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Research Article

Experimental Research Using Physical Models for Architecture: Creation and Optimisation of Air-Actuated Kinetic Cushion Structures

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Abstract

This paper presents a brief history about the use of scale model testing by relevant pioneers, and experimental research using physical models to create and optimise air-actuated kinetic cushion structures for architecture. Air-actuated kinetic cushion constructions could improve assembly, erection, and transportation of structures. Analysis and testing on physical models are useful for developing complex structures as it does not require to use simplified hypothesis to reduce mathematical difficulties, and the process of making models sometimes provides insights that were unforeseen. The Structural Combination Matrix (SCM) is created and used as an open-ended system for creating innovative architectural structures. Six elements of the SCM have been modelled and analysed.

Keywords: Experimental Research; Physical Models; Kinetic Structures; Cushion Structures; Architecture.

INTRODUCTION

Experimental research using physical models has been used for centuries to test the structural viability of buildings. They were the architects and engineers' tool for designing before the appearance of structural theory. In scale-model testing there is no need to use simplified hypothesis to reduce mathematical difficulties [1]. Since the 1920s, wind-tunnel testing of models is used for tall buildings and non-standard structures such as shell structures. From the 1960s, due to the development of computers, there has been a decline in physical model testing.

Scale-model testing, in some cases, could just be considered an alternative to simulations. Figure 1 shows a graph created by [2] to explain the relationship between calculus method, computer simulations, and scale models. The conclusion of the graph is that the more complicated the analysis is, the less effective are computer simulations. In the case of the most complex problems (eg. wind loads in shell structures and skyscrapers), scale-model testing is required. However, for simple or standard problems, simulations are the more optimal solution.

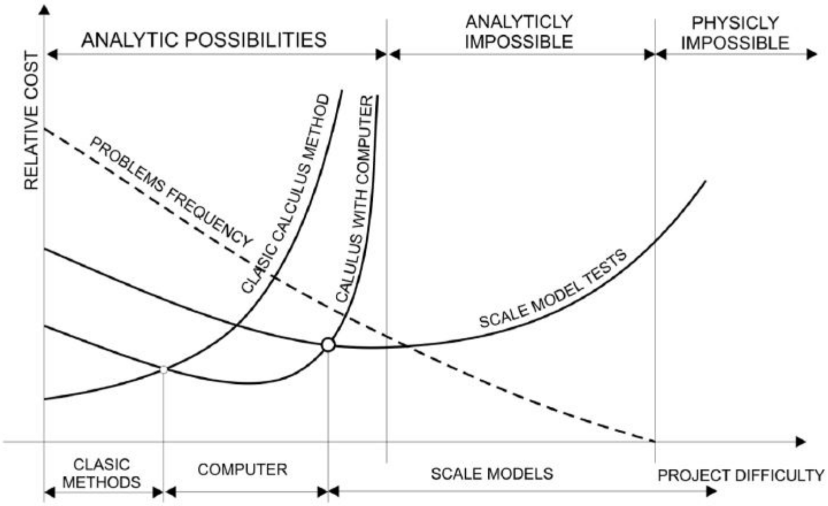


Figure 1. Hossdorf interpretation of the relation between project difficulty (x-axis) and relative cost (y-axis) [2].

For example, tall buildings are designed using as a tool physical model in wind tunnel tests. Calculus method and computer simulations of wind loads are not appropriate for tall buildings because the wind load formulas from codes have been developed mainly for low-rise buildings [3].

When working with physical models, the scale effect should be considered. Galileo Galilei (1564 - 1642) was the first person to realise that scale effects are often non-linear. In 1638, Galileo published the book entitled 'Dialogues Concerning Two New Sciences' where he clarified the scale effect. It is the relationship between length, area, and volume and why objects cannot be of any arbitrary size. The 'Square-Cube Law' states that when an object is scaled up, its area increases by the square of the multiplier while the volume increases by the cube of the multiplier. According to this law, if the size of a scale model would be increased, it is required to increase the strength of the structure or make it lighter to compensate the increasing volume.

RESEARCH METHODOLOGY

The research methodology used is based on previous model-making methodologies. The model-making methodologies of pioneering predecessors from the 19th century to the 21st century have been studied. It includes Antonio Gaudí, Eduardo Torroja, Emilio Pérez Piñero, Pier Luigi Nervi, Buckminster Fuller, Félix Candela, Heinz Isler and Frei Otto. They all have carried out research based on intuition, experimentation using physical models, and analysis by observation to achieve new structural types. Their expertise spanned different subject areas, including design, research, invention of new construction techniques, and knowledge about nature.

Experimental studies are necessary in many structural problems for two reasons: the complexity of the problem for a theoretical approach, and the cost of the analysis.

Furthermore, the process of making models sometimes in itself provides insights that were unforeseen and provides the opportunities for a deeper understanding of the phenomena.

Model-making is assumed to be a tool suite including small scale models, prototyping, and simple calculations and drawings for problem solving and to develop understanding. For example, both Antonio Gaudí and Eduardo Torroja used model making as a methodology to achieve structures of exceptional elegance [4-8]. It included small scale models that were assessed, developed, and improved in future prototypes. Emilio Perez Piñero used to start with concept drawings and simple paper models, later tested in small scale models and finally improved in prototypes before building the final structure.

In history, the research of complex structures such as forms active structural systems (arch structures, cable structures, tent structures and pneumatic structures) and surface-active structural systems (plate structures, folded structures, and shell structures) was based on physical models.

Methodology Background

Antonio Gaudi (1852–1926) is one of the architects most internationally known for using models as a research tool. Gaudí was a Modernist Spanish architect, whose architectural work was influenced by nature. Gaudí's technical innovation was the use of scale models to calculate structures (geometry, forces and element sizes). He used this method in several of his projects such as the church of the Colónia Güell in Barcelona. For this church, Gaudí built a 1:10 scale model with a height of 4 metres in a shed next to the building. He drew the plan of the church in the ceiling of the shed and hung strings loaded with small sandbags, for the weight, from the supporting points of the building such as columns and walls intersections. These weights produced a catenary curve both in the arches and vaults that allowed him to get the inverted profile of the building by photographing the models or looking the inverted system in a mirror placed under the empirical model. The inverted photographs showed the structure, columns and arches, that he was looking for [4]. After that, Gaudí painted over these photographs with gouache or pastel every single detail of the building from architectural details to decoration. Colónia Güell was designed purely based on empirical structural considerations. The shape of the building and the shape of its structural elements were determined under the assumption that the most efficient vaulted masonry structure is attained by adhering as closely as possible to the funicular polygons, internal lines of force, of the loaded structural elements [4].

