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Rapid Deployable Shelter Structure and their Suitability for Defence Applications

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Abstract

Today's battlefield is very dynamic and thus defence equipment is being upgraded at a fast pace. The technical advancement of defence equipment and operation is increasing day by day and that necessitates the shelter structures used for them to be technically advanced. This needs deployment by reducing time for command post, tactical operations centre, communications center and surgical support station in remote and combat areas. The present study explains basic requirements of rapid deployable shelter structure for defence applications and explains the available design concepts of shelter structure. The suitability of these designs to defence applications is analysed with the help of TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method and ranked based on the outcome. The analysis based on this method shall be highly useful in selecting the shelter structure for a particular application.

Keywords

TOPSIS, Rapid deployable structures, Product design concept, MADM, Defence

Introduction

A deployable structure is the transformation of the structure from compact form into a predetermined expanded form through some safe and stable mechanism, wherein it can sustain load in stable condition [1]. It is widely used in civil, architecture, aerospace and space structure with multiple applications such as morphing structures, foldable antennas, temporary shelters, bridges etc. The evaluation of complete deployed configuration of a structure is necessary to examine its architectural functions [2]. The main challenge in the design of deployable structure is to confirm their reliability in stiffness and function [3]. Research interest on the deployable structure started in the late 90s. Merchan [4] submitted his master thesis at the Massachusetts Institute of Technology (MIT) describing the classification of deployable structures. This classification consists of two categories, strut-cable structures, and surface structures. Strut-cable structures include the scissor hinge mechanism, sliding mechanism and hinged collapsible mechanism while surface structures include inflatable or pneumatic structures, folded structures, and telescopic ones. After a decade of Merchan's work, Gantes [5] submitted his PhD Thesis "A design methodology for deployable structure" at MIT and described a new type of deployable structure that is stable and stress free in both deployed and folded configuration. He classified structures as earth-based structures and structures for space applications. Earth based structures are further classified as pantographs, two-dimensional panels, cable and membrane structures, pneumatic structures, tensegrities, and retractable roofs. Hanor and Levy [6] done the most common categorization of deployable structures based on their morphology and their kinematic behaviour. They mentioned two categories, rigid link structures and deformable structures. Rigid link structures include pantographic (scissor structure) and foldable plates structures. On the other hand, deformable structures are classified as strut-cable and tensioned membrane structures. Fenci and Currie [7] and Chai and Tan [8] critically reviewed the deployable structures classifications. Although extensive research on deployable shelter structures has been conducted over the past two decades, prime requirements, and applications of these types of structures for defence purposes are rarely discussed. Therefore, this work investigates the key requirements and compares the available design through TOPSIS method.

Shelter Structure Requirements and their Weightage

The following principal requirements, as shown in table 1, should be available in the design of the shelter structure to make it completely suitable for defence purposes. In the presented work, weightage to each criterion and rating to each design are given based on mutual consultation of the authors.

Table 1: Structure requirements and their weightage.

Sr. No.	Requirement	Weightage
1	Lightweight and Portability	0.20
2	Modularity	0.20
3	Textile integration and Compatibility	0.15
4	Fast and Easy erection	0.20
5	Sturdy and Robust	0.15
6	Durability	0.05
7	Mass producibility	0.05

Suitable Design of Shelter Structures

Though many authors characterized deployable structures based on different criteria, the concepts which are suitable to develop shelter structures are only few such as are Air inflated structures, Strut-cable structures, Scissor like element structures and Origami inspired structures (Figure 1).

Air inflated structure

These are air supported structures. There are mainly two types of air inflated structure, Air bubble tent and air beam supported tent. In Air bubble tents, structural stability depends on the pressure difference between the atmosphere and pressure developed internally in the fabric bubble with the help of external source. Since there is no internal support frame, the internally developed pressure defines the overall shape of the structure. In the case of Air beam tents, they offer a great degree of transport flexibility and reduction in weight as compared to metallic frame structures. In place of metallic frames, Air-inflated beams support the air beam structure. Hpping [9] developed Automated Command Post for Defence application. Verge [10] presented a comprehensive study of different types of air beam structures.

