Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Proposal for a Responsive Canopy Integrating Curved Line Folding Technique and Cable-Driven Systems

Pınar NEŞELİLER* and Yenal AKGÜN[a]

* Izmir University of Economics
Faculty of Fine Arts and Design, Department of Architecture, 35330, Izmir, Turkey.
pinar.neseliler@iue.edu.tr

[a] Faculty of Architecture, Department of Architecture, Dokuz Eylül University, 35210, Izmir, Turkey

Abstract

Responsive architectural structures measure actual environmental conditions using sensors and allow buildings to adapt their form, shape, color, or character responsively using actuators. However, the use of multiple actuators and relying on rigid body hinges can decrease the applicability of these responsive architectural structures. The exploration of new actuation methods may have the potential to contribute to practicability. The technique of curved line folding (CLF), which originated from the Bauhaus School by using paper material through origami art, is a folding method that could be an alternative technique to decrease the number of actuators. This paper aims to introduce a responsive canopy integrating cables into CLF to offer a novel actuation strategy since CLF systems have not been addressed yet with cable-driven systems. The methodology is derived into three parts; critical investigation of responsive adaptive structures; exploration and geometric variabilities of CLF utilizing cables; and designing a responsive canopy. The study has shown that the capability of acting on multiple modules with one actuator makes it possible to decrease the complexity of adaptive responsive structures. Moreover, it may lead to the development of new adaptive architectural structures or devices.

Keywords: curved line folding, kinetic architecture, responsive canopy, cable-bending systems, biomimetics

1. Introduction

Responsive building envelopes have been essential in terms of the sustainability of buildings since up to 60% of all heat transmission in buildings occurs through heat gain and loss through the envelope to and from the surrounding environment (Ascione et al. [1]). These envelopes use technology and innovation to adapt to changing environments, conserve energy, reduce emissions, and effectively increase indoor comfort (He et al. [2]). The transition to dynamic building envelopes represents a significant change in the energy efficiency of buildings (Favoino et al. [3]). These adaptable elements can change their properties dynamically, resulting in significant performance improvements compared to traditional façades (Perino and Serra [4]). Studies on the capability of adaptation to ever-changing situations, such as functional, environmental, or aesthetic, lead to improvements in responsive building elements. In addition, adaptive façades and systems enable buildings to change their thermal properties in response to external conditions, contributing to energy efficiency (Favoino et al. [3]).

On the other hand, responsive canopy structures present an intelligent approach to the adaptation concept, even though the umbrella is an ancient structure (Friedman [5]). In architectural examples, canopy structures comprise various mechanisms, and these can be classified as rigid bodies or compliant mechanisms. Most responsive canopies consist of rigid body hinges. These structures may not be applicable in terms of sustainability issues. Complex mechanisms and high energy-demanding implementations cannot provide feasible solutions in technical and economical ways. Several actuators and hinges are used to initiate the motion, which leads to increased complexity in responsive canopies.

To address this issue, compliant mechanisms, which are elastic systems that transmit force and motion through elastic body deformation, may offer great potential for applicability in responsive structures. Compliant mechanisms can be seen in everyday devices, such as bag locks, paper clips, one-piece plastic lids, tape measures, battery clips, mouse buttons, and snap-fit pieces. Although the traditional design of mechanical components may be arranged by assigning various tasks to individuals, and each part is responsible for a specific purpose, compliant mechanisms can be designed as numerous functions within a reduced number of components (Howell [6]). Comparing these mechanisms to rigid-body mechanisms, they possess various advantages, including the ability to accomplish certain goals with fewer components. Since there are fewer parts required, manufacturing and assembling processes are simplified, which reduces both time and money (Jagtap et al. [7]).