Gaudí´s design process was based on science of graphic statics. However, when a complicated three-dimensional form was involved, he used scale models to determine the final building shapes. That was the case in the Church of the Sagrada Familia, in which Gaudí worked from 1884 until his death in 1926 [4]. The design approach was like the church of the Colónia Güell based on drawings, models, and photographs. Gaudí's final solution for the Sagrada Familia was based on a long and careful empirical study of inverted loads by means of ropes or cables and graphic calculations. With these models he determined the inclination of the supporting tree-columns and optimised the structural way of carrying the loads to the core [4]. He achieved elements working in compression, and minimised bent elements. The loads of the structure are carried out by the major interior pillars instead of the perimeter buttresses.

Not only have architects used small scale models to understand and analyse structures but also engineers such as Eduardo Torroja have taken advantage of the simplicity that small scale models have for designing shell structures when there was not enough mathematical knowledge to design them. Eduardo Torroja Miret (1899 – 1961) was a Spanish engineer who developed the design, analysis and construction technique of shell structures using a method based on physical models. Eduardo Torroja founded in 1959 the International Association for Shell and Spatial Structures (IASS) whose goal is the achievement of further progress on the field of lightweight structures and shell structures. Between 1940 and 1961, Torroja was the head of the Laboratorio Central de Ensayo de Materiales de Construcción at the Civil Engineering Department of the Technical University of Madrid. A particularly interesting use of models by Torroja is the asymmetric shells for Frontón Recoletos built in Madrid in 1935. Torroja describes the structural behaviour of the shell in his book ´Reason and being of structural types' using a sheet of paper as an example [5]. The roof covered a space 55 meters long by 32.5 meters wide. The shell was reinforced concrete with a thickness of only 8 centimetres.

Nowadays, there is a mathematical background, and shells can be fully calculated without the need of creating models but at the beginning models were the only mean to determine the correct shape of a shell. Shell structures are structures that, due to their shape, offer an optimal load-bearing capacity. They are material-efficient because their form reflects the forces flowing through them. Its qualities, in accordance with the principle of minimum material to withstand the maximum load, have been demonstrated in nature as for example in the seashells, eggshells and bones. Its natural elegance lies in the forms that have been developed based on the supported forces. The first shell structures appeared in the 1920s but only in the 70s the finite element analysis software was created. The construction of shell structures rapidly expanded in the first part of the 20th century, driven by improvements in the concrete and the development of forms associated with famous architects and engineers such as Eduardo Torroja, Felix Candela, Pier Luigi Nervi and Eugène Freyssinet. However, in the latter part of the 20th century, the ratio between wages and material costs increased. Formwork was approximately half of the total cost of concrete shell structures construction costs. It dramatically penalises concrete shell structures compared to other solutions. Since then, steel and glass lattice shells have been designed.

In the summer of 1955, Eduardo Torroja and Fruto Vivas designed The Club Tachira in Caracas, Venezuela. Two shell structures were proposed, one of steel and the other in reinforced concrete. The reinforced concrete building generates a parabolic membrane with conical shape. This was the more complex and larger shell designed by Torroja with a length of 60 meters and a width of 40 meters. As Torroja did numerous simplifications due to the difficulty of the structural calculation, experimental verifications using a large-scale mock-up was needed to verify if the structural calculation was satisfactory.

Emilio Pérez Piñero (1935 – 1972) was a Spanish architect who built his own tools and using waste materials created models at different scales of innovative three-dimensional scissor system structures. The pictures below show his design system based on the creation of models. The paper models were used at the beginning of the design process to finish with extremely detailed prototypes.

Figure 2. Models by Piñero exhibit in his Foundation

Pier Luigi Nervi (1891 – 1979) was an Italian structural engineer who contributed to create an outstanding period of reinforced concrete for structural architecture in the early years of development of this material. He had a dual role of designer and builder. Nervi's innovative projects were based on the combination of prefabrication and ferrocement. Nervi created a model for testing the structural behaviour of the barrel shell of the Orvieto Hangar completed in 1935 and destroyed in 1944. It had a span of 44.8 m and a length of 111.5 m. The tests were carried out in a physical model to verify if the structural calculation was satisfactory [6].

Buckminster Fuller (1895- 1983) was an American architect who was mainly known for creating the geodesic domes. He created and developed several structural systems by designing and building several small-scale models. As Fuller quoted ´You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete´. It proves his strong conviction that to understand and create structures you must build them in small scale models.

Félix Candela (1910 – 1997) was a Spanish-Mexican architect famous for his reinforced concrete paraboloid hyperbolic shell structures. The paraboloid hyperbolic is a doubly ruled surface shaped as a saddle. *Los Manantiales* Restaurant in Xochimilco, Mexico is formed by eight parts that come from the intersection of four paraboloid hyperbolic shell structures which are also called 'hypar' structures. This type of structures allows complex curves to be constructed using straight lines. The Capilla de Palmira in Lomas de Cuernavaca, 1959, was the biggest paraboloid hyperbolic structure without edge beam built until that date. It generates an open space free of columns. Candela studied and developed his research about hypar shell structures through models and prototypes before creating the real size structures. The formwork needed to create the optimal concrete shell structures does not make them cost-effective. Therefore, shell-structures have become less popular and nowadays only very few concrete shells are built.

The Swiss engineer Heinz Isler and the German architects Frei Otto have experimented with physical form finding techniques. Heinz Isler (1926 – 2009) was known for using physical models to design his shell structures. He was against computer and numerical analyses for the design of shells as he believed that theoretical considerations are always based on simplifications of the assumptions [7]. Isler stated that a further danger of numerical calculations lies in the fact that the computer can only answer the question asked and cannot identify questions that were not raised. In 1959, Heinz Isler presented his paper 'New Shapes for Shells' [8] where he described three methods for shaping shells: a freely shaped hill, a membrane under pressure and a hanging cloth reversed. The models created by Isler were mainly simple and study models for form-finding. The method more used by Isler to create concrete shell structures was the hanging cloth reversed.

