer grid (SLG) dome-like structures, which can be transformed inwards-outwards their centres by rotating or pushing their elements.

Pantographic structures have the same characteristics of space grid structures; they can offer wide span transformable roofs and have multiple form variations. These structures have also diverse applications, for instance, prosthetic limbs [17]. Moreover, Pantographic structures can be covered by a wide selection of materials such as fabrics and foldable plates of rigid materials (e.g., sandwich panels).

Additionally, pantographic structures that have primitive forms (e.g., sphere) can be fabricated by duplicates of modular elements (i.e., scissor like elements) which enables mass production of these structures, and accordingly reduce their production cost.

In terms of composition, according to figures 14 & 15, pantographic structures can have forms that looks like stars of Islamic patterns such as eight- or twelve-point stars [18], that can be applied either in building facades, roof, or canopy structures.

INTERNATIONAL JOURNAL OF
ARCHITECTURAL ENGINEERING AND URBAN RESEARCH
VOLUME 5, ISSUE 2, 2022, 344 – 359.

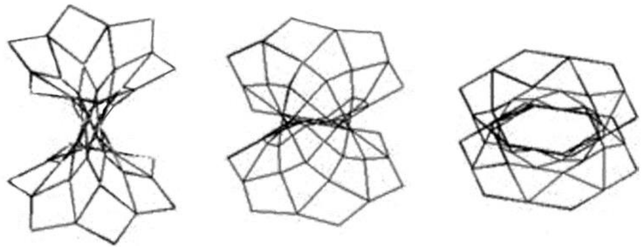

Figure 13 : Deployable hexagonal hyperboloid [19, 20]

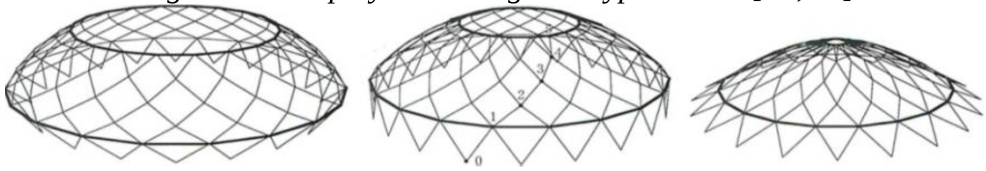

Figure 14 : multi-angulated spherical SLG structure, the movement occurs by pushing the bars inwards/outwards [21].

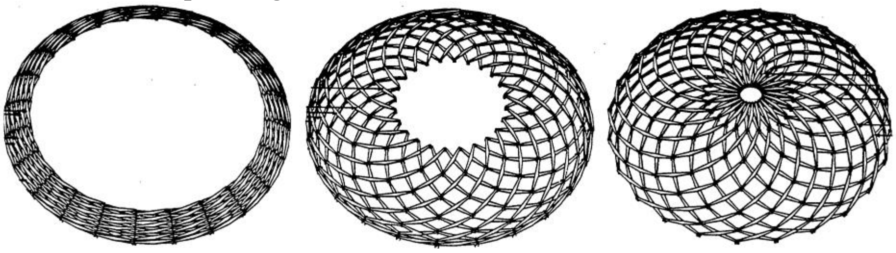

Figure 15 : Schematic drawing for Hoberman's iris dome, the transformation occurs by rotating the SLG untriangulated bars [22].

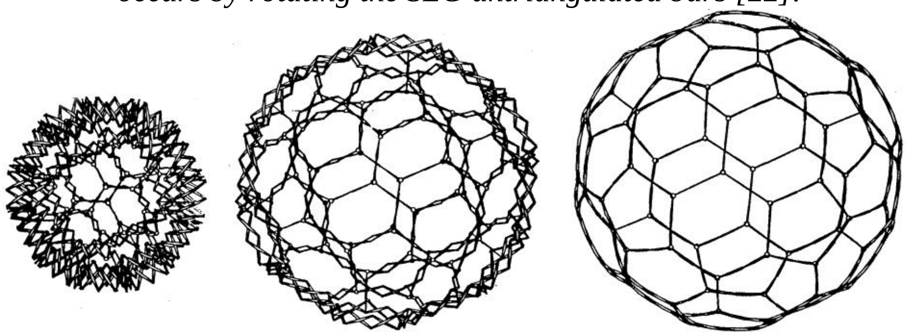

Figure 16 : Expandable sphere by Hoberman [22].