Since curved line folding does not require a rigid hinge within the framework of compliant mechanisms, it enables elastic deformation via flexible components. Researchers have primarily focused on designing mosaic patterns and small-scale surface panels based on CLF for conceptualized installations and pavilions rather than for architectural space or practical applications. As a state-of-the-art computational design, the technique has been utilized for kinetic installations actuated by separate motors. However, responsive canopy structures contain multiple motors that initiate motion, which increases the complexity of systems. Therefore, this research investigates a solution to decrease the number of actuators engaging compliant mechanisms based on the CLF technique seen in Figure 1.

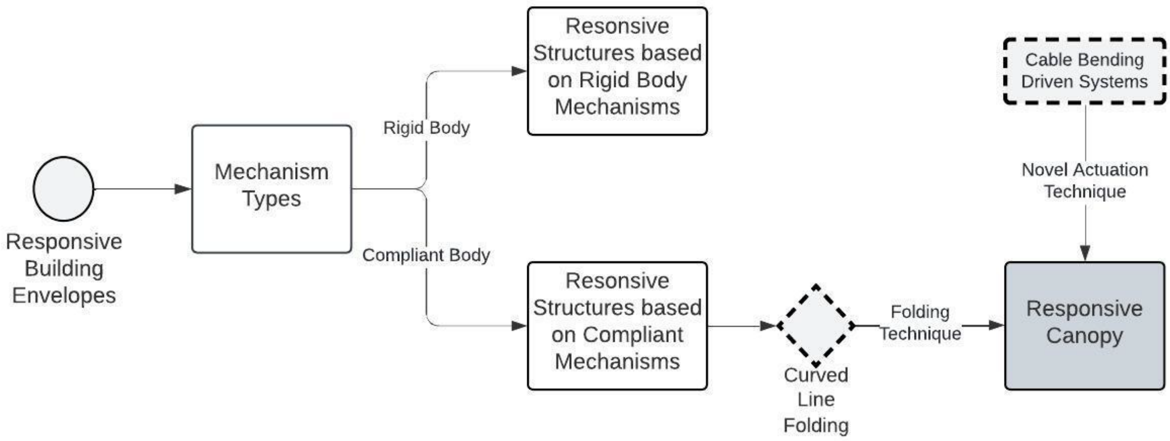

Figure 1: The Methodology of the Research Proposal

2. Background

Throughout the climate action that emerged in the built environment, innovative solutions played an important role in enhancing the adaptability concept. This emphasis on adaptability underscores a fundamental shift in design philosophy, where structures are conceived not as static entities but as dynamic systems capable of responding intelligently to their surroundings.

Thanks to the innovation of new materials and technologies, as well as building management systems to control and manage energy demands, the building industry has been influenced. The understanding of current strategies and technologies behind the mechanisms brings out new solutions criticizing the developed projects. These are varied by large-small scale prototypes, installations, façade, roof applications, or canopy designs. In the scope of actuation type, the responsiveness can be considered as active, triggered, and controlled by energy sources, and passive methods which are stimulated by environmental changes such as wind, temperature, light, humidity, etc. without the need for external energy. The other essential criteria may be controlling systems. Thanks to the improvement of management systems comprehending electronically controlled and mechanically driven systems, initiating the movement has been possible utilizing different actuation methods that can be classified into four types; motor-based, hydraulic, pneumatic, and material-based (Harry, [8]). Therefore, responsive structures are investigated to clarify the relationship between mechanism type and actuation method from the previous examples (Table 1).

Table 1: Examples of responsive structures in terms of differences of actuation

Project Year	Application Area	Project Name/Type	Actuation Type	Actuation Method	Mechanism Type	Reference
2010	Canopy	Prophet's holy Mosque	Active	Hydraulic Actuation	Linkage with revolute joints	[13]
2012	Façade	Al Bahr Tower	Active	Motor-based	Linkage with revolute joints	[12]
2013	Sculpture	The Surya shading screen	Active	Motor-based	Linkage with revolute joints	[9]
2014	Façade	Reactive Media Towers	Active	Hydraulic Actuation	Linkage with revolute joints	[10]
2015	Prototype	Large Scale-Prototype	Passive	Material-Based	Compliant mechanisms	[22]
2017	Installation	Large Scale	Active	Motor-based	Compliant mechanisms	[16]
2018	Façade	Arch(K)inetic	Active	Pneumatic Actuation	Compliant mechanisms	[16]
2019	Installation	Flectofold	Active	Pneumatic Actuation	Compliant mechanisms	[16]
2020	Façade	Small Scale-Prototype	Passive	Material-Based	Compliant mechanisms	[23]