In 1954, Isler experimented with pneumatic structures to create shells. Isler tested a rectangular cushion clamped to a wooden frame supported on four vertical legs. The black membrane's cushion has a reticular pattern in white made of squared elements that allow to measure strains in the model.

Figure 3. Isler's pneumatic form model [7].

Isler classified the form-finding methods for shell structures in three main groups: analytical methods, experimental methods, and others [8]. The first group is based on mathematics and geometry. The second, the experimental methods, is formed by membranes under tension, pneumatic membranes, hanging reversed membranes, and flowing forms. The last group includes sculptured forms, simulation of shells in nature and all the form-finding methods that are not included in the previous two groups.

In the case of shell structures as in the case of pneumatic structures, form follows force. There is a clear connection between shape and stresses in the membrane or shell. Isler and prominent predecessors in the field such as Gaudí, used inverted membranes or catenaries to find the final shape of their buildings. Isler realised that starting the design process of shell structures from a predefined mathematical form as it was done traditionally, not only was not favourable for the mechanical point of view but also did not satisfy aesthetics [7]. He observed nature and arrived at the conclusion that physical laws determine a natural form, so he based his form-finding process on this principle.

Frei Otto (1925 - 2015) was a German architect known for using models to define and test his structures. Otto researched with soap bubbles to create new structures such as the Tanzbrunnen in Cologne, Germany. Bubble's models are an example of how optimal-complex structures could be achieved using a simple, but ingenious, method for building structural study models.

These eight gifted pioneers were able to develop mechanically controlled shapes with an aesthetically component. Experimental methods are intuitive methods to understand and create optimal structures that follow the natural laws.

The Mixed Model Methodology

This research deals with the development of deployable and movable structures, based on inflatable concept, for applications in architecture as for example long-span roofs [9]. At the outset of this research, the author has carried out a literature review [10] and realised that research combining deployable structures with pneumatic cushions should be undertaken due to its huge potential for architectural use. The aim of this research is to study, prove and analyse the possibility to achieve self-deployed structures with air-cushions and to use the internal air pressure change to move the structure. This paper presents a classification table for these new structural systems, and the creation of several small models that show the skin and frame behaviour of the systems while the cushion volume changes. This new structural concept generates adaptive cost-effective structures that could simplify the transportation, assemblage and construction process at the same time and that have a reduced weight compared to traditional construction methods. It is important to consider that their lightness will also lead to relative reduction of the foundation size which is another advantage of the system.

The research methodology combines experimental qualitative and quantitative data [11]. The methodology is cyclical and formed by seven steps. The starting point is the main research questions formulated after studding the context, and the process progresses through to the final conclusions which would influence the future context and close the cycle, see Figure 4.

The first step is the research context which is based on the kinetic structural research field, the pneumatic structures field, and the air cushions for architectural use field. The second step is the creation of the research questions such as, is it possible to actuate a deployable structure with the inflation pressure of air cushions? and how could new structural types be created in a systematic way? The third stage is the creation of the data source management which is a complex matrix called ´The Structural Combination Matrix´ (SCM), see Figure 5. It is an innovative design approach that combines structural elements that have not previously been integrated, enabling the systematic creation of an unlimited range of new structural types. This approach fills a gap in current design methodologies for generating novel structural forms. It has 10 rows and 12 columns that result from combining shapes of air cushion systems, with mechanical motions. It creates 120 matrix elements. However, the SCM is considered an open-ended system for creating innovative structures. It could be potentially expanded by increasing the types of mechanical motions and the shapes of pneumatically stressed membranes.

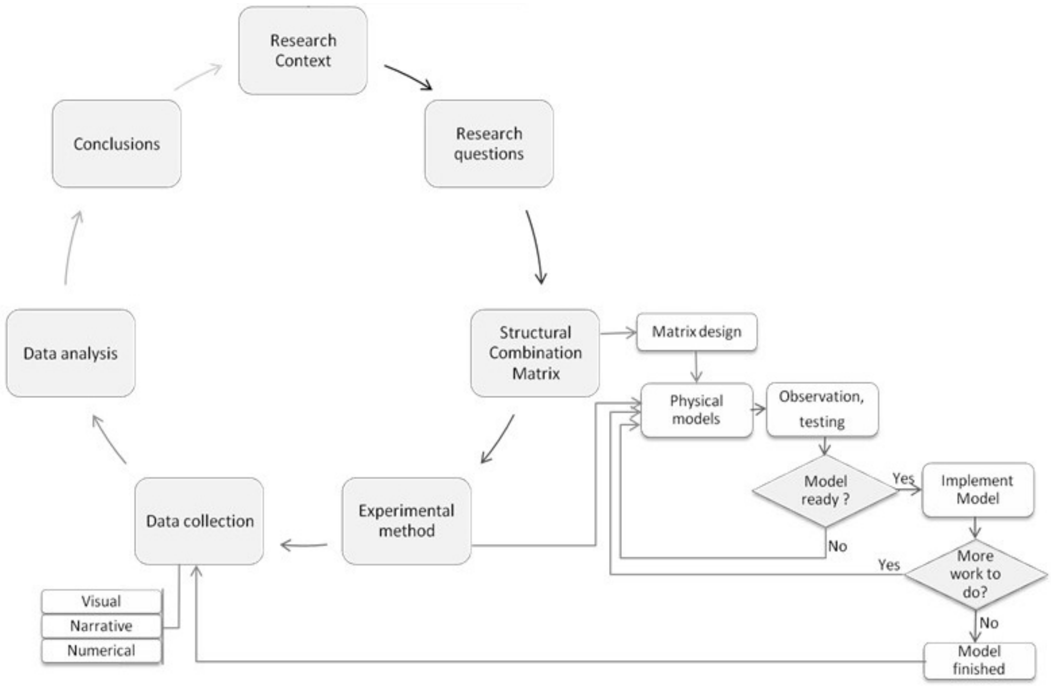


Figure 4. Methodology flowchart

The columns of The Structural Combination Matrix are formed by the different air cushion shapes for both, planar boundaries and spatial curved boundaries as classified by Moritz [12]. The rows of The SCM are some of the mechanical motions suggested by Michael Fox and Miles Kemp [13] for the MIT Kinetic Design Group (KDG) Matrix. Each of the elements of the matrix such as A1, A2, etc. is an innovative kinetic air cushion structure. A sampling decision based on a non-probability purposive sampling strategy has been made to decide which elements of the matrix would be studied. The experimental models are evaluated based on criteria including volume change, frame behaviour, and skin performance. These parameters are measured using digital image correlation, finite element analysis simulations, and high-speed video analysis.

