IOP Conference Series: Earth and Environmental Science

Review on deployable structure

Review on deployable structure

T J Chai[1,3], **and C S Tan**[2]

[1]Jabatan Pendidikan Politeknik & Kolej Komuniti, Aras 5, Galeria PjH, Jalan P4w, Persiaran Perdana, Presint 4, 62100 Wilayah Persekutuan, Putrajaya.
[2]School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor.
[3]Corresponding author: tjchai7607@gmail.com

Abstract. In construction industries, deployable structure has the capability to transform the structures components into predetermined configurations, safe and designated final known direction to achieve their architectural function. This construction technique provides ease of transportation and erection, more space and rapid completion time. This review aims to provide an overview of current potential deployable structure and system towards prefabrication modular construction application to overcome space and transportation limitation. This paper reviews the principle, application, characteristics, types and classification and design consideration of the deployable structures. Based on the literature reviewed, the deployable structure with simple folding configuration principle in linear direction is practical in application. Beside, the strength and stiffness of deployable structure depends on the proper design, material quality, elements thickness, dimension, joint rigidity and deployment technology. However, shape and direction of movement for deployable structure elements need to be determined in the initial stage to minimize the design failure. The findings from this review will contribute to the transformation of prefab volumetric construction practice to solve the limited space and transportation constraints issues.

1. Introduction

Deployable structures can be defined as folded construction made of plates or sticks by their relationship in space [1]. This type of construction technique enable the structure to transform and capable for adapting in alter circumstances and fulfil functional requirements such as space, transportation limitation, etc due to their shape geometry, materials, mechanical properties, deployment with kinematic behavior and the adaptability to change external climate factors to improve the indoor climate performance of the building [2, 3, 4, 5, 6].

The current design and construction of deployable structure are aimed to achieve more constructive height, space application, transportable, ease of deployment, greater rigidity, lightweight, re-compactness, reusable and thus embracing the concept of sustainability [1, 2]. Therefore, this construction technique has been used since the twentieth century in the civil engineering application associated with the development of reinforced concrete technology [1, 3]. However, not many constructions such as prefab construction apply this construction to achieve more constructive space and ease transportable issue [7]. Due to this, the prefab deployable modules with mobility will be the alternative solution.

This paper reviews the available deployable structure system, application, classification and design consideration. It is hope that the deployable structure principle will achieve the construction productivity, space, rapid, efficient and sustainable delivery environment. This paper is expected to benefits the prefab modular players in Malaysia to achieve the transformation of Malaysia construction industry in line to solve the space and transportation limitation.

2. Deployable structure

Deployable structure is the transformation of structures by using mechanisms to achieve their changing circumstances such as shape or function [4]. According to [1], the term deployable structure defines a folded form of construction. This type of structures is spatial structures system formed by the elements in the plane and different in form [1]. The deployable shape is mechanism which provides the structure mobility to deploy from compact configuration to larger expanded state [8, 9].Their final expanded configuration must be evaluated to execute its architectural function such as shelter [4].

2.1 Deployable structure application

Folded structures is an inspiration for engineers in the fields of civil engineering, architecture, biotechnology, medicine, space engineering and other technical applications [10, 11] including timber structure and construction[12]. The availability of numerical and robotics technologies since 21th century has pushed the advanced transformable structures applied in civil engineering and architecture [3]. In the applications of deployable structure, the primary importance are their potential for compact storage, transportability, easy erection and dismantling and outweighs the limitations imposed by the need for complex design and detailing, which are necessary to achieve deployability[9]. According to [9], the applications of space deployable structures main challenge remains to ensure high reliability in deployed geometry, stiffness and function. In engineering field, deployable structures take inspiration from, or are directly derived from origami folding to increase stiffness at minimal expense of weight[13].

In civil engineering, the application of deployable structures can be in various structural elements in the principle of deployable structures such as bridges, retaining walls and etc. According to [14], the application of deployable structure in civil engineering is potentially interesting structure. The principle of greater stiffness of individual constructive element, by the introduction of deployable form has been found to be applied in many consumer products [1]. The famous deployable bridge such as London Tower Bridge can be raised to allow ships to pass underneath as shows in Figure 1[15]. Another iconic and world famous pedestrian deployable bridge at Paddington Basin in London is rolling bridge that curls up to allow boats to pass through the gap as illustrated in Figure 2[2].