2.1 Responsive Structures Based on Rigid Hinges

Responsive canopy structures are constructed through various solutions according to context and design ideas, as demonstrated in recent studies. Most of these have similar approaches, such as sun shading. For instance, Rex Studio designed a 400-foot-tall kinetic sculpture that works to protect the fine arts of the art gallery from sun glare. The Surya sculpture is a thin, free-form ring made of aluminum that has been formed to minimize disruption of view from the surrounding built environment while efficiently blocking the majority of reflected light. Spokes conducting sun-reactive panels radiate outward from the sculpture's center; these panels automatically expand in intense sunshine and shrink in normal circumstances (Fazzare [9]).

Madrid Pavilion, Shanghai Expo, China The concept involved enabling each umbrella to be manipulated via a pulley system, facilitating interaction for individuals. Besides the pulley, the mechanics mirror those of a standard umbrella, with variations including stainless steel for mechanical components, aluminum frames, and a thin Corten exterior surface (Frearson [10]). The umbrellas form a flat facade when entirely extended, effectively blocking out strong winds and a large amount of sunlight. On the other hand, when they are opened, they permit in enough of light and become attractive sticks in the shape of stars with aerodynamic profiles (Premier [11]).

In contrast to rigid panels, convertible examples cover the courtyard of the Prophet's holy Mosque. These twelve large umbrellas, measuring 17m x 18m when fully open, stem from F. Otto's developed system (Asefi et al. [12]). These umbrellas provide visual and thermal comfort shading during days and ventilation. The parasol has a hydraulic cylinder located on the column axis that opens and closes the parasol (nd, [13]). The upper end of the cylinder is pin-connected to each of the active arms. When the parasol is closed, the hydraulic cylinder is fully driven out at the top. To open the parasol, it drives down, pushing the parasol arms—which are attached to the upper end of the hydraulic cylinder.

Another responsive proposal was developed for flood protection against natural disasters such as hurricanes and storm surges. These constructions, frequently taking the shape of inclined hyperbolic paraboloidal shells, are engineered to serve as flexible and graceful substitutes for conventional floodwalls and levees. Through the application of smoothed particle hydrodynamics (SPH) and parametric modelling of depth-limited wave spectra, the effectiveness of kinetic umbrellas can be thoroughly assessed during severe weather events (Wang et al. [14]).

According to the investigation of canopy structures, one of the general deficiencies is familiarity with various management and operation procedures. For these structures, a high level of building construction management is necessary. Megahed [15] summarized the weakness of the umbrella structures as part of canopies. Firstly, the economic issues should be considered because the construction of the installations may result in high costs. Secondly, the consumption of energy needs to be optimised by simulations and the experience of users. Moreover, the main problems might be the regulation of noises, training of occupants, and heavy load of supported frames and structures.

2.2 Responsive Structures Based on Compliant Mechanism

According to the investigation of compliant mechanisms, several fields such as building, architecture, structural engineering, and materials science have been heavily influenced by adaptive structures based on curved line folding. The studies have shown that principles of curved-line folding are abstracted from natural systems like skin wrinkles or underwater plants and used to develop adaptive shading systems for architectural facades (Körner et al. [16]). This means that they can build up an approach for designing structures in a way in which they can dynamically respond to their environment without any strict linear translation or rotational axes. Moreover, it allows reversible surfaces to be made, which can deform through CLF. It can be demonstrated that the formation of reversible surfaces based on curved-line folding creates not only stiffening elements for structures but also shows the flexibility and adaptability of systems of this type (Matini and Haghnazar, [15]).