The step four is the experimental method based on physical models. The fifth phase is the data collection which is based on visual data, videos, photos, and drawings; narrative data and numerical data. The sixth step is the data analysis. The experimental models are used to produce data that is collected using photographs and videos. In the seventh step, evidences are produced from which the conclusions of the research are drawn. The conclusions will influence the future context of the research topic.

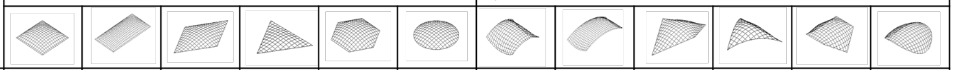
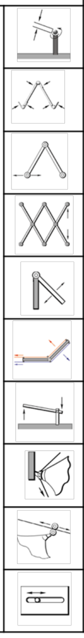
Pneumatically stressed membranes		Planar boundaries						Spatial curved boundaries					
													
Mechanical motions		A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}
		B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}	B_{11}	B_{12}
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
		D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}	D_{12}
		E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}
		F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}
		G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9	G_{10}	G_{11}	G_{12}
		H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	H_{11}	H_{12}
		I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}
		J_1	J_2	J_3	J_4	J_5	J_6	J_7	J_8	J_9	J_{10}	J_{11}	J_{12}

Figure 5. The structural Combination Matrix (SCM)

EXPERIMENTATION AND ANALYSIS USING PHYSICAL MODELS

Rectangular Cushion with a Pivoting Mechanical Motion, A2

The first model studied was the element A2 of the matrix. It is a structure that combines a rectangular-shaped cushion with a rotational pin movement. This system has been calculated by a Finite Element Analysis [14] and studied using an experimental model.

A2 Conceptual Intention

The first model created was made with rectangular air cushions. The longer the cushion, the longer will be the deflections of the lateral clamping frames. Rectangular cushions were studied because they represent the worst-case scenario.

A model with three cushions was selected to observe the behaviour of the central clamping frames and the lateral frames. The central frames are defined as the frames localised between two cushions. This means that they clamp the edges of two cushions, compensating forces. The lateral frames are defined as the frames localised on the edges of the model. This means that they only clamp a cushion on one side, leaving the other side free. The cushions' short frame edges have the pivoting points in the middle of the member to allow rotation. These pivoting points have wheels on the border to allow the movement in the horizontal plane. This is based on the idea of the pivoting point of scissor systems which allows a good deployable movement.

On one side of the model the wheels of the pivoting points were sliding over a flat surface which was supported by a portal frame. It allows movements in two directions of the same plane. On the opposite side, the wheels slide on the slot of a C-channel which also was supported by a portal frame. It allows movement in one direction of the plane. The main intention is to observe how the movement of the cushions is produced, study the wrinkles that appear during the retraction process and how the clamping members deflect for this configuration.

A2 Model Description

The model consists of three double layer plastic cushions of 100 mm by 600 mm each. The frame is made in wood strips of 10mm by 4mm or 12mm by 6mm that are at both sides of the cushion long edges. There are two different dimensions for the strips because the intention is to analyse and observe the influence of the rigidity of the frame, so both options are studied. The frame strips are attached together by 5 screws 3 mm in diameter which are 170 mm apart from each other at exception of the first and last screws that are at 40 mm from the short edge of the cushion. The frames of the edges are made of wood and measure 9 mm by 9 mm each. The cushions are supported at both ends by portal frame structures. On one side there is a C-channel strip of 12 mm by 12 mm. The depth of the C-channel hollow is 3 mm. This beam is supported by two rectangular wood sections of 9 mm that work as columns at both sides. On the other side, the cushions are supported by a 20 mm by 9 mm wood beam that transfers the loads to two rectangular wood columns which are identical to the other columns. There are brass wheels of 20 mm of diameter and 2 mm thickness located in the middle of the span of the short cushion side wood elements. On one side of the model, they are restrained in the C-channel shaped wood element. On the other side, the vertical movement is restraint but not the horizontal movement.

There is a pipe for air supply in each of the cushions. The three pipes meet in a metal pipe that connects to the air pump, see Figure 6. The whole model is supported by a medium density fibreboard base of 800 mm long by 600 mm wide. The thickness of the board is 6 mm.

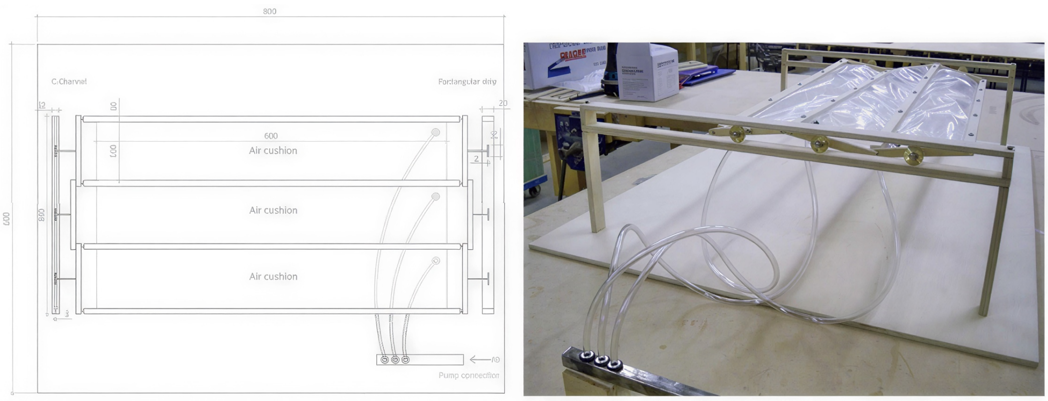


Figure 6. Plan view and model A2

A2 Analysis 0f Volume Change, Frame Behaviour, and Skin Performance

This model has been created and studied using physical experimentation and finite element analysis [14]. This paper focuses on experimental research using physical models, so the physical model analysis would be described. There is a horizontal force, the internal pressure inside the cushion, and the radius of curvature of the cushion. In an eye shaped cushion there is a horizontal force while in a circular cushion, the retention force is equal to cero. The edges of the cushion rotate around their centre 45 degrees. As the short ends of each cushion rotate in opposite directions it generates in the central portion of the cushion a circle section while there are eye-shape sections at the ends due to the close boundary condition.

