Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 1825-1833

ECCOMAS
Proceedia

COMPDYN 2021
8th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Streamed from Athens, Greece, 28 - 30 June 2021

ADAPTIVE BENDING-ACTIVE MODULES FOR A TENSILE SOLAR SHADING SYSTEM

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Abstract. *Adaptive façades can be a solution to many urban aspects such as sustainability and energy efficiency. Along these lines, a parametric analysis has been conducted to investigate the geometrical reconfigurations of the proposed adaptive solar shading system, the daylight performance with Rhinoceros and the plugins Grasshopper and ClimateStudio as well as the structural behaviour with Karamba3D. A skeleton structure synthesized by GFRP bending-active elements and stabilized by a secondary system of cables with variable length and a PTFE tensile skin leads to a lightweight modular structure with embedded actuation. The control system is capable of flexible patterns and multi-stages of open, semi and close configurations for different sun shading effects, depending on the changeable weather conditions and the relative response required in every part of the façade. The mechanism recalls a Class-2 Tensegrity system with springed hinges, where the rigid members and the hinges are substituted by lamellas, which can be bend by controlling the length of the cables. Furthermore, the ever-changing modular structure, especially to the plethora of different configurations, results in an aesthetically pleasing and organic dynamic filter for a tall building. Further research can be carried out about the wind load, how the structure can be naturally wind-resistant, and convective factors triggered by air movements between the façade and the building itself.*

Keywords: Adaptive Façade, Bending-Active Elements, Daylight Performance, Parametric Design.

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi:10.7712/120121.8602.18826

1 INTRODUCTION

Adaptive building envelope design may provide a real-time process of reconfiguration on a daily and seasonal basis enlivening the environmental performance of the building and enhancing the end-users’ internal comfort. A viable design for adaptive shading systems is necessary, especially when the building sector absorbs 40 % of the total energy use, even greater than the transport and industry sectors [1]. Current numerical studies evaluate the performance of external shades by scoping the impact of them with regard to the building envelope and the indoor environment [2-6]. Different typologies of shadings such as overhangs, vertical fins, horizontal shading, egg-crate shading, perforated screens and exterior blinds are giving potential opportunities for energy savings and improvement of indoor environment.

The sustainability role of the external shading elements can be further extended by means of adaptability either following environmental spaces and user needs or increasing the efficiency and optimizing the materials in order to reduce energy consumptions [7]. The effectiveness of kinetic façades in terms of energy savings is demonstrated in [8] with three existing buildings, Al Bahar Towers, Council House 2 and Q1 Headquarters Building. Adaptive folding shading systems placed externally on the Al-Bahar Tower in Abu Dhabi obtain different configurations, in order to regulate solar radiation and maximize the energy savings on cooling. In tracking the sun position, the kinetic system applied on the western façade of the Council House 2 in Australia provides full shading while minimizing the electricity consumption by 85 %. Following the sun path with three different configurations by the motorized swivel vertical louvers of the Q1 Headquarters Building in Germany, the adaptive external shading system succeeds in minimizing the electricity consumption, glare, as well as maximizing the heat gain and natural air ventilation.

A systematic analysis for daylight performance of an adaptive façade shading system integrated on a multi-storey office proves that rotation of the external shades and inclination of the slats may considerably influence the indoor daylight performance. Furthermore, shades can control the amount of incoming solar radiation and block the solar heat gain admitted into the open-space offices, while their impact on the air indoor temperature is significant by reducing the overheating and cooling loads [9-10]. Indoor environment is related to the comfort of the occupants and inevitably affects the well-being, productivity and consequently provokes the economic benefit. For example, the rising demand for lighting energy is also associated with the visual discomfort. Adaptive façade systems can lower the thermal load of the building by blocking the sunlight effectively, while daylight can be used properly during the day enhancing occupant comfort [11].

Adaptive sun shading systems can meet the changing solar radiation and provide an optimal shading as well as maximization of the daylight use [12]. Relevant adaptive and kinetic systems that reflect principles of embedded actuation and meditated to sustainable issues, functionality and aesthetics considerations are presented in this paper. An experimental prototype in full-scale of a tensegrity structure is actuated in obtaining a responsive behavior through adjustment of tension members and actuators [13]. In this context, a conceptual development of an adaptable structure aiming at structural simplicity and reduced energy consumption during the reconfiguration is presented in [14]. The proposed actuation method conveys the ability to the structure to obtain different geometrical reconfigurations. The methodology approach of the responsive skylight modules leading to the integration of architectural kinetic elements and computational devices is presented in [15]. Design requirements of the project are the optimization of the thermal and daylighting conditions. The prototype system is based on tensegrity principles incorporated with photovoltaic panels in its structure.