The examples are varied in different scales and functions. Motor-based, material-based and pneumatic actuators have been utilized to foster the movement as seen in Table 1. However, most adaptive examples based on curved line folding techniques use a pneumatic actuator in the middle part of the hinge zone. Through the research and demonstrated installations, a maximum of 3 modules have been set in motion with one pneumatic device.

3. Case Study

The studies have shown that investigation has begun into the realm of responsive canopies. Even though these are all rigid linkages and mechanisms, they are seamlessly incorporated into canopies that dynamically change their configuration to provide shade, shelter, and ventilation, among other things. The folding technique, known as CLF, studies are mostly focused on geometric optimization, materiality, and actuation methods. On the other hand, several examples in terms of responsive canopies developed rigid linkages and mechanisms. Therefore, this research presents a responsive canopy incorporating the CLF technique and cable-driven systems.

3.1 Exploration of Curved Line Folding Utilizing Cables

Since the research aims to reduce the usage of actuators in responsive systems, the case study focused on exploring a pattern integrating a cable-bending-driven method. The approach inspired the integration of a new actuating mechanical component within the CLF module for the active proposal (see Figure 2). This exploration not only broadened the horizons of actuation techniques but also played a fundamental role in reducing actuator usage in adaptive systems.

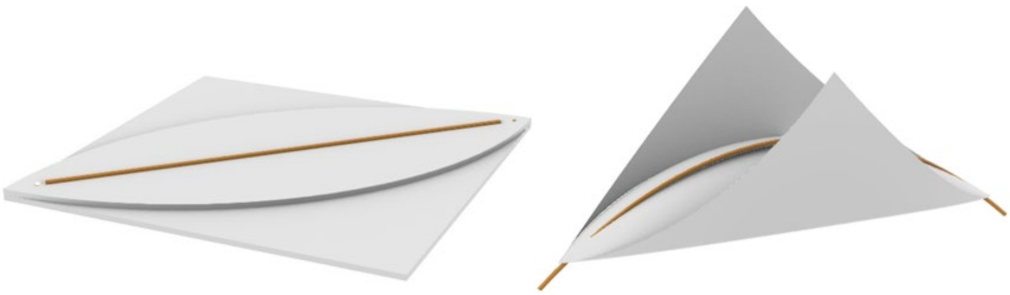

Figure 2: Schematic Illustration of Cable Bending Method

The principle of cable bending-active systems is comprehended in the study offered by Phocas et al. [19] in the context of adaptability and elastic capabilities. Another example was proposed for a convertible roof system. Cables have been added to bending-active plates to establish stable deformation processes and broaden the span range for which the structures can withstand external loads. Takahashi et al. [20] proposed a kinetic system in which the cladding parts are separated into triangular sections that are joined to light-detecting sensors and servo motors, which drive the mechanism using a web of cables. The other proposal was telescopic arches stabilized by a network of cables controlled by servo motors, making up the primary functional component.

Comprehending the principles of cable systems, the exploration of the fixation of cables provides a better pulling effect on the system. The cables are attached from one corner, which are reeved from the opposite side of the module. Therefore, the load application in the simulation should be in both corners due to the fixation of cables (see Figure 3). While multiplying the modules, four cables through the modules are pulled from the middle of the frame, as seen in the model in the Rhinoceros, to make a prototype (see Figure 4).

Following the successful integration of four modules, the goal was to grow up to 16 modules in accordance with the primary goals of the thesis. This extension was methodically carried out by producing 3D-printed models and prototypes. Four separate frames were put together into a larger frame in the prototyped model, and the cables were systematically routed via a secondary frame. The folding and unfolding of CLF modules via cables are illustrated in Figure 5. However, the dimensions proposed for a responsive canopy are expanded, offering a detailed insight into the practical implementation of the developed system.