Figure 1. London Tower Bridge [15].

(a) Curls up (b) Deploy state (c) Pedestrian bridge

Figure 2. Pedestrian deployable rolling bridge at Paddington Basin, London [2].

While in architectural applications, mobile deployable structures are capable of transforming from a compact small, closed or stowed configuration to a big space, open or deployed configuration to perform their architectural function such as emergency shelters for disaster relief, maintenance facilities, exhibition and recreational structures[4]. These are typically small to medium scale applications which allow portability, ease and faster erection at site. Beside, this principle also increase in strength with aesthetic appeal for architectural applications[14]. A wide range of structural systems have been used for mobile deployable structures such as scissor or pantographic structures, deployable tensegrity, origami structure, foldable membrane structures and more recently tensairity [4]. According to [16], the non-singular, rigid foldable typology has a high potential to be applied in architectural field due to it easily realized with rigid panels and hinges and structure can be stabilized by fixing the supports.

2.2 Deployable structure principle and classification

A deployable structure requires the whole structural system or at least some of its elements to be able to change their geometry by using mechanism where their deployment is definitely related to a morphological variation of the structure[9]. The deployable structure principle of simple fold is originated from a sheet of paper fold along a straight line in linear direction and known as the ancient Japanese art of paper folding called “Origami”[17, 18]. This folding concept apply one side of the sheet is free to rotate with respect to the other side along the folding line[17].

The main reason for recent interest in deployable structures has been their potential application in space technologies and limited size for transportation constraints [1, 6, 19]. The construction in low gravity environment is quite difficult, so some space structures such as shelters are designed as deployable assemblies for easier access and transportation purposes. The materials used for deployable structure components will influence the structure capacity, possible form and their application [1].

In principle, deployable structures can be classified based on their deployable mechanism on structural components such as Rigid Component Deployable and Deformable Component Deployable [2, 18]. These two main types are an initial point to create an assembly of typologies which include classes and subclasses with the potential for architecture and design [2]. Another approach is concentrates on movement and form inspired by various sources originated through conceptual principles under Generative Technique such as origami, paper pleat techniques, and biological systems phenomenology [2, 18]. According to [2], there are others new structural typologies such as Flexible Deployable and Combined Deployable.

Space-based deployable structures can be categorized into three primary classes where articulated structure with rigid members contain sliding contact joints or are folded at hinge points and pivot to deploy, often locking into place normally adopt in building construction. This type of structure is shown in the example of deployable container house as in Figure 3.

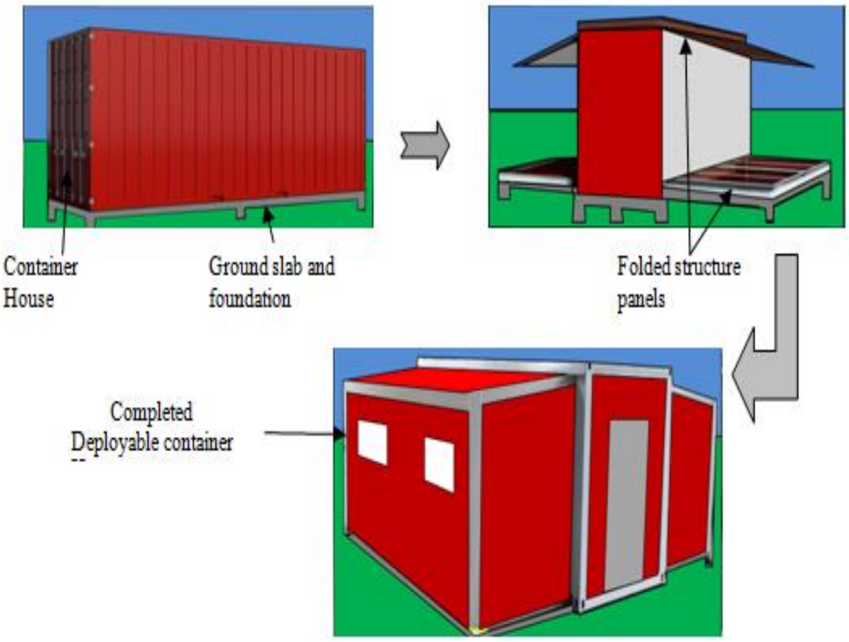
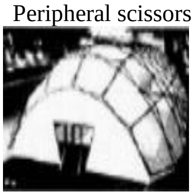
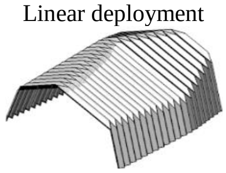
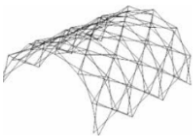
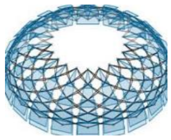
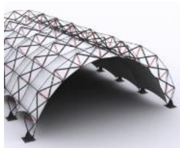
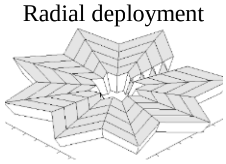