A similar approach on adaptive tensegrity architecture mimics the dynamics of a blinking sail as a dynamic sun-screen harvesting device presented in [16].

The current research project refers to the design and analysis of adaptive bending-active modules for a tensile solar shading system using as a case study the SFB1244 demonstrator tower located in the campus Vaihingen of the University of Stuttgart in Germany. A synergistic architectural and engineering approach of the adaptive bending-active modules leads to the design of a high efficiency envelope system with improved load-bearing performance. Essentially, the goal was to increase energy efficiency by controlling the light transmission and thus provide energy savings on cooling, heating and lighting demands. The characters of lightness, aesthetic quality and utilization flexibility were the most important to consider at the beginning of the designing process. The software used for the parametric analysis include Rhinoceros and Grasshopper for the 3D modeling, ClimateStudio for the daylight analysis and Karamba3D for the structural analysis; both ClimateStudio and Karamba3D work in the Rhino/Grasshopper environment. The daylight simulations were carried out on different days and times throughout the year, to test the response and effectiveness of the various configurations that the adaptive system is capable of, using the parameterization of the Grasshopper model.

2 DESIGN

2.1 Adaptive bending-active modules

The first idea was to use tensegrity for the mechanism of each module - specifically, a Class-2 tensegrity system for the vertical ribs of the shells, consisting of two cable-controlled rigid bars connected by a springed hinge. This approach, though, would have required a change of shape through approximation; this is why, at the end, the bending-active approach was chosen. This approach could keep the structure in the lightweight range, providing almost the same mechanism and the possibility of keeping the shape just as it was designed. The bending-active solution for the module mechanism recalls the bow-and-string principle; the original frame of bending-active elements consisted of a single vertically oriented bow in the middle. This disposition was eventually modified (as shown in Figure 1) to have two vertical elements instead, spaced enough to have a more even area distribution of the membrane.

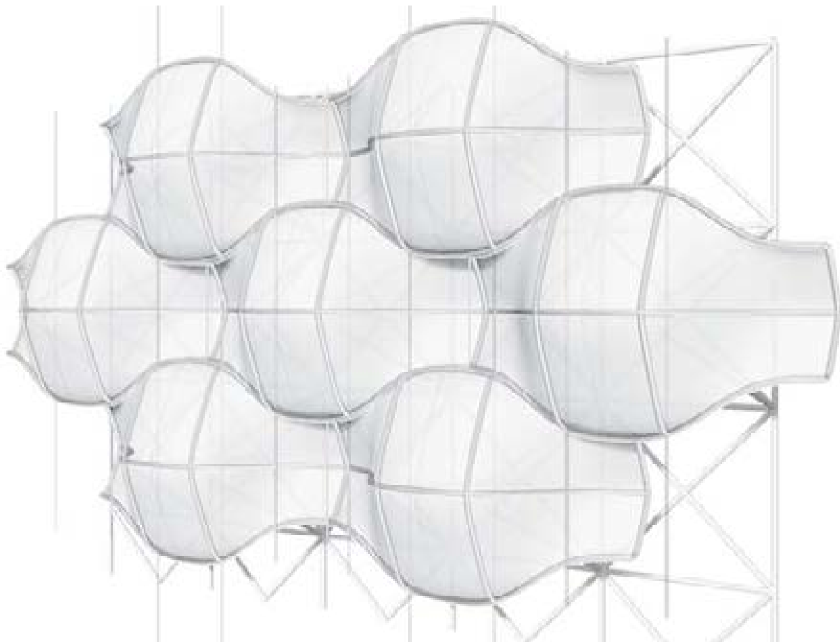

Figure 1: Adaptive bending-active system.

Each sun-shielding module is 2,00m wide and 0,90m tall, and its shape allows for each row to aesthetically interlock with the previous ones, with a 1,00m horizontal offset. The modules open and close by being constrained to the horizontal plane (identified with the midpoints of each row) by controlling the length of cables.

Glass Fiber Reinforced Polymer (GFRP) was chosen as the material for the bending-active frame; this material allows good behavior on long-term deformation cycles and a very high strength-to-weight ratio. Architectural Polytetrafluoroethylene (PTFE) was chosen as the material for the membrane; the resin-painted fiberglass has excellent properties for a second skin facade, thanks to its weather resistance and self-cleaning behavior.