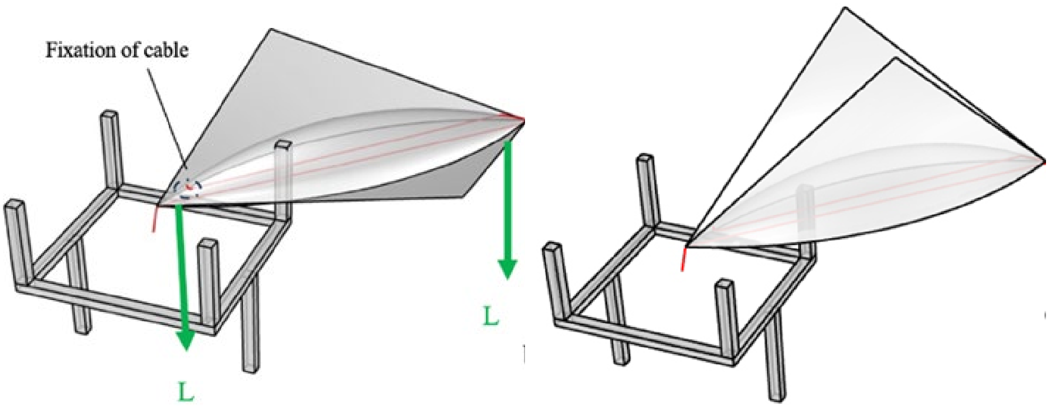

Figure 3: a) The unfolded geometry of one module and the application of loads in theory b) The folded geometry

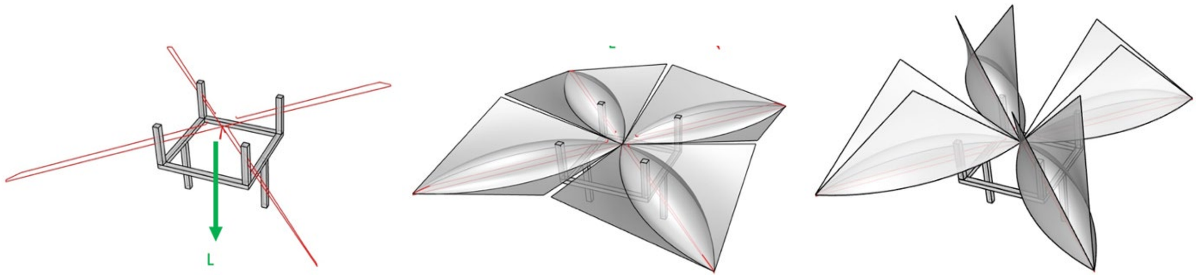

Figure 4: Systematic integration of cables and CLF modules

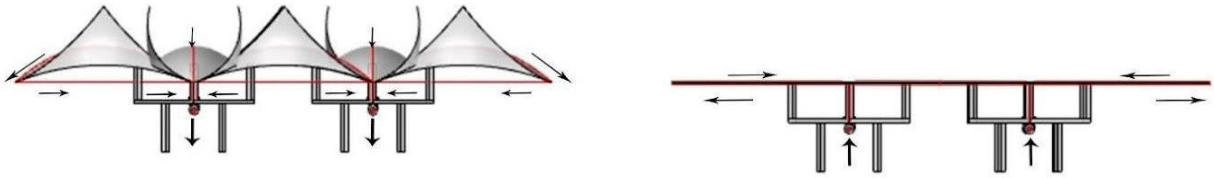

Figure 5: a) Folding of CLF modules via cables b) Unfolding of CLF modules

3.2 A Proposal for Responsive Canopy

In the context of materiality, the development of material technology has been critical for CLF, as the technique cannot be considered without materialization due to the need for an elastic capability for the curved crease. In state-of-the-art materialization and additive manufacturing, CLF is utilized to simplify fabricating the sustainable material that natural fiber-reinforced polymer was investigated (Rihaczek [21]). According to the obtained data from the existing studies on the topic, the most commonly used material types employed in CLF applications can be summarized as polypropylene sheets, wood composites containing spruce, maple, and various timber elements, GFRP combined with elastomer or polypropylene, and wood filaments. In this proposal as the capability of elasticity, polypropylene sheets are utilized.

