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Numerical analysis of a bending-active plate for a sun-shading façade system

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ABSTRACT

Unitized curtain walls with integrated sun-shading systems are widely used for high-rise building façades. A sun-shading façade system is presented that consists of bending-active plates of glass-fiber reinforced polymer arranged in three layers over the height. The elastic plates are point supported on the four corners by diagonal steel members arranged in pairs. A rotating actuator installed on each diagonal pair modifies the respective opening angle of the members inducing thus elastic deformations on the connected bending-active plates. The steel members act as scissor-like elements while they are supported on the curtain wall mullion using extruded aluminum pressure plates and U-channel rails. The bending-active plates act as external horizontal louvers of the building façade providing different levels of sun-protection through respective reversible deformed shapes obtained. In the current paper a bending-active plate is numerically analyzed in its structural behavior based on a Finite-Element Analysis. Different symmetric curvatures of the bending-active plate are obtained based on the scissor-like elements actuation. Specific opening angle values of the scissor-like elements are appointed for the simulation and the form-finding of the plate. The analysis refers to the form-finding and load-deformation behavior of the bending-active plate under actuation of its supports and external wind loads.

1. INTRODUCTION

In recent years, many adaptive facades have been implemented in medium to high-rise buildings, which compose the project's building envelope together with the curtain walls. The geometry of the members, the connections and the boundary conditions constitute basic critical parameters for the design of adaptive facades. These parameters define the kinematics of the systems applied, i.e., the transformational possibilities and kinetic characteristics, e.g., direction and magnitude of transformation (Schumacher et al. 2012). In this framework, different typologies can be produced from every type of

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movement based on the degrees of freedom (DOF) related to geometrical restrictions, such as the number of coordinate axes (Fiorito et al. 2016). 3-DOF can be identified for each type of motion based on the form of change in position, or orientation with regard to one, two, or three axes. For example, rotation can produce three different typologies: swivel (restricted rotation), revolving (free rotation) and swing (off-center rotation flap) (Schumacher et al. 2012). Moreover, combining two primary movements, translation and rotation, can generate other typologies, such as expanding, contracting, folding, directional twist, or rolling.

With the advancement of new simulation methods and computational tools, form-finding strategies are increasingly implemented in the development of adaptive systems. An example of new possibilities emerging from a physically informed digital design process comprises the research on bending-active structures. Bending-active attributes describe various structural systems that employ large deformations as a form-giving and self-stabilizing strategy (Phocas and Alexandrou 2018a; Phocas and Alexandrou 2018b). These systems use the elastic deformations of planar, off-the-shelf building materials to generate structures emerging from the combination of curved elements (Lienhard et al. 2014; Phocas et al. 2019). While the traditional maxim in engineering is to limit the amount of bending in structures, elastic systems use bending to create complex and lightweight designs. Many aspects qualify a structure as bending-active, while the sizeable elastic deformation of its constituent elements comprises the most prominent constraint for proper design. To maintain the strain within the elastic limits of the material, the building elements must be necessarily thin and slender, and the material of a relatively low elastic modulus and high strength (Kotelnikova-Weiler et al. 2013). Within this frame, planar surfaces can form single or double curvature surfaces according to the type and magnitude of the force applied (Lienhard et al. 2014).

A recent example of a textile-based hybrid system with adaptive properties is the “Softhouse” project. The responsive façade is formed by textile membranes with embedded photovoltaic (PV) cells and glass-fiber polymer (GFRP) members, resulting in a hybrid system of form- and bending-active members. Each strip is a textile hybrid system with a 4.0 m open mesh membrane attached to a 6.0 m cantilevered pultruded GFRP board of 500x10 mm dimensions (Lienhard et al. 2015). A further example is the kinetic media façade of the Thematic Pavilion for the Expo 2012 in Yeosu, South-Korea. The facade is 140 m long and 3.0 to 13.0 m high. It consists of 108 kinetic GFRP louvers, which are supported on the top and bottom edge by fixed supports on one corner and extendable actuators on the other corner. The actuators push the upper and lower edges together and lead to an elastic bending and a side rotation of the GFRP elements (Knippers and Speck 2012).