Despite the possibilities of pantographic structures, they have many issues. First, they have complex structural compositions that requires complex mathematical and geometrical calculations which makes the design (e.g., kinematic design) and evaluation (e.g., structural simulations) processes of these structures is challenging. Second, despite the modularity of these structures, they have multiple components of bars and joints that increase the complexity of the construction process and reduce the durability and lifespan of the structure. Therefore, such structures require regular maintenance to increase their lifespan which accordingly increase their life cycle cost [11].

3-2 Reciprocal Structures

This type of structures is composed of a set of linear elements or plates, at least three, that are mutually supported on each other (figure 17) [23]. The outer end of each element is supported by the structure's perimeter, the inner end is supported on an adjacent element without the necessity of having an inner support. Reciprocal structures can have mostly three configurations: single unit, multiple units or integrated (figure 17). Moreover, such structures can be transformed either by folding of its grids or rotation of its elements (i.e., bars or plates) (figure 18) [11].

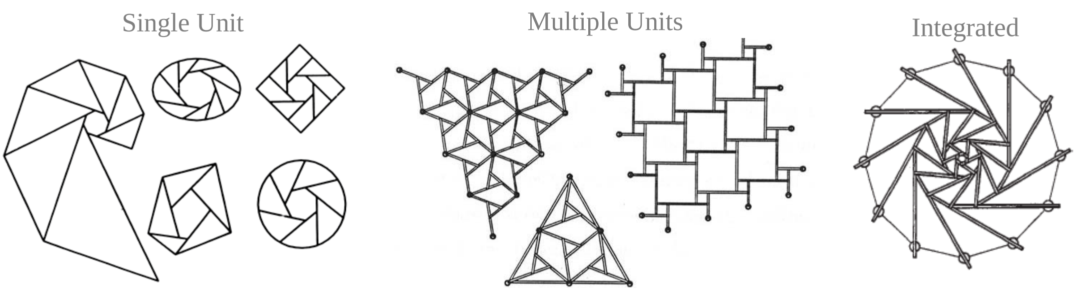

Figure 17 : layouts of reciprocal structures [23]

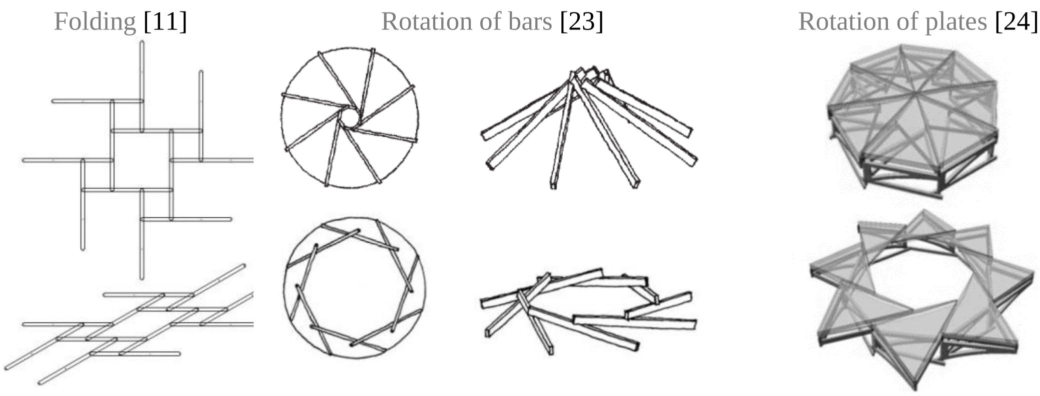

Figure 18 : the forms of transforming reciprocal structures.

In terms of composition, reciprocal structures share similarities with Islamic Mafrooka patterns (i.e., kite chase patterns), and can be employed in roof structures with foldable bars or plates according to the design requirements.

Reciprocal structures can have multiple form variations and can cover diverse building layouts. They are also simpler, more reliable and cost efficient than pantographic structures [11]. Additionally, they can be fabricated in modular or foldable grids, which can ease their fabrication and transportability.

INTERNATIONAL JOURNAL OF
ARCHITECTURAL ENGINEERING AND URBAN RESEARCH
VOLUME 5, ISSUE 2, 2022, 344 – 359.

Unfortunately, Reciprocal structures have some design limitations, as the structure should have a fixed perimeter to support the while structure system. Additionally, the structure is totally dependent on each other, this can cause issues in its reliability, a failure in one element can cause a total collapse of the structure.