After the prototyping process of frames on a small scale, the canopy function has been improved. In the realm of a responsive canopy, the dimension of one module is 90*90 cm. When it multiplies in one device it provides a 16 square meter shading area and the column height is 3.5 meters. Moreover, the canopy in which unfolded and folded versions is demonstrated through the digital modeling in Figure 6.

In detail, one canopy is made up of four arms total: four middle diagonal arms provide the main frame. Four quadruple modules are joined to each other by a short passive arm in the main frame. This strategic arrangement allowed the controlled movement of the flaps across all 16 modules with one motor. To foster the movement stepped motor is located on the column axis which leads to the opening and closing of the device. Through this integration, the proposal can contribute to the ongoing exploration of responsive architecture, offering new insights and possibilities for the design of adaptable built environments.

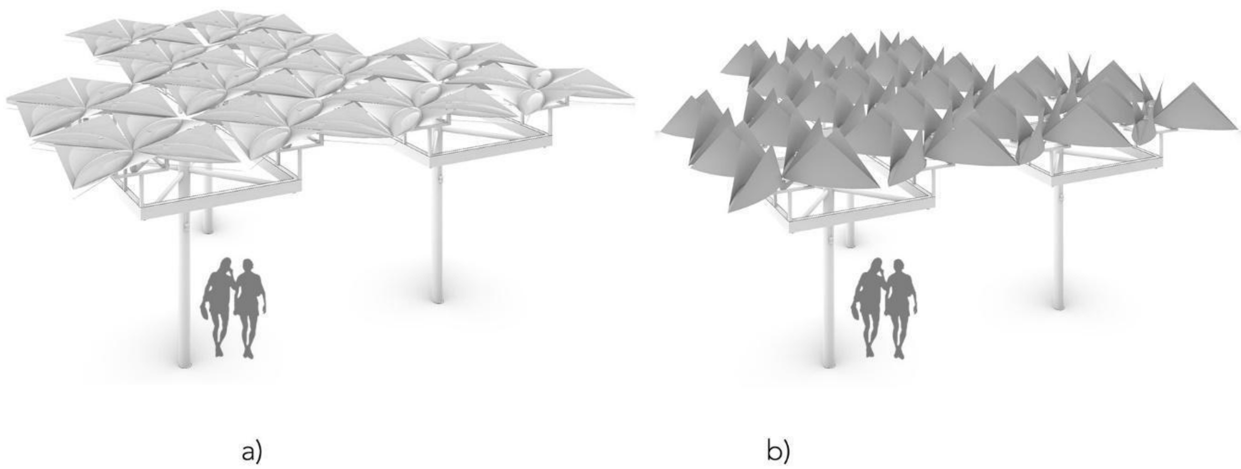

Figure 6: a) Unfolded version of kinetic canopy structure b) folded version of kinetic canopy structure

4. Conclusion

The designed canopy demonstrates how the cable bending systems can be utilized as a part of the actuation method, which has not been proposed in previous experiments. Although this integration has been achieved by understanding biomimetic knowledge, it has never been combined with cables. This method leads to open of multiple modules in the canopy structure by pulling the cables from the center of the frame. Thus, it offers advantages such as reducing noise and requiring less energy to initiate movement due to the decreasing number of motors. Moreover, the investigation of these mechanisms provides flexibility that allows the orientation of alignment and movements without causing damage, as it relies on compliance. The presented canopy can provide different opening situations according to user desires and the path of the sun, which differentiates this adaptability concept compared to traditional canopies and umbrellas. The research is presented as a hypothetical proposal for the building industry, however; it could search for different materials that have variable transparency and sustainability issues. Durability and material strength tests to withstand wind could be conducted in further research.