Reflecting on the examples above, the current paper refers to a hybrid unitized curtain-wall system design with integrated kinetic sun-shading units directly supported on the panels' split mullions. Specifically, the façade units can be entirely prefabricated and assembled before an on-site installation. The sun-shading units have been presented in their design composition and parametric associative design of their deformed shapes in Sergidis and Phocas (2022). The present paper presents the Finite-Element Analysis (FEA) of the corresponding bending-active plate of the units for symmetrical deformations under actuation of its supports and under external acting wind loads. The following section presents the design concept of the sun-shading units. Section 3 presents the developed structural model for the FEA of the bending-active plate and its deformed shapes based on respective rotations of its supports. Section 4 includes the conclusions of the analysis.

2. DESIGN CONCEPT

The sun-shading units consist of a bending-active GFRP plate arranged in three layers over the height of each unitized curtain wall panel, which is supported on 50 cm long steel bars of scissor-like elements on the four corners of each plate. The scissor-like elements are connected to an aluminum U-channel over brackets and on the panels' split mullion through use of custom mullion extruded aluminum pressure plates. Fig. 1 shows a façade unit elevation, a vertical section and the connection principle of the unitized system panels. The elastic plates have a rectangular geometry of 1.40 m length and width. A rotating actuator installed on the pin connection (i.e., bracket) of each scissor-like elements pair modifies the respective relative opening angle of the elements, in inducing elastic deformations of the connected bending-active plates. Through reversible deformability of the bending-active plates, the latter act as external horizontal louvres. Based on the actuation of the scissor-like elements, different curvatures of the bending-active plates are obtained.