Strut-cable structure

Strut-cable systems come under deformable structures category of flexible link structures [6]. The basic unit of these

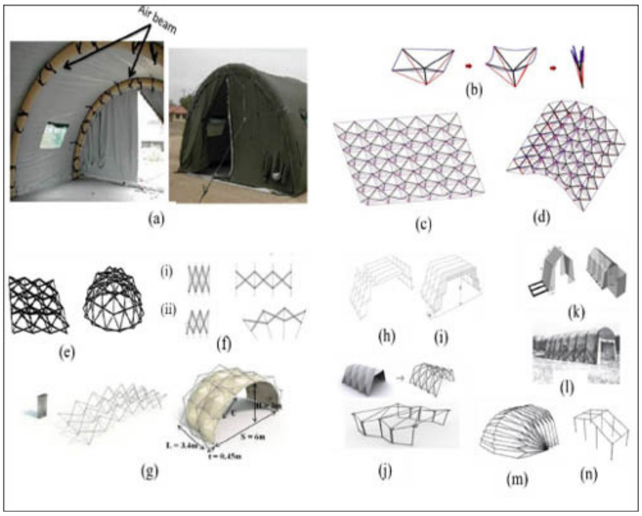

Figure 1: (a) Small tactical Air beam shelter [10], **(b)** Folding process of a CP unit, **(c)** Planar truss system, **(d)** Barrel vault system [12], **(e)** Flat and Curved configuration of SLEs structure [5], **(f) (i)** Translational and **(ii)** Polar Scissor element, **(g)** Shelter structure composed of Translational and Polar SLEs [15] Origami inspired plate structure, **(h)** Decomposed form, **(i)** Composed form (W: width and H: height for single module) [20], **(j)** Transformation of plate type into bar type origami inspired structure [21], **(k)** Modular rigid wall structure [22], **(l)** Soft wall accodian shelter, **(m)** Rigid wall accodian shelter [23], and **(n)** Modular frame with self-resetting lock mechanism [25].

types of structures is a crystal cell pyramid (CP) that consists of two pyramids with same top polygon. Wang and Li [11] stated that the strut-cable structures have higher structure efficiency than the conventional space trusses. Cai et al. [12] developed the prototype of barrel - vault strut cable structure based on the CP unit concept.

Scissor like elements structures

The basic structural unit of these type of structures is scissor like element (SLE) which contains two straight bars, hinged at the center point or other than center with a pivotal connection and hinged at their end nodes to end nodes of other SLEs. Gantes et al. had done the detailed analysis of flat and curved geometrical configuration and presented geometrical constraints for flat configuration [14]. Koumar et al. analyzed the deformation behaviour and stress distribution in the scissor element [15]. Mira et al. developed a prototype of a structure based on this concept [16]. They also optimized SLE to get universal element [17]. Maden et al. reviewed the planar scissor structure mechanism, geometric principle, and design methodology [18].

Origami inspired structures

Origami is ancient paper folding art, originated in Japan. In this art, sheet of paper is folded along the straight line. There are multiple folds to compact the structure in small and tight configuration. These folds are designed in such a way that in full erection of the structure, it fulfils its architectural aim. Mousanezhad et al. [13] described the analytical method for modular construction of origami inspired closed loop unit. Curletto and Gambarotta [14] presented a novel and efficient parametric design approach for a rigid thin plate structure. Temmerman et al. [15] transformed the kinematic and folding behaviour of a triangular plate origami structure into bar type structure. Foldable plate type structure connects along their edge and allows the structure to fold. Thrall et al. [16] has a US patent of a Modular rigid wall deployable structure having four panel connected to each other at edges. Thrall and Quaglia [17] also reviewed the origami inspired soft wall and rigid wall accordion shelter. Bzorgi [24] have a US patent on a foldable hinged wall structure. Brain et al. [18] designed a modular frame that consists of a number of joints with self-resetting lock mechanism.

Suitability of these Designs to Defence Application and TOPSIS Ranking

The suitability of the prescribed design concepts is examined based on the requirements of ideal rapid deployable shelter. Since there are seven attributes or requirements to select and develop the best possible shelter structure, it requires a multi attribute decision-making (MADM) method to compare all design concepts. TOPSIS is one of the most popular and widely used MADM techniques to rank the given alternatives [26]. The steps of classical TOPSIS are shown below:

Step 1: Creation of Decision Matrix and define the weight of criteria

Let A = a_{ij} be a decision matrix W = [w_1, w_2, w_3…w_n] are a weight criterion, where, $a_{ij} \in$ R, $w_j \in$ R and $w_1 + w_2 + w_3 \ldots + w_n = 1$

Step 2: Normalized Decision Matrix elements n_{ij}

$$n_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^{2}}}$$

Step 3: Weighted Normalized Decision Matrix elements (x_{ij})

$x_{ij} = w_j n_{ij}$ for i = 1, 2, ..., m; j = 1, 2, ..., n

Step 4: Identification of positive ideal solution (D^+) and negative ideal solution (D^-)

$$D^+ = (x_1^+, x_2^+, \ldots, x_n^+) = ((_i \max x_{ij} \mid j \in I), (\min x_{ij} \mid j \in J))$$

$$D^+ = (x_1^+, x_2^+, \ldots, x_n^+) = ((_i \min x_{ij} \mid j \in I), (\max x_{ij} \mid j \in J))$$

Where, I denotes benefit criteria and J denotes cost criteria for i = 1, 2, ..., m; j = 1, 2, ..., n