A physical model with three cushions was built. Each cushion has a pipe that connects to the main air supply pump. Pictures of the model were taken showing the wrinkles that appear during the inflation of the cushions. The pictures were taken with a Canon EOS 500D set with a self-timer in drive mode for capturing ten images continuously with one second intervals between the photos. To take a sequence of 25 pictures, this system was set three continuously times. The following five pictures were selected to illustrate mayor changes.

Figure 7 shows that the wrinkles at the beginning of the inflation process are disorganised and specially located close to the clamping frame. The number of wrinkles increases with the time when air is introduced in the cushions. It is observed that the wrinkles start to follow a pattern with an inclination angle of 45 degrees. As the 45 degrees pattern in the wrinkles appear, the wrinkles at one side of the cushion have the opposite 45 degree to the wrinkles of the other side, as mirrored. There is also some wrinkle formations in stressed points close to the screws that fixed the cushions.

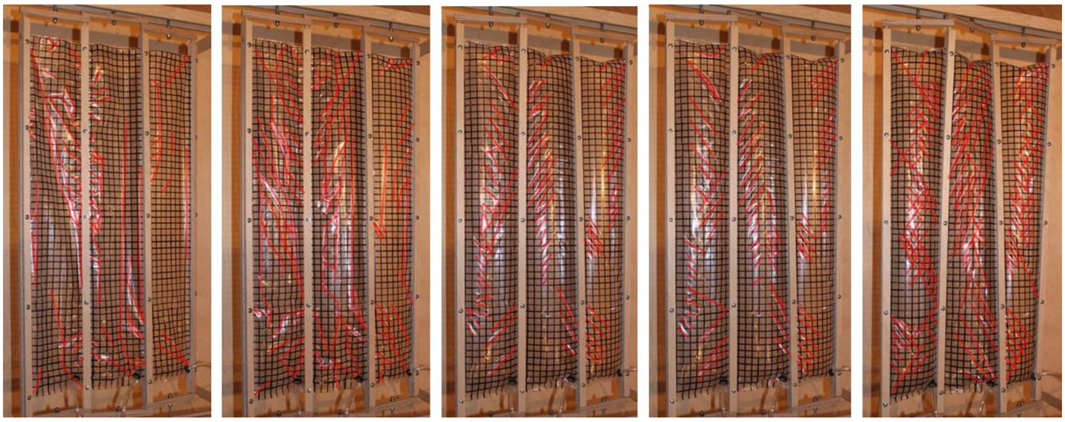


Figure 7. Inflation process: 1, 7, 13, 19, 25 seconds. Images edited to highlight the wrinkles

The shear stress changes the principal stresses in the membrane and when they become zero, wrinkles appear. The cushions resist the bending moment due to its pretension induced by the inflation pressure. If the pretension is reduced to zero with the increase of the moment, wrinkles spread across the cushions. When the cushions are almost fully inflated, the wrinkles are more localised. When the cushion is fully inflated, it is full of wrinkles, especially in the central part of the pillows. It is associated with the high concentration of stresses in the membrane.

In this model the cushions rotate around the middle point of their short edges. The first cushion rotates 45º around its central point without horizontal movement. The second cushion moves horizontally closer to the first cushion since it is linked to this first element of the chain, and the first cushion pulls it. The third cushion is pushed by the second cushion, and its rotation point moves horizontally closer to the first cushion twice the value of the second cushion displacement. The total displacement turns out to be 72.68mm that is two times 36.34mm [14].

One of the observations related with this model is that the extreme cushion´s side beams are not stiff enough because when the air pressure is introduced in the cushions, deformation by bending of these beams occurs. It is due to a not compensation of stresses at both sides of the beam.

After several inflation and deflation processes, it has been observed that the movement of the model had changed. Both short edges rotated 45 degrees but not in opposite directions, so the twist is not observed anymore. This change on behaviour could have been caused by the creep of the plastic material of the cushions. Plastic, as a viscoelastic material, could have viscoelastic creep that implies a time-dependent increase in strain. An important fact is that the behavioural change has been detected during the summer, a year after the pictures of figure 10 were taken in winter. The temperature has a high influence on the creep in plastic materials.

Rectangular Cushion with Folded Ends, A2(1)

A2(1) Conceptual Intention

Inspired by the stomata (pores found on the surface of plants to take in carbon dioxide and release oxygen) Biomimetic principle, A2(1), a variation of the model A2 was created as can be seen in Figure 8. In the model A2, the short boundaries of the cushion did not have a frame and therefore there was a deflection when the cushions were inflated. This model was created to investigate if changing the shape of the short boundaries of the model for a shape taken from nature would reduce the deflections and how would the behaviour of the model change. The stoma shape, from biology, was considered an appropriate shape to reduce deflections and increase the efficiency of the first model described. This shape was selected because it was observed from the first model that the central area of the rectangular cushions tends to get into a circular shape. A circular shape on the short boundaries would facilitate the movement of the cushions. The closed welded line on the short boundaries of the first model was reducing partially the movement of the cushions.

A2(1) Model Description

The short boundaries of the model were welded and introduced into the cushion to create a stoma shape applying the principles of biomimetics. Biomimetics makes use of ideas inspired from nature to use them in architecture, engineering and other scientific fields [10].