Figure 3. Deployable shipping container house with incorporating a mechanism.

The most common classification of deployable structural system is based on their morphology and their kinematic behaviour by Hanaor and Levy[20]. The morphological properties refer to building mean height, volume, number of faces, ground surface area, facades surface area, roof surface area, envelope surface area, type of roof, envelope surface area to ground surface area complexity, envelope surface area to total volume complexity and total volume to number of faces complexity[21]. The majority uses some sort of structural mechanism to provide the necessary transformation as in Fig. 4 [4, 9, 20].

<table>
<tr><td></td><td></td><td colspan="4">Morphology(Form, shape or structure)</td></tr>
<tr><td rowspan="7">Kinematics(features or properties of motion in object)</td><td></td><td colspan="3">Lattice</td><td>Continuous</td></tr>
<tr><td rowspan="6">Rigid links</td><td>Discs-Large(DLG)</td><td>Short Linear Glucan (SLG)</td><td>Spine</td><td>Plates</td></tr>
<tr><td colspan="3">Pantagraphic(Scissors)</td><td>Folded Plates</td></tr>
<tr><td>Peripheral scissors
</td><td>Angulated scissors
</td><td>Masts and
</td><td>Linear deployment
</td></tr>
<tr><td>Radial scissors
</td><td>Retractable roofs
</td><td>arches
</td><td>Radial deployment
</td></tr>
<tr><td colspan="3">Bars</td><td>Curved surface</td></tr>
<tr><td>Articulated joints</td><td colspan="2">Ruled surface</td><td></td></tr>
</table>

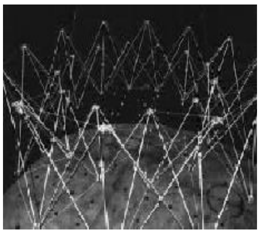
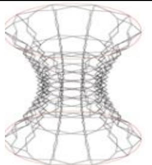
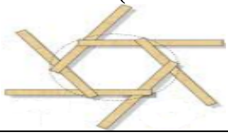
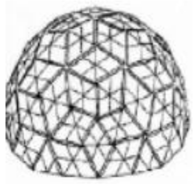
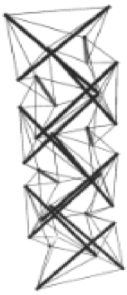
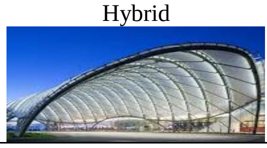
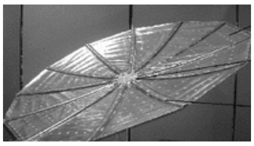
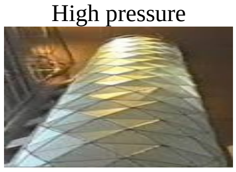
			 Reciprocal Grids (Dismountable) 	
	Deformable	**Strut-cable systems**	**Tensioned membrance**	
		Tensegrity	Fabric	Pneumatic
			Hybrid 	Low pressure 
			Ribbed 	High pressure 

Figure 4. Deployable structural systems classification based on their morphological and kinematic characteristics [4, 9, 20].