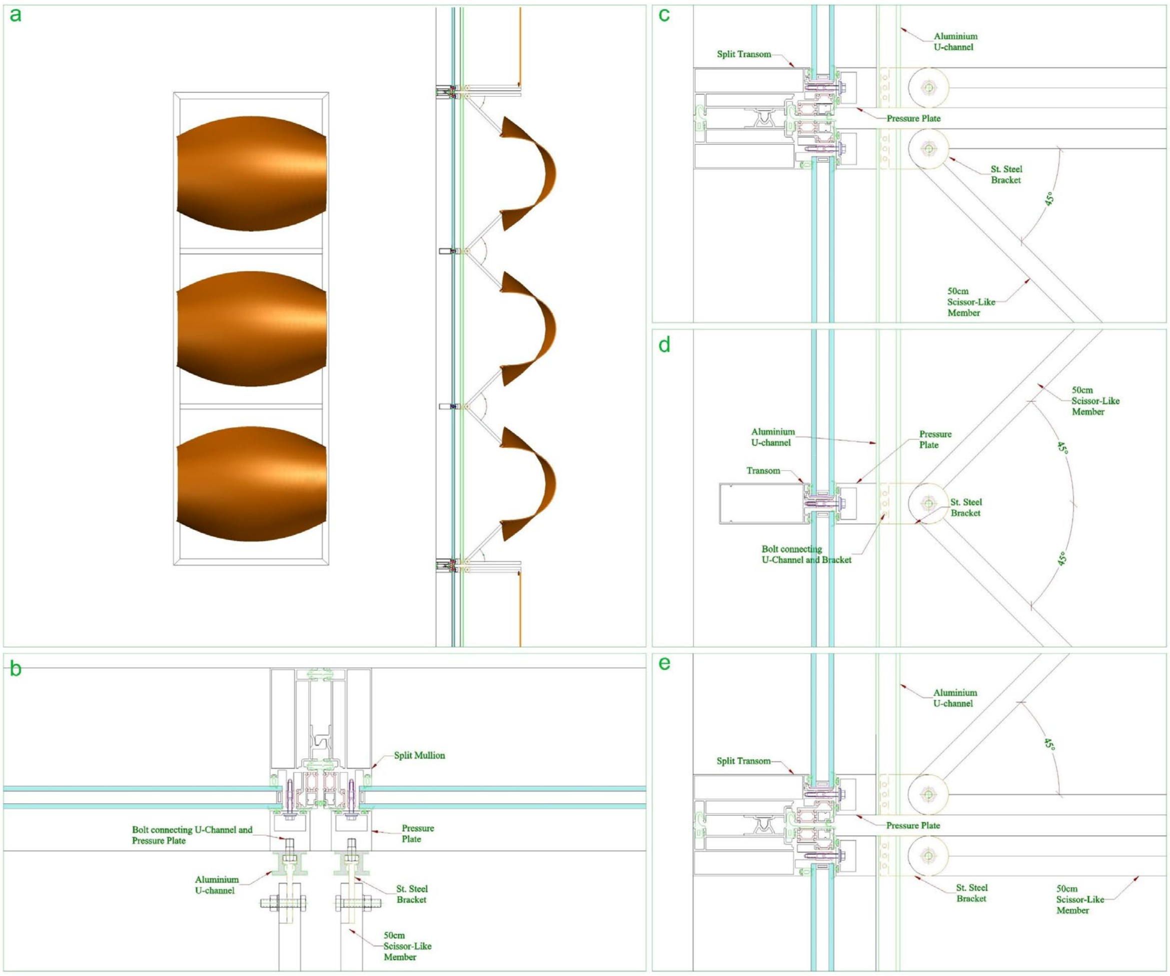

Fig. 1 Façade unit design concept: a) Unit elevation (left) and vertical section (right); b) Horizontal section showing the joint and connection between adjacent units; c)-e) Vertical section of adjacent units.

3. STRUCTURAL MODEL

The numerical investigation of the model of the sun shading system was conducted through a progressive form-finding and load-deformation FEA with the software program SOFiSTiK® (SOFISTIK AG 2014a). The plate's bending was simulated by taking into consideration both, the self-weight of the panel and internal material stresses, as well as the external wind loads. The system simulations are based on the nonlinear third-order theory, considering geometrical nonlinearities and large displacements. In addition, a linear stress-strain behavior of the material of the elastic plate has been assumed in the analysis, in order to focus on the geometrical aspects of the active formation process of the element. The materials and cross-sections were defined through AQUA (SOFISTIK AG 2014b), a module of SOFiSTiK's main database, while the geometrical definition of the system was produced through the McNeel Rhinoceros program (Robert McNeel &

Associates 1993-2018). The SOFiLOAD module (SOFISTIK AG 2014c) was used for the definition of load, while ASE (SOFISTIK AG 2014a) was used as the general static analysis solver. SOFiLOAD and ASE were handled through the alternative text input tool provided by SOFiSTiK, TEDDY. The analysis follows an incremental induction of bending deformation, where inner stresses of the material developed in each step are stored in the model.

The primary component of the sun shading unit, the GFRP plate, has been modelled with quadrilateral elements of a mesh of 14x14. The GFRP plate has a thickness of 5 mm. Its material properties, including a Young's modulus of 195 GPa and a yield strength of 500 MPa, have been incorporated into the model. The scissor-like elements are constructed from S355 structural steel with a solid square section of 25x25 mm. The material properties of the steel, including a Young's modulus of 210 GPa and a yield strength of 355 MPa, have been incorporated into the structural model. To accurately simulate the motion of the scissor-like elements, prestressing steel cables with a diameter of 10 mm have been utilized as substitutes for the actuators. By adjusting the length of these cables, the desired opening angle of the scissor-like elements is achieved. Fig. 2 presents the initial form and the deformed shapes of the bending active plate for specific scissor-like element relative opening angles of 0, 15, 30 and 45 degrees.