References

[1] F. Ascione, N. Bianco, G. Mauro, & G. Vanoli, "A new comprehensive framework for the multi-objective optimization of building energy design: harlequin", Applied Energy, vol. 241, p. 331-361, 2019. https://doi.org/10.1016/j.apenergy.2019.03.028

[2] Y. He, H. Zhou, & F. Fahimi, "Modeling and demand-based control of responsive building envelope with integrated thermal mass and active thermal insulations", Energy and Buildings, vol. 276, p. 112495, 2022. https://doi.org/10.1016/j.enbuild.2022.112495

[3] F. Favoino, Q. Jin, & M. Overend, "Towards an ideal adaptive glazed façade for office buildings", Energy Procedia, vol. 62, p. 289-298, 2014. https://doi.org/10.1016/j.egypro.2014.12.390

[4] M. Perino and V. Serra, "Switching from static to adaptable and dynamic building envelopes: a paradigm shift for the energy efficiency in buildings", Journal of Facade Design and Engineering, vol. 3, no. 2, p. 143-163, 2015. https://doi.org/10.3233/fde-150039

[5] N. Friedman, "Investigation of highly flexible, deployable structures : review, modelling, control, experiments and application," Ph.D. dissertation, \'Ecole normale supérieure de Cachan - ENS Cachan ; Budapesti műszaki és gazdaságtudományi egyetem (Budapest), 2011.

[6] L. Howell, "Compliant mechanisms", 21st Century Kinematics, p. 189-216, 2013. https://doi.org/10.1007/978-1-4471-4510-3_7

[7] Jagtap, S. P., B. B. Deshmukh, and S. Pardeshi, "Applications of compliant mechanism in today's worldA review," in *Journal of Physics: Conference Series*, vol. 1969, no. 1, p. 012013, IOP Publishing, July 2021.

[8] S. Harry, "Dynamic adaptive building envelopes – an innovative and state-of-the-art technology", Creative Space, vol. 3, no. 2, p. 167-183, 2016. https://doi.org/10.15415/cs.2016.32004

[9] E. Fazzare, "Rex + Front Studio Create Sun-responsive shade to protect Dallas museum," The Architect's Newspaper, https://www.archpaper.com/2013/11/rex-front-studio-create-sun-responsive-shade-to-protect-dallas-museum/ (accessed Mar. 25, 2024).

[10] Amy Frearson | 23 April 2013 "Umbrella facade for the Madrid Pavilion by 3Gatti Architecture Studio," Dezeen, https://www.dezeen.com/2013/04/23/umbrella-facade-madrid-pavilion-by-3gatti/ (accessed Mar. 18, 2024).

[11] Premier, A. Deho. "Unconventional solar screens", Tenda International, vol. 1, pp. 72–85, 2013.

[12] M. Asefi, M. Mitton, S. Currie. "A New Foldable Kinetic Architectural System: Through an Evaluative Approach of Built Examples, Case Studies: Resonant Chamber, Cheiljedang Research Center, Madina Shadi Project," معماری و شهرسازی آرمان شهر, vol. 10, no. 18, pp. 1–12, 2017.

[13] "Umbrellas in the mosque of the prophet's courtyard and surrounding open spaces," Abdullatif Al Fozan Award for Mosque Architecture, https://alfozanaward.org/mosques/umbrellas-in-the-mosque-of-the-prophets-courtyard-and-surrounding-open-spaces/ (accessed Mar. 18, 2024).