2.2 Reconfigurations and integration to the Demonstrator

The system is designed to flexibly work in various sunlight conditions, thanks to the ability of each module to change in configuration to a certain degree, from completely closed to completely open. This is possible thanks to the GFRP skeleton of each module, stabilized by cables and a PTFE membrane. The embedded actuation system, controlled by sensors, makes it possible to have different sun shading (and aesthetic) effects, visible as gradients on the façade throughout the day (as shown in Figure 2).

The connection with the Demonstrator tower is realized through a steel space grid-like structure that gives the needed support to the panels and keeps the whole system lightweight, without obstructing the view from and to the building.

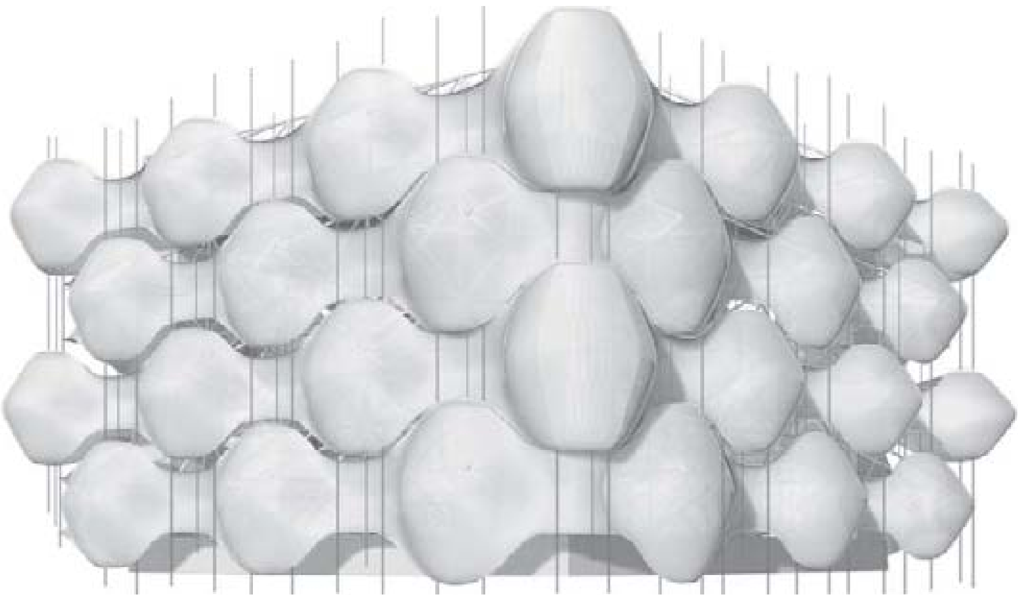

Figure 2: Gradients in the adaptive configuration model.

3 STRUCTURAL ANALYSIS

The structural analysis was originally intended to be carried out in SAP2000; in order to do that, the 3D model had to be assembled in GeometryGym, a software that works in the Rhino/Grasshopper environment and helps exporting the model to SAP2000, thanks to the controlled IFC conversion of the files. The issues had with such a work outline were in the double curvature of the shell elements. Said software works best when synthesizing big models, deconstructing them in smaller parts; when the mathematical conversion needed, from the Grasshopper boundary representation to a mesh, interests smaller elements with tighter tolerances it becomes a problem. The approximation was excessive and it resulted in troubles related to the bijective individuation of points; this was especially an obstacle for the external forces and support placement. The ideal solution was to control the degree of approximation of the curvature of each element through a software that was closer to the Grasshopper native environment. For this reason, in the present work, it was decided to carry out the analysis in the Rhino environment with Karamba3D; this software made it possible to better control the approximation of the original shape, for both the frame and the membrane. The membrane was meshed, and its area was used for the wind load; its support was the frame, deformed, while the supports of the frame itself were placed in the intersection between the central vertical and horizontal elements. The support structure was designed as a space grid structure, in order to be well distributed and light in both aesthetic and structural terms, while allowing for the full movement of each module.

3.1 Wind load

The main loads considered were self-weight and wind load; the latter was calculated from the local legislation and the Eurocodes. The obtained wind load was related to a wind speed of 81km/h; this was the worst-case scenario, and in Stuttgart this condition is very rare (less than 30 hours per year). Another scenario was taken into account, imagining the request of the client to have the structure designed for 50km/h and 60km/h (wind conditions still rare for the city), to consider the advantages in terms of lightness and economy at the expense of having the façade closed when said wind velocities are reached. Tangential wind was also considered.