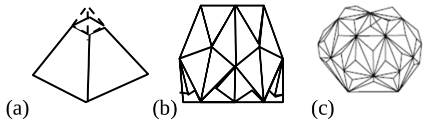
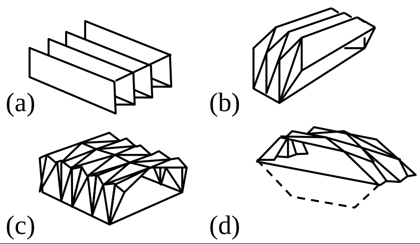
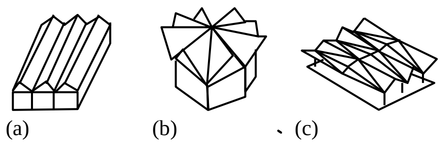
2.3 Deployable structure characteristics, types and design consideration

Deployable structure primarily capable to transform from compact configuration to an expanded configuration. The transformation process can be reversed and repeated. This is achieved by incorporating a mechanism which provides the structure with one or more kinematic degrees of freedom or certain mobility. Thus, it has the capacity to transform from one state or compact configuration to a larger size or space due to transportation constraints, expanded state in which it can fulfil its architectural function such as providing shelter [4, 22, 23]. The design of deployable structures requires solving three problems that are geometrical, mechanical and structural[23]. According to [23], the design of deployable structures falls in the interface between biology, mathematics, art, architecture and engineering. The relations between various disciplines and integrating their potential during the conceptual phase will enhances the design quality and lead to a coherent design[23].

The most direct deployable model refers to rigid facets with linear fold lines and perfect hinges joint. During folding process, the closure of the folded surface consists simply in locking the kinematic degrees of freedom where only relative rotation is allowed along fold lines. The corresponding internal forces which are transmitted along folds are resultants along the whole fold line [17]. According to [8], only resultant which is not transmitted through the fold is an axial torque since it is the internal force working with the hinge rotation. Therefore, internal forces are only resultant along the whole fold line and extremely difficult to determine and describe the actual internal forces react inside the structure [17]. The main advantage of the rigid systems is good shape control while the disadvantages are the complexity of the parts, friction in joints, weight and precision necessity, structures may be costly in parts and assembling [5].

In structural perspective, the shape of deployable structures is the importance parameters since it would affect the transmission of load and direction of relying on folded structures [1, 24]. According to [1], the deployable structures can be divided into three based on their direction of relying such as linear folded plate structure, radial folded plate structure and spatial folded plate structure. The types of deployable structures were summarized in Table 1. The literature review on the design consideration of deployable structure was summarized in Table 2 according to difference authors.

Table 1. Types of deployable structures [1, 24].

Deployable structures based on geometric shape		
Types	Explanation	Shape
Spatial deployable plate structures	• Spatial constructive set is formed by combining mutually the elements of a deployable structure. • (a)Pyramidal folded plate structures, (b)polyhedral deployable plate structures, and (c)combinations.	
Deployable plate frames	• Represent constructional set. Elements of each segment of the folds mutually occupy a frame spatial form. Known as spatial organization of two or more folds in the plane. • (a)Continuous, (b)two hinged, (c)three hinged and (d)deployable plate barrel (cylindrical deployable structures).	
Deployable plate surfaces	• All the highest and lowest points of the elements of the deployable structure belong to two parallel planes. • (a)Linear additions, (b) combinations of additions and (c) radial additions.	

Differences of deployable structures
Geometric form, performance manner, methods of forming stiffness, function and position in the building and material used.

Deployable construction shapes		
Rectangular	Trapezoidal	Triangular

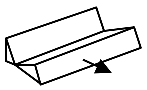
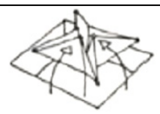
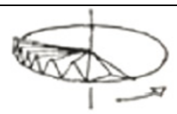
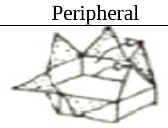
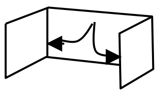
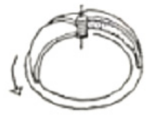
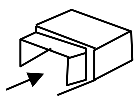
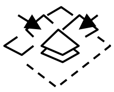
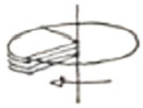
Deployable structure movement matrix				
Types of movement	Direction of movement			
	Parallel	Central	Circular	Peripheral
Folding				
Rotating				
Sliding				

Table 2. Literature review on the deployable structure design consideration.