[14] S. Wang, M. Garlock, & B. Glišić, "Parametric modelling of depth-limited wave spectra under hurricane conditions with applications to kinetic umbrellas against storm surge inundation", Water, vol. 13, no. 3, p. 251, 2021. https://doi.org/10.3390/w13030251

[15] N. Megahed. "An exploration of the control strategies for responsive umbrella-like structures,", Indoor and Built Environment, vol. 27, no. 1, pp. 7–18, 2018.

[16] A. Körner, V. Eshraghi, A. Zolfaghari, L.A. Haghighi, M. Kalantari, & J. Knippers, Arch (k) kinetic Curved-line folding for elastic, adaptive building envelopes. In *Proceedings of IASS Annual Symposia*, Vol. 2018, No. 10, pp. 1-8, 2018.

[17] A. Vergauwen, L. D. Laet, and N. D. Temmerman, "Computational modelling methods for pliable structures based on curved-line folding," *Computer-Aided Design*, vol. 83, pp. 51–63, Feb. 2017, doi: https://doi.org/10.1016/j.cad.2016.10.002.

[18] M. Matini and R. Haghnazar, "Design of a curved-line bending mechanism inspired by skin wrinkles for elastic–kinetic structures in architecture", International Journal of Space Structures, vol. 33, no. 3-4, p. 124-137, 2018. https://doi.org/10.1177/0266351118804954

[19] M. C. Phocas, O. Kontovourkis, and K. Alexandrou, "The structural design and construction of a cable bending-active structure," *WIT Transactions on the Built Environment*, Jun. 2014, doi: https://doi.org/10.2495/mar140051.

[20] K. Takahashi, A. Körner, V. Koslowski and J. Knippers, "Scale effect in bending-active plates and a novel concept for elastic kinetic roof systems." In *Proceedings of IASS Annual Symposia*, vol. 2016, No. 16, pp. 1-10, 2016.

[21] G. Rihaczek *et al.*, "Curved Foldable Tailored Fiber Reinforcements for Moldless Customized Bio-Composite Structures. Proof of Concept: Biomimetic NFRP Stools," *Polymers*, vol. 12, no. 9, p. 2000, Sep. 2020, doi: https://doi.org/10.3390/polym12092000.

[22] D. M. Wood, D. Correa, O. D. Krieg, and A. Menges, "Material computation—4D timber construction: Towards building-scale hygroscopic actuated, self-constructing timber surfaces," *International Journal of Architectural Computing*, vol. 14, no. 1, pp. 49–62, Feb. 2016, doi: https://doi.org/10.1177/1478077115625522.

[23] Y. Tahouni *et al.*, "Self-shaping curved folding:," *Symposium on Computational Fabrication*, Nov. 2020. doi:10.1145/3424630.3425416

Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine De Wolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Copyright Declaration

Before publication of your paper in the Proceedings of the IASS Annual Symposium 2024, the Editors and the IASS Secretariat must receive a signed Copyright Declaration. The completed and signed declaration may be uploaded to the EasyChair submission platform or sent as an e-mail attachment to the symposium secretariat (papers@iass2024.org). A scan into a .pdf file of the signed declaration is acceptable in lieu of the signed original. In the case of a contribution by multiple authors, either the corresponding author or an author who has the authority to represent all the other authors should provide his or her address, phone and E-mail and sign the declaration.

Paper Title: Proposal for a Responsive Canopy Integrating Curved Line Folding Technique and Cable-Driven Systems

Author(s): Pinar Neseliler[a] and Yenal Akgun[b]

Affiliation(s): [a] Faculty of Fine Arts and Design, Department of Architecture, 35330, Izmir, Turkey.

[b] Faculty of Architecture, Department of Architecture, Dokuz Eylül University, 35210, Izmir, Turkey

Address: Fevzi Cakmak, Sakarya Street, No: 156, 35530/Izmir

Phone: +90 (534) 247 7556

E-mail: pinar.neseliler@ieu.edu.tr

Printed name: Pınar Neşeliler

Signature:

Location: İzmir/Turkey

Date: 24.05.2024