3.2 Results

After having the model assembled in Karamba3D, a strict hierarchy was followed in the relationship between each element of the façade, so to have their structural behavior connected just as expected in working conditions. A nonlinear analysis was needed, because of the bending-active approach used; after solving using the specific analysis tool, the ModelView tool allowed the visualization of displacements (Figure 3) and stress on each of the models. A specific set of tools was placed on the Grasshopper canvas to get the axial stress results on each element. The highest displacements measured on the module frame were 2,83mm at the extremes, without considering the stabilizing effect of the steel cables. The highest value of tension measured on the support system is 0,61 kN, while the highest value of compression is 0,43kN.

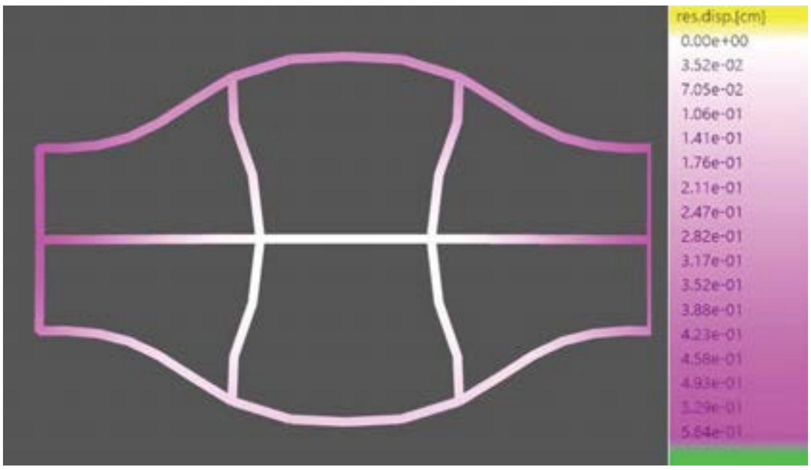

Figure 3: Karamba3D result window.

3.3 Support system sections

Following positive outcomes related to buckling, displacement and axial stress tests, the profiles chosen for the original wind condition (81km/h) were the EN10210 33,7x3,2mm with circular section. The provided results for a lower wind condition (60km/h) have led to a thinning of the profile section, now the circular EN10210 26,9x3,2mm, which leads to increased lightness and economic convenience.

4 DAYLIGHT ANALYSIS

The daylight analysis was carried out in ClimateStudio; the chosen days for the simulations were the two solstices and the two equinoxes, and for each day the hour chosen was 9:30 am, 12:30 am and 15:30 pm.

All materials have been assigned to each element of the 3D model. Three case studies have been considered in this project: the bare structure, fully open configuration and adaptive configuration.

4.1 Parameterization

The parameterization of the façade allowed each corner to independently open and close, causing a dynamic gradient on each side of the building. By changing the corner values in order to follow the sun position at a certain time, the ideal overall configuration was researched each time (as shown in Figure 4 for March 20th, 15:30). Issues with the model were related to the cable slits, excessively large, and the BRep approximation from Grasshopper to ClimateStudio, that caused some light to creep in. The solution was to reduce the slits and to mesh the entire façade, so the software could read it properly.