3-3 Tensegrity Structures

Tensegrity structures, or so-called cable-strut structures, are structures that integrate the tension and compression elements. The word tensegrity is composed of two parts, tension, and integrity. These structures depend on the continuity of tension members unlike traditional structures which are dependent on continuity of compression members. That is why Buckminster Fuller [25] described these structures as “islands of compression in an ocean of tension”.

Tensegrity systems have various forms and configuration because they are a modular system composed of basic modules called simplexes [26]. These simplexes have different forms such as triangular, rectangular, pentagonal and icosahedron prisms (figure 20). Moreover, the composition tensegrity modules can have different classes (figure 20) based on the number of connected compression members; a class 2 tensegrity module means the module has joints with two connected compression members [27, 28].

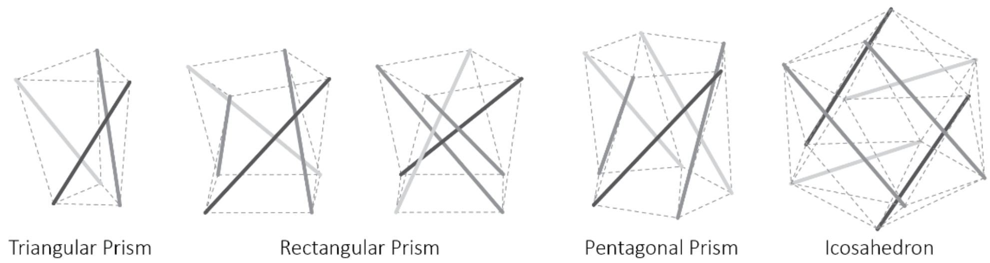

Figure 19 : forms of tensegrity simplexes.

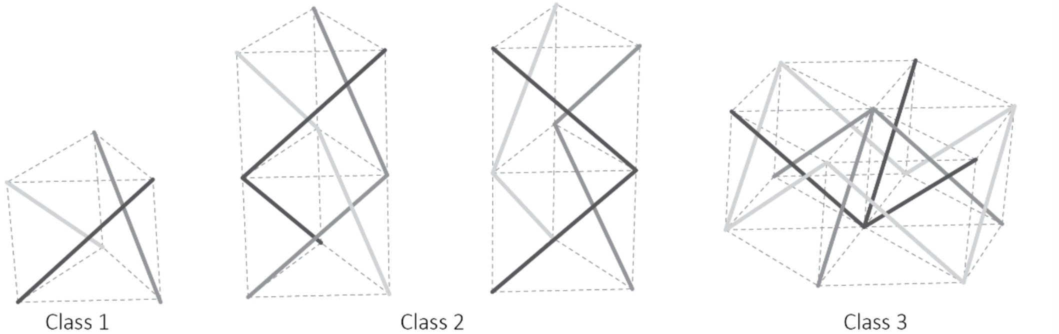

Figure 20 : classes of a tensegrity system

INTERNATIONAL JOURNAL OF
ARCHITECTURAL ENGINEERING AND URBAN RESEARCH
VOLUME 5, ISSUE 2, 2022, 344 – 359.

The transformation of a tensegrity structure can be achieved by either controlling the pre-stress state of the structure [29]. This can be achieved by either controlling the tension (i.e., loosen or tighten) of the cables (i.e., tension members), or the length of the struts (i.e., the compression members) (e.g. using linear actuators) or by integrating the actuation of tension and compression members [30]. The folding process can be either in one direction or two directions (figure 21). Other folding techniques were proposed by keeping the modules prestressed states either by rotation, rotation-translation, and shear (figure 22) [31].

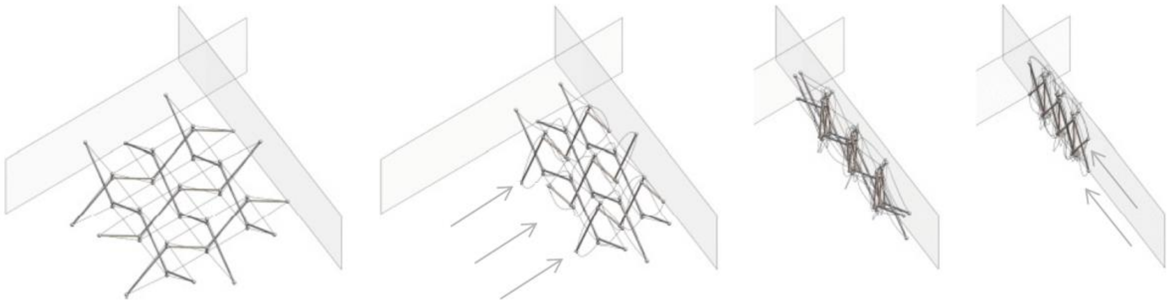

Figure 21 : an example of folding planar class 2 tensegrity systems [30].