Design consideration of deployable structure	References
Structure components connectivity. Evaluation on final expanded configuration to achieve architectural function.	[4]
Deployment technology determines the choice. Rigid joints for structures rigidity and flexible assemblies.	[5]
Deployable structure strength and stiffness depends on proper design, material quality, elements thickness and dimension form it.	[1]
Simple fold with mobility is good design approach and build ability. The most efficient solicitation for a folded shape is plane faces. Structures faces thickness is considered if folding required movement. Deployable shape is mechanism.	[17]
Deployable structure rigid surface is common practice to unfold completely a model and remains continuously to ensure the motion of each vertex is compatible to its neighbours	[26, 27]
Quality materials with no high level of dimension change and strength. Emphasize on initial design phase planning.	[25]
The deployable structure performances must be examined from initial, middle to final state to satisfy the kinematic and structural dynamic constraints for design purposes.	[28]
Final expanded configuration to execute its architectural function is evaluated. Consider the relationship between shape geometry, kinematic behaviour, structural performance and other variable such as socio-cultural. Software tools can assist and speed up the design process and simultaneously provide insight to the designer. An interactive design environment can be integrated with analysis components, resulting in direct feedback on the design choices made. Physical scale models and prototypes revealing overlooked design flaws and verifying the digital models.	[29]
The longitudinal pattern was the best pattern for folded plate structures in analysis compared with facet, egg-box and Miura ori origami modules.	[10]
Five design criteria used to determine the temporary shelters for suitable crease pattern, geometry, and material such as easily deformable, comfortable, height, support condition and good material quality.	[30]
In engineering application, folded textured sheet for deployable structure indicates that the dominant mechanics are a result of the geometry rather than the exact material properties.	[31]

3. Discussion

Based on the reviewed findings, the deployable structure has been applied in civil engineering since twentieth century associated with reinforced concrete materials. The latest deployable structure technique has pushed the construction industry towards space-based volumetric construction eliminate development. This construction technique apply one side of the structure element is free to rotate with respect to the other side along the folding line in two possible directions of rotation either mountain or valley folds. The current development of deployable structures on applied materials and connection method has led to the construction realized in steel, timber, glass and others modern transportation limitation.

Deployable structure is primarily capable to transform from compact configuration to an expanded configuration with mobility. The initial planning stage is importance since the deployable structure is designed to their final designated pathway and followed by deployment stage. The deployable structure final expanded configuration must be evaluated to achieve their architectural function [1]. Due to this, it is importance to determine the deployable structure shape and direction of movement in initial design stage. This is because the shape of deployable structures is a mechanism and it will affect the transmission of load and direction of relying of deployable structures [1, 11, 22]. Besides, the materials used must be material with good quality, no high level of dimension changed and have strength to withstand the loads [23].

The good design approach and builds ability of deployable structure is simple fold shape in plane faces with mobility [11]. The design factors must consider the relationship between their shape geometry, kinematic behaviour, structural performance, deployment technology availability and other variable such as socio-cultural. These factors are importance to achieve their final architectural function. In order to produce more efficient and withstand deployable structure, it is important to select the good design approach, quality materials, determine the elements thickness and dimension to form it. All these parameters will affect the deployable structure strength and stiffness. The rigid joints design also important to achieve the deployable structure rigidity and good shape control design.

4. Conclusion

Based on the literature review's findings, there are some conclusions that can be drawn for the studies as stated below;

1.The deployable structure principle is based on the folding concept that apply one side of the structure element is free to rotate with respect to the other side along the folding line.

2.There are several materials that can be used to develop deployable structures such as steel, timber, glass and others modern materials as compared to reinforce concrete.

3.The good design approach of deployable structure is simple fold shape in plane faces linear direction movement with mobility.

4.The design consideration of deployable structure included shape and direction, element thickness and dimension, kinematic behaviour, structural performance, joint rigidity, strength and quality material, deployment technology availability and socio-cultural.

5.The recent interest in deployable structures has been their potential application in space and limited size for transportation constraints. This will be a good construction technique to solve the space and transportation issue for prefab volumetric construction.

5. References

[1] Nenad S, Jelena I S and Jasna C T 2012 Folded structures in modern architecture *Architecture and Civil Engineering*. **10** L16

[2] Esther R A 2015 *Deployable structures* (United Kingdom : Laurence King Publishing Ltd)

[3] Doroftei I and Doroftei I A 2014 Deployable structures for architectural applications – a short review *Applied mechanics and materials.* **658** L 240

[4] Temmerman N D, Alegria M L, Vergauwen H A, Hendrickx and Wilde W P D 2012 Transformable structures in architectural engineering. *WIT Transactions on the built environment*. **124** L468