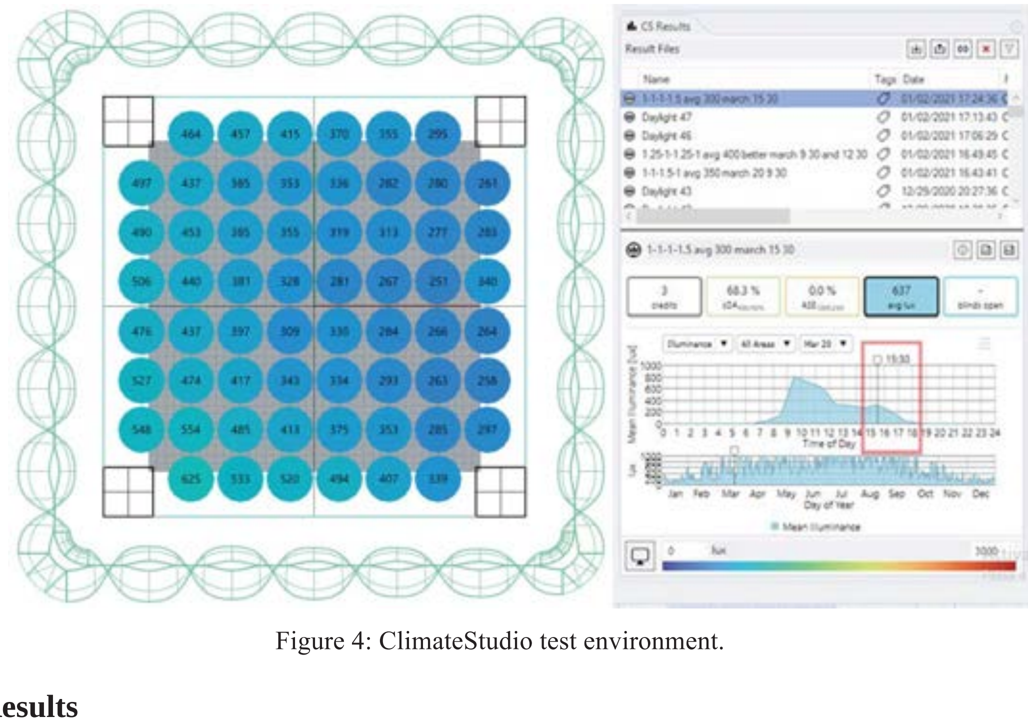

Figure 4: ClimateStudio test environment.

4.2 Results

The results (Figure 5) show that the adaptive configuration always respects the ideal lux range (350-450), with peak values hardly over 500; the completely open configuration has worse results, especially during the cold months. The worst condition is, by far, the bare structure, with average peak values of over 600lux. Furthermore, the façade shows its dynamic aesthetic value the most when following the sun position in the adaptive configuration.

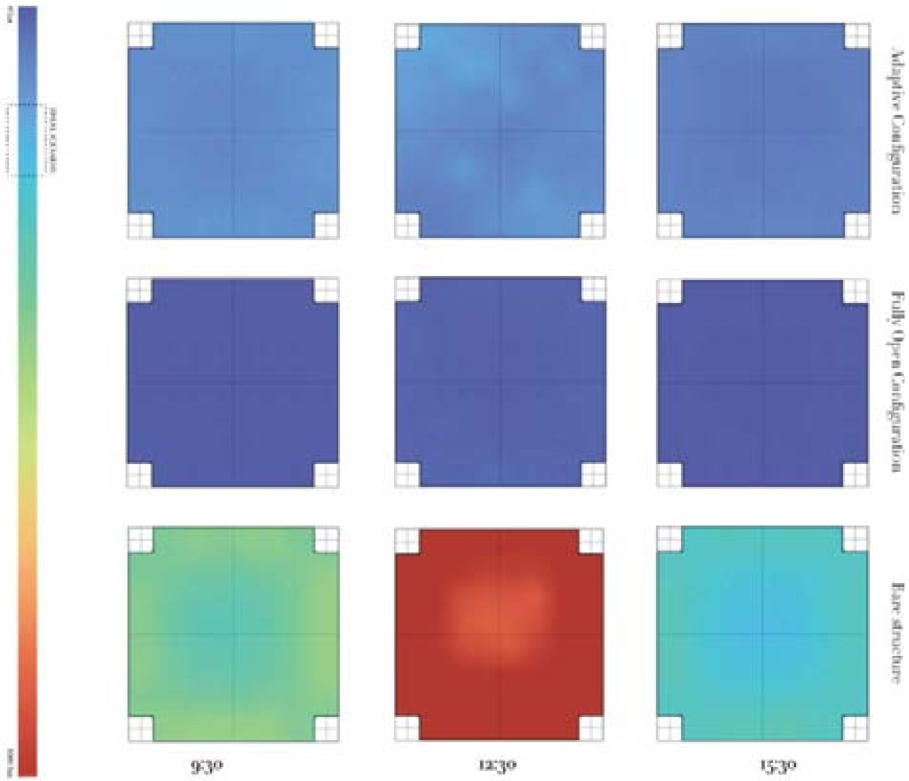

Figure 5: Daylight simulation results (21st of December).

5 CONCLUSIONS

5.1 Overall results

The designed adaptive façade proved to be very effective in its dynamic sun-shielding behavior, providing the right amount of daylight even when most exposed to the sun radiation. The structure, including the support system, is lightweight and thin, which is convenient for both its cost and aesthetic value. Furthermore, the sculpted feel given to the building helps create a sense of dynamism and the character of the façade becomes the character of the building.

5.2 Further considerations

The structure, especially the support system frame, can benefit from form-finding approaches aimed at optimizing the mass and geometry distribution of its elements. Furthermore, a tensegrity solution for the same space grid can be researched.
Form-finding can also be used for the modules, to consider a change of shape related to the dynamic action of the wind in any configuration. This requires a new parameterization and the use of accessory tools in the Grasshopper environment.

ACKNOWLEDGEMENTS

Partly funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project-ID 279064222 – SFB 1244.

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