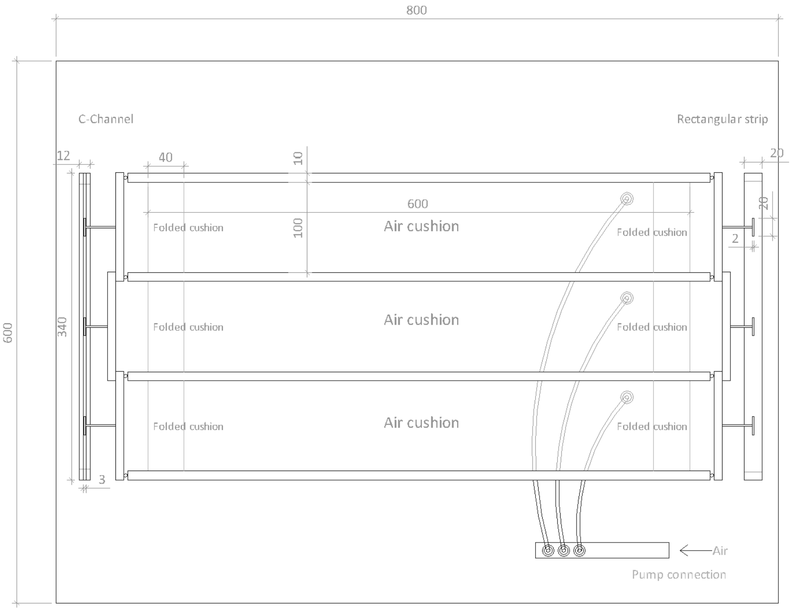


Figure 8. Plan of the model A2(1)

The cushions on this model were moved with air pressure introduced by a pump combined with the flexibility that the pivoting points were giving to the model. No external motors were used to generate movement.

A2(1) Analysis of Volume Change, Frame Behaviour, and Skin Performance

In this model, both short sides of the cushion rotate in the same direction, see Figure 9. It can be attributed to the stoma shape cushion endings that reduce the restrain of the cushion on these sides. During inflation, the stoma shape boundary of the cushion appears to be highly wrinkled. Furthermore, the side frames were under considerable bending. The deflection of the long-side clamping beams is higher than in the first model because the stoma shape ending gives more freedom to the cushion and it can expand further. It also explains why this model is inflated faster than the first model. The deflections of the clamping beam might not be accepted in a real structure. The maximum deflection of the side beam is established by codes such as, for example in the United Kingdom, it will have to follow the limits established in the British Standards or the Eurocodes.

(a) (b) (c)

Figure 9. Cushions (a)-without air, and cushions after (b)-6 and (c)-8 seconds of inflation

The maximum rotation of the short edge beams is also as the first model, 45 degrees. The short beams move in a zigzag way. The behaviour of the cushion, the frame and the change in volume of the model on a sunny summer day after a year of the creation of the model is the same. This system, compared to the first system, produces higher deflections of the clamping beam and less wrinkles in the cushions. The maximum deflection of the edge beam is 20 mm.

Rectangular Cushion with Closed Ends and Triangulations, A4

A4 Conceptual Intention

The system A4 could be considered another variation of the first model A2. A4 has welding lines on the cushions that produce 25 smaller cushions. The three main cushions are subdivided in 11 triangular shaped cushions, 8 trapezoidal shaped cushions, 4 irregular pentagons, and 2 irregular hexagons. It allows studying different shaped cushions in a model, see Figure 10.

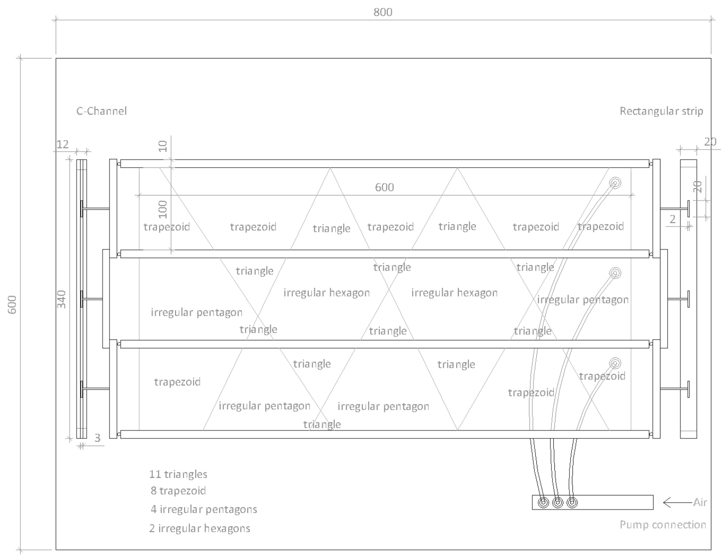


Figure 10. Plan of the model A4, and model

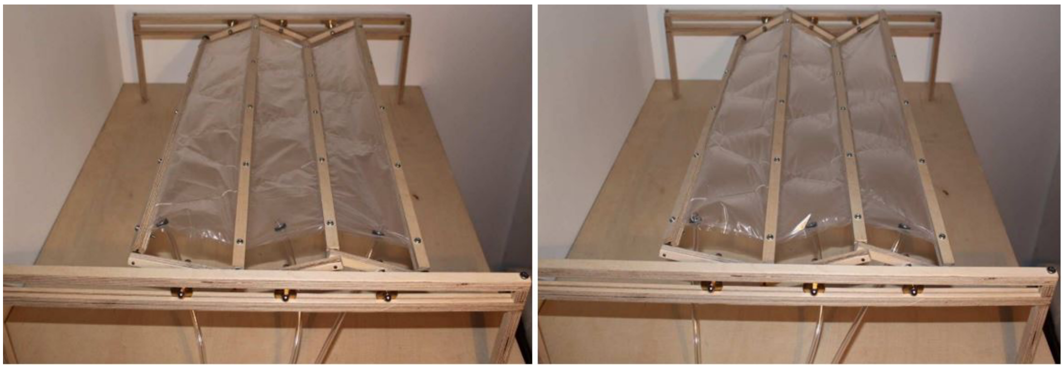
A4 Model Description

The model is like the first model described but with added welding lines to the cushions. The welding lines generate triangular cushions, hexagonal irregular cushions, trapezoidal cushions and irregular pentagonal cushions in each one of the main rectangular framed cushions. The intention is to observe the behaviour of the skin, frame and volume changes related to the different shapes obtained due to the welding lines. All the cushion shapes mentioned above that are inside the same rectangular framed cushion have just an inflation pipe. All the cushions of the model are inflated because three spaces were left in each of the welding lines during the welding process.