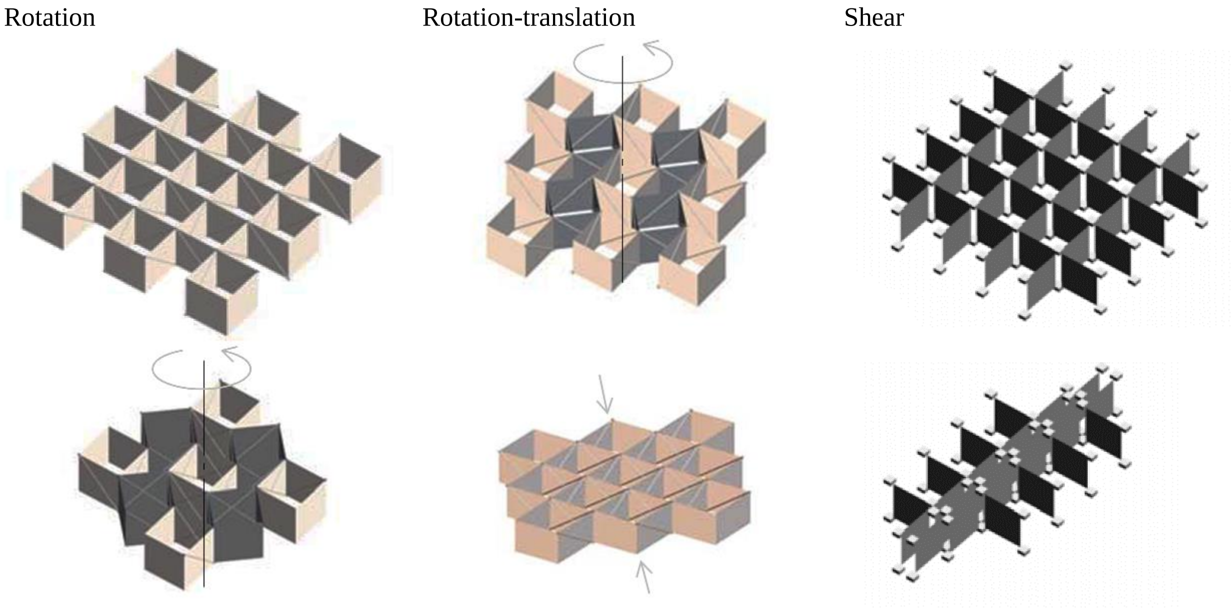

Figure 22 : The transformation of tensegrity structures by keeping their pre-stress state [31]

Tensegrity systems are efficient lightweight structures that can be applied in roofs and canopies. Moreover, transformable tensegrity systems can be more compacted compared to the other two systems. They are also cost efficient and consume less material compared to conventional steel structures, besides their composition of modular elements can enable mass production that ease their manufacturing process. Furthermore, and more resistant to earthquake loads due to their structural integrity [32].

In terms of composition, they can deliver diverse geometrical configurations based on triangular, hexagonal, or octagonal elements that apparently looks like Islamic perforations and patterns such as 8 and 12 pointed stars.

Unfortunately, tensegrity systems have three major issues. First, they are complicated to design, fabricate and assembly. Second, they have major reliability issues; a failure in the tension elements causes a complete structure failure due to the continuity of the tension elements, which is why they are not widely used in architectural applications. Finally, the transformation behaviour of these structures is not easy to control and need complex software and systems to design and predict the stability and consistency of the structure during the transformation process.

4 Discussion & Conclusion

According to the review, Transformable structures were commonly used within Islamic architecture context with two major typologies, tent structures (e.g., umbrellas) and moveable grid structures (e.g., moveable domes).

Although pantographic, reciprocal and tensegrity structures can offer geometrical configurations that can be employed within Islamic architecture context, they may not be utilised because of their complexity of design and fabrication in addition to their reliability issues.

5 Recommendations

Making the designer exposed to the possibilities of kinetic and transformable may help them achieve novel solutions for architectural design problems, and not to be limited to common and repetitive solutions.

Designers should understand the design considerations of transformable structures to define their possibilities and limitations, to achieve realistic and reliable solutions. Transformable solutions may achieve creative forms that may not be reliable nor feasible in architectural applications.

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