[5] Gokhan K and Eres S 2009 *Proc. for 4th Int. Conf. on Recent Advances in Space Technologies*(Istanbul :Turkey)

[6] Simon D G 1994 *Deployable structures: concepts and analysis.* (United kingdom: University of Cambridge)

[7] Fred E B, J H Kim and J T Kim 2016 Performance of modular prefabricated architecture:case study-based review and future pathways *Sustainability*. **8** L16

[8] A. Lebee. From folds to structures, a review 2015 *International journal of space structures.* **30** L74

[9] Andrea E Del Grosso and Paolo B 2013 Deployable structures *Advances in science and technology*. **83** L 131

[10] Wojciech G, Jan P and Paulina S 2014 A comparative study of origami inspired folded plates *Procedia engineering*. **91** L 225

[11] Y Nishiyama Y 2012 Miura folding: applying origami to space exploration *International journal of pure and applied mathematics*. **79** L 179

[12] Wojciech G, Jan P and Paulina S 2014 Origami inspired timber structures – construction and numerical modelling. *Annals of Warsaw University of Life Sciences – SGGW Forestry and Wood Technology.* **85** pp 57-61

[13] Maanasa V LȦ and Sri R L R 2014 Origami-innovative structural forms & applications in disaster management *International journal of current engineering and technology*. **4** L 3436

[14] David D 2012 An overview of mechanisms and patterns with origami *International journal of spatial structures*. **27** L14

[15] Tower of London Bridge London and Partners / Britain on view EXPIRES 2018 2016 Greatdays travel group (London:United Kingdom)

[16] Ruud van K, Arjan H and Patrick T 2016 Deployable structures using non-singular rigid foldable patterns *Procedia Engineering.* **155** 388–97

[17] D Mousanezhad, S Kamrava & AVaziri 2017 Origami-based building blocks for modular construction of foldable structures (*Scientific report 7*) (United State;Springer)
[18] Giulia E F & Neil GR C 2017 Deployable structures classification: a review *International journal of space structures*. **32** L130
[19] L J Fei and D Sujan 2013 Origami theory and its applications:a literature review *International journal of humanities and social sciences.* **7** L 233
[20] A Hanaor and R Levy 2001 Evaluations of deployable structures for space enclosures *International journal of space structures*. **16** L 219
[21] Claudio C, Vitor S and Francois G 2009 *Proceedings of the international conference on computational science and its applications Part 1* (Verlag Berlin Heidelberg:Springer) p 205
[22] Wag D, Bond I, Weaver P and Friswell M 2007 Adaptive structures: engineering applications (Chichester: John Wiley & Sons)
[23] S Krishnan 2017 Deployable structures: an interdisciplinary design process *Proceedings of the 2017 ASEE conference and exposition* (Columbus :American Society for Engineering Education 2017).
[24] N Friedman 2012 Investigation of highly flexible, deployable structures: review, modeling, control, experiments and application Budapest University of Technology and Economics (BME) (Budapest : Hungary)
[25] Firdaus B, Prastyatama A Sagara and R N Wirabuana 2017 Deployable bamboo structure project: a building life-cycle report *AIP conference proceedings 1903*(American Institute of Physics :United state).
[26] H Stachel 2017 A kinematic approach to kokotsakismeshes *Comput. Aided Geom. Des.* **27** L 437
[27] W Wu and Z You 2010 Modelling rigid origami with quaternions and dual quaternions *Proc. R. Soc. A Math.Phys. Eng. Sci.* **466** 2155–74
[28] L Dai and F L Guan 2014 Shape-sizing nested optimization of deployable structures SQP *Journal of Central South University* **21** 2915−20
[29] Temmerman N D , K Roovers, L Alegria Mira, A Vergauwen, A Koumar, S Brancart, L D. Laet and M Mollaert 2014 Lightweight transformable structures: materialising the synergy between architectural and structural engineering (*Electronic Materials* vol 136) (United Kingdom :WIT Press) p 20
[30] Monica N and Kaveh A 2017 Origami applications in structural engineering: a look at temporary shelters *Proc. of the 2nd World Congress on Civil, Structural, and Environmental Engineering (CSEE'17)* (Barcelona: Spain/ Avestia) pp 1-8
[31] Mark S and Simon D G 2011 *Origami folding: a structural engineering approach* ed M Yim(Bristol, UK:A.K.Peter's) origami 5 pp 291-304