A4 Analysis of Volume Change, Frame Behaviour, and Skin Performance

This system generates several wrinkles in the areas of the welding lines which are the highly stressed areas. On the other hand, the deflection of the clamping beam is minimal.

It could be because the cushion' span is reduced along the beam. In this model, the rotation of the short edges of the beams is also as in the first model, 45 degrees in opposite directions in each short cushion side. It is observed that the smaller the cushion, the higher is the number of wrinkles. The reason is that for the same pressure, less area must be inflated, so the stresses in the membrane are higher. The edge beam in this model deflects considerably less than in the models A2 and A2(1).



(a) (b)

Figure 11. Model after (a)-2 and (b)-10 seconds of inflation

Square Cushion 3D Folded, B1

B1 Conceptual Intention

This model B1 has a three-dimensional movement. When we observe the process of inflation of model B1 cushion in slow motion, it is possible to appreciate a similar shape to a Hyperbolic Paraboloid. Furthermore, this shape is also like the shape that we can appreciate in some origami models. This optimal shape has been used by several architects like for example, Felix Candela.

A square kinetic model made with latex rubber was created. The same kinetic structure was experimented with a fluoropolymer plastic, 1000 times stiffer than the rubber material. When comparing both models, the latex rubber model presented less wrinkles than the fluoropolymer plastic model.

B1 Model description

It is a deployable bar structure formed of bars 12 mm long that produces a three-dimensional movable structure. The cladding is an elastic material (latex) which forms a two-layer cushion of 8 mm long on each side. The deployable structure is created with bars which have eye shaped screws at both ends. These eye shaped screws were used to achieve movement in the joints of the movable structure. The rotation points are created by the connection of the eye shaped screws with a wire.

The structure opens by the internal air-pressure of the cushion. The behaviour of the frame and the skin are optimised because there are very few wrinkles in the envelope and the clamping frames do not deflect. It is a good example of an air-actuated deployable cushion structure.

B1 Analysis of volume change, frame behaviour, and skin performance

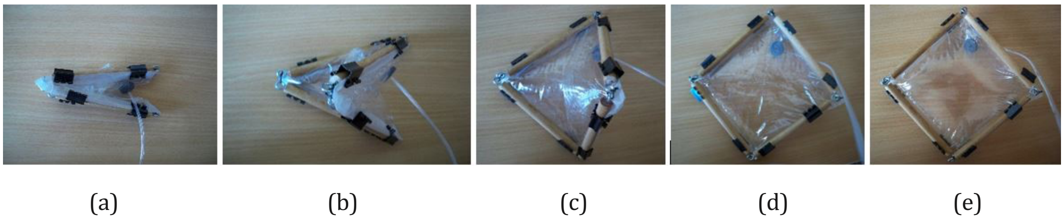


Figure 12. (a)-stowed state and inflation process at (b)-3, (c)-5, (d)-7, and (e)-9 seconds. .

Triangular Cushion Origami, B4

B4 Conceptual intention

The origami structures have been applied to plain rigid structures in several constructions, however, a combination of cushions, as pneumatic structures, and origami structures would be innovative. The experimentation process started with a paper model that was generating two right triangles that were inflated as shown below.

The triangular cushion origami combines four equilateral triangles. At the same time, two of these are divided in four right triangles. Each of the triangles is connected to a pump. The air inside of the cushions generates the movement of the whole structure with no need of external actuators. An isolated module has been designed. This module can be repeated to create bigger structures like for example a stadium's roof [15]. The Spanish architect Emilio Perez Piñero has for example created larger structures with repeated units or modules. These modules were previously tested in isolation by laboratory research and after that assembled to create a bigger structure.

This model is based on the origami shown in figure 13. Only one module has been built with cushions, but if several are placed together the result will be a structure like the shown in figure 13.

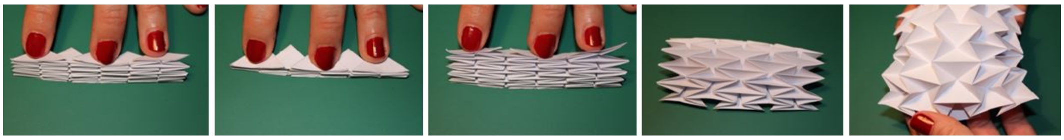


Figure 13. Origami deployment sequence

B4 Model Description

The model is a plastic square of 360 mm by 360 mm with two diagonal welding lines, from opposite corners of the square, intersecting in the centre of the cushion. Another welding line is created going through the central point of the cushion and the central point of the laterals.

B4 Analysis of volume change, frame behaviour, and skin performance

Wrinkles appear in the most stressed regions which are the areas close to the welding lines. In those zones the wrinkles are perpendicular to the welding lines. As the valve is heavy steel, it influences the movement of the structure. It can be improved changing it for a lightweight valve.

This model is a structure that behaves as a nature structure due to its analogue deployment sequence. For example, its deployment process is like the opening of a flower in nature.

Figure 14. Deflated origami-cushion structure, inflation process, and deflation process.

Trapezoidal elastic cushion with half scissor system, C3 / D3

C3 / D3 Conceptual intention

This model was made with latex rubber. The latex was clamped by the two short edges of the cushion. Secondary clamps to the frame were used on the long edges of the cushion.

The four edges of the cushion were clamped to the frame. There were four pivoting points, but only two of them were attached to the elastic bands. Two forces were required to keep the model stowed and they were located on the two pivoting points where the model did not have elastic bands.