Step 5: separation measures from positive ideal solution (S_i^+) and negative ideal solution (S_i^-)

$$S_i^+ = \sqrt{\sum_j^n (x_{ij} - x_j)^2}\ ;\ S_i^- = \sqrt{\sum_j^n (x_{ij} - x_j)^2}\ ,$$

i = 1, 2, ……, m

Step 6: Relative closeness values C_i to the positive ideal solution

$$C_i = \frac{s_i^+}{s_i^+ + s_i^-}$$

Step 7: Ranking of the alternatives based on their relative closeness value

The first step of the TOPSIS analysis is creating a decision matrix that shows the rating value of each criterion for each design and the weight for each criterion. The criteria that maximize the performance are known as benefit criteria while those that maximize the cost known as cost criteria. For benefit criteria, higher value is better but for cost criteria, lower value is better. Since many criteria are expressed in different units, the second step develops the normalized decision matrix to represent the attributes in dimensionless form by using any of the available normalization schemes. In the third step, each element of a particular design alternative row is multiplied with the weight of respective column criterion which results weighted normalized decision matrix. The fourth step identifies the positive ideal solution by taking the highest value among all benefit criteria and lowest value among all cost criteria. While for negative ideal solution, the lowest value among all benefit criteria and highest value among all cost criteria is identified. The fifth step measures the separation of each design alternative from the positive ideal solution and negative ideal solution by calculating the standard deviation. In the sixth step, relative closeness of each design alternative to positive ideal solution is calculated. The seventh and last step ranked the alternatives based on their relative closeness value.

All the qualitative criteria are described using linguistic variables and rated on a 1 - 6 number scale (Table 2). The decision matrix (Table 3) is developed based on table 1 and table 2. The design criteria C1, C2, C3, C4, C5, C6, and C7 are Lightweight and Portability, Modularity, Textile integration and Compatibility, Fast and Easy erection, Sturdy and Robust, Durability, Mass producibility respectively. The designs D1, D2, D3 and D4 are Air inflated structure, Strut-cable structure, SLE structure, and origami inspired plate and bar structure respectively.

In this way, the order preference of the designs is achieved i.e., Scissor like element structure (D3), Air inflated structure (D1), Strut-Cable structure (D2), and Origami inspired plate and bar structure (D4) as shown in table 4.

Conclusions

According to the prescribed study, following conclusions

Table 2: Scale of ratings for qualitative criterion.

Scale	Rating
Satisfactory	1
Good enough	2
Good	3
Fairly Good	4
Very Good	5
Excellent	6

Table 3: Decision matrix.

Weight	0.2	0.2	0.15	0.2	0.15	0.05	0.05
Criteria / Design	C1	C2	C3	C4	C5	C6	C7
D1	6	3	6	6	2	6	5
D2	5	4	4	3	5	4	5
D3	4	5	4	5	5	5	6
D4	4	5	1	4	6	5	6

Table 4: Relative closeness to positive ideal solution.

Design	Relative Closeness to positive ideal solution	Rank
D1	0.60266	2
D2	0.48700	3
D3	0.61018	1
D4	0.42912	4

are drawn:

- The ideal design of the shelter structure must be aimed to get large constructive height, space application, transportability, high rigidity, lightweight, compactness, reusability and thus grasping the sustainability concept.
- TOPSIS method, used in present study, is an effective tool to analyze the main four design concepts found in the literature, suitable for shelter in defence applications. First, second, third, and fourth ranked designs are Scissor like element structures (D3), Air inflated structures (D1), Strut-Cable structures (D2), and Origami inspired plate and bar structures (D4) respectively.
- The two top ranked designs, SLE structures (D3) and Air inflated structures (D1), have the highest and almost equal relative closeness value. The greater suitability of these two designs is due to their high rating for high weighted criteria. The highest rated criteria (very good and excellent scale) for SLE structures (D3) are Modularity, Fast and Easy erection, Sturdy and Robust, Durability, Mass producibility. While in the case of Air inflated structures (D1) highest rated criteria are Lightweight and Portability, Textile integration and Compatibility, Fast and Easy erection, Durability, Mass producibility.
- The first and second ranked design has almost equal closeness value. Though both the designs, Scissor like element structure (D3) and Air inflated structure (D1) are suitable for defence purposes, there is still a scope to develop a new design or to modify them for better performance.

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None.

Conflict of Interest

The authors declare no conflict of interest that are relevant to the content of this article.

Credit Author Statement

Divyansh Dwivedi: Conceptualization, Methodology, Data acquisition, Analytical study, Writing - original draft preparation, Writing - review and editing; Vidya Shankar Pandey: Methodology, Writing - review and editing; Jitendra Nath Srivastava: Methodology, Writing - review and editing, Supervision. All the authors read and approved the manuscript.

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