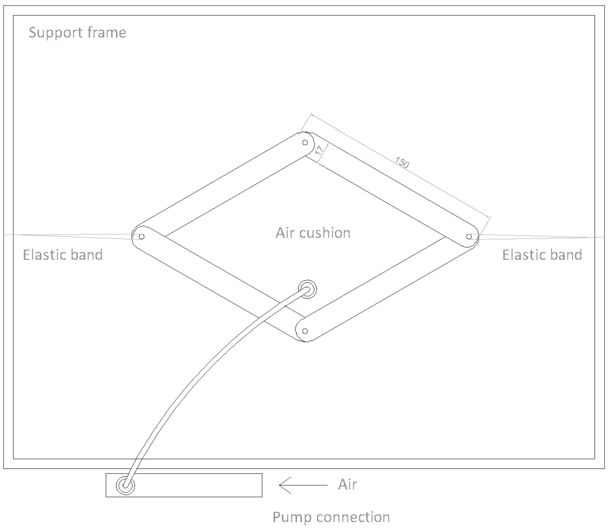


Figure 15. Plan of the third option of model C3/D3

C3 / D3 Model description

The model is generated with bars 150 mm long by 17 mm wide. There are four pinned connections to achieve the movement of the structure. The material used for the cladding is an elastic material, latex.

C3 / D3 Analysis of volume change, frame behaviour, and skin performance

Table 1 summarises the experimental performance of the different models studied, comparing their behaviour in terms of cushion volume change, frame response, and skin/membrane performance during inflation and deployment.

Table 1. Comparative model's performance

Model	Volume Change	Frame Behaviour	Skin Performance
A2 - Rectangular cushion with pivoting motion.	Moderate volume expansion. Cushions rotate around short-edge pivot points producing chain displacement.	Noticeable edge bending.	Wrinkles approx. 45° near clamps
A2(1) - A2 with folded ends.	Faster inflation than A2 due to reduced boundary restraint.	Higher long beam deflection than A2.	Fewer wrinkles overall but concentrated at folded ends.
A4 - Rectangular cushion subdivided with triangulated welding lines.	Controlled via subdivisions.	Minimal beam deflection because welding lines reduce span and act as reinforcement.	Wrinkles along welds, dense in smaller cushions.
B1 - Square cushion with 3D deployable frame.	Efficient 3D deployment.	Stable frame with negligible deflection.	Very few wrinkles, especially when using elastic materials as latex. Membrane adapts to a hyperbolic paraboloid shape.
B4 - Triangular origami cushion module.	Inflates with origami-like motion.	Stable frame/welding line.	Wrinkles near welding lines.
C3/D3 - Trapezoidal elastic cushion with half-scissor system.	Air inflates cushion but does not significantly actuate structure.	Structure movement mainly controlled by mechanical frame rather than pneumatic force.	Smooth latex membrane, few wrinkles.

Additionally, it was observed that the air was only used to inflate the cushion but not to move the structure. The structure was moving the cushion [15].

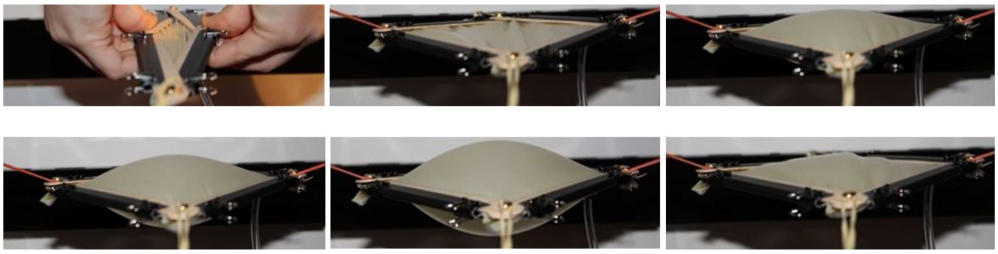


Figure 16. Font view of the model deployment process at 0, 2, 4, 6, 8, 10 seconds

SUMMARY AND CONCLUSION

In this research six elements of the Structural Combination Matrix have been studied, five of them (A2, A2(1), A4, B1 and B4) made with a fluoropolymer plastic material, and one (C3/D3) with latex rubber material. In the model C3/D3 a cushion with a material that could change form in a planar position was needed due to the two-dimensional motion of the structure. In the A series and the B series models, as the motion was a three-dimensional motion, the cushions with fluoropolymer plastic were satisfactory. In summary, if the deployable structure has a spatial motion, the cushions could be made of fluoropolymer plastic; otherwise, if the structure has a planar motion, an elastic material such as latex is required.

The models studied prove that it is possible to actuate a deployable structure with the inflation pressure of air cushions. Lightweight deployable structures are easier to move but, the stresses in the beam produced by the inflation of the cushions can create large beams deflection that could not be considered satisfactory according to the code of the beam material. For example, in the model A21 the beam deflection is excessive. It demonstrates that deployable cushion structures are likely to be limited for deflection of the beam instead of deflection of the cushion. The model A4 has a smaller deflection on the beam. It is because the large rectangular cushions are subdivided in smaller size cushions and the welding lines work as reinforcement, reducing the deflection of the edge beam.

In the case of the model A2, a different motion has been observed with the time and the change of temperature. The material behaviour is strongly affected by the effect of the strain-rate and the temperature because the yield stress decreases with the increase in the temperature, and it increases with the strain rate. The temperature influence on fluoropolymer plastic material is dramatic.

In the model B1 it is very interesting to observe how during the three-dimensional deployment of the structure, the cushion adapts to a hyperbolic paraboloid form before being totally deployed.

The model B4, the origami cushion, has been studied hanging from four points and laid on the floor. In both cases, it has a good behaviour. The inflation of the cushions produces the opening of the structure, while when the air is taken off, the structure self-folds. It is an important fact, because this structure could be self-deployed with the air pressure of the cushions and self-folded when the air is taken off. It makes the structure to work like a natural structure, so it could be considered a biomimetic system.

Wrinkles along the seams appear in all the systems, especially on the systems created with fluoropolymer plastic. The latex is a more elastic material, so it has fewer wrinkles. In conclusion, inelastic characteristic results in more wrinkles. Fluoropolymer plastic was the least flexible of both films, so it is the worst-case scenario for wrinkles.

These air-actuated cushion structures could be applied in various contexts, such as adaptive architectural façades, emergency shelters, pavilions, and stadium roofs. Future research may include the development of full-scale prototypes, certification testing, and implementation in real-world projects.

CONFLICT OF INTERESTS

There is no conflict of interest associated with this publication.

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