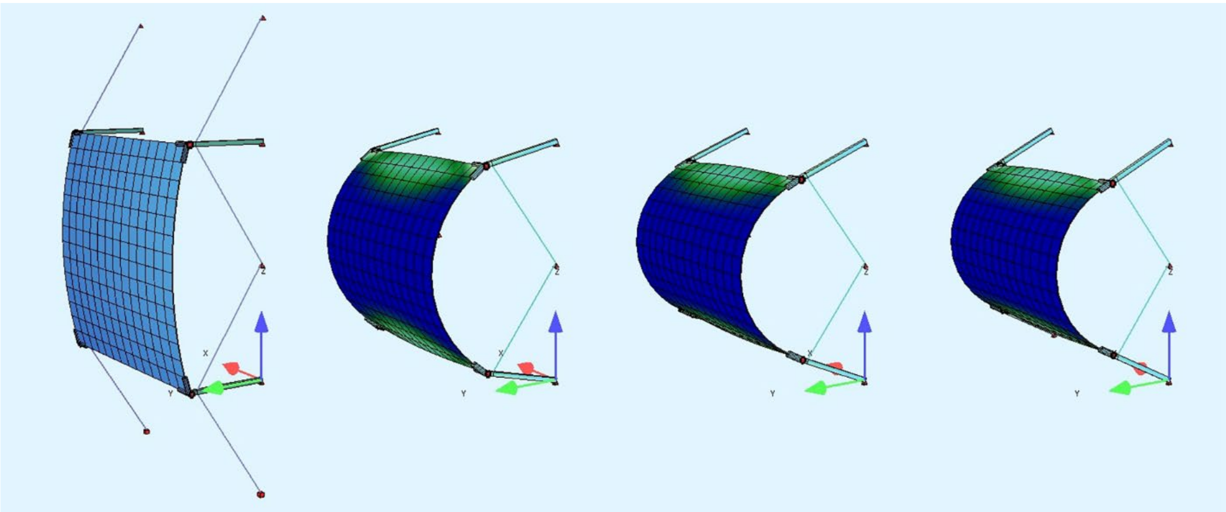

Fig. 2 Initial and deformed shapes of bending active plate for scissor-like elements' relative opening angles of 0, 15, 30 and 45 degrees from left to right.

3.1 Structural Analysis and Results

The structural analysis of the sun shading system provided the maximum absolute and relative deformation of the plate, stress, bending moment, shear and axial force with regard to the relative opening angle of the scissor-like elements under self-weight and an external wind load of 1 kN/m^2 acting on the plate's surface. The maximum deformation of the plate occurs when the scissor-like elements reach an opening angle of 45 degrees. This highlights the importance of considering the structural behavior of the system at its maximum operating conditions. The application of wind load does not significantly affect the results compared to the analysis without wind load. Furthermore, the maximum stresses and bending moments developed within the plate increase proportionally with the relative opening angle of the scissor-like elements. Interestingly, a negative relative deformation was observed at an opening angle of 35 degrees, indicating a decrease in the plate's deformation compared to the previous angle of 30 degrees. This suggests the existence of an optimal range of motion for the scissor-like elements that minimizes the plate's deformation and shear forces. Additionally, the self-weight of the plate has a minor impact on the deformed shape. Lastly, the recorded shear and axial forces are slightly lower after application of the wind load, indicating that the wind load partially relieves some of the forces acting on the system. Table 1 summarizes the maximum recorded values obtained for the scissor-like elements' relative opening angles. Table 2 summarizes the respective results under the applied wind load on the plate surface. Figures 3-8 present the FEA results in diagrammatic form.

Table 1. FEA maximum values for scissor-like elements' relative opening angles and plate's self-weight

Opening Angles	Max deformation [mm]	Relative deformation [mm]	Max stress [MPa]	Max M [kNm]	Max V [kN/m]	Max N [kN]
0	0.01	N/A	0.05	0.00	0.00	0.06
5	142.80	142.80	54.10	0.23	1.27	88.50
10	215.50	72.70	88.40	0.37	2.28	97.70
15	260.90	45.40	115.80	0.48	2.72	122.90
20	288.00	27.10	139.10	0.58	3.12	139.60
25	301.30	13.30	160.00	0.67	3.59	149.80
30	303.10	1.80	179.10	0.75	4.01	157.30
35	298.00	-5.10	201.70	0.84	3.24	228.60
40	299.30	1.30	213.50	0.89	4.81	172.40
45	322.30	23.00	235.50	0.98	3.50	248.50

Table 2. FEA maximum values for scissor-like elements' relative opening angles, plate's self-weight and wind load

Opening Angles	W-Max deformation [mm]	W-relative deformation [mm]	W-Max stress [MPa]	W-Max M [kNm]	W-Max V [kN/m]	W-Max N [kN]
0	5.00	N/A	9.81	0.05	0.25	47.80
5	142.90	137.90	55.30	0.24	1.29	51.60
10	215.90	73.00	89.70	0.38	2.06	83.70
15	261.40	45.50	117.10	0.49	2.54	108.50

20	288.70	27.30	140.60	0.59	2.98	125.50
25	302.00	13.30	161.60	0.68	3.44	135.80
30	303.90	1.90	180.80	0.76	3.86	143.90
35	298.90	-5.00	203.80	0.85	3.11	210.80
40	299.30	0.40	215.30	0.90	4.64	159.40
45	322.30	23.00	229.10	0.99	3.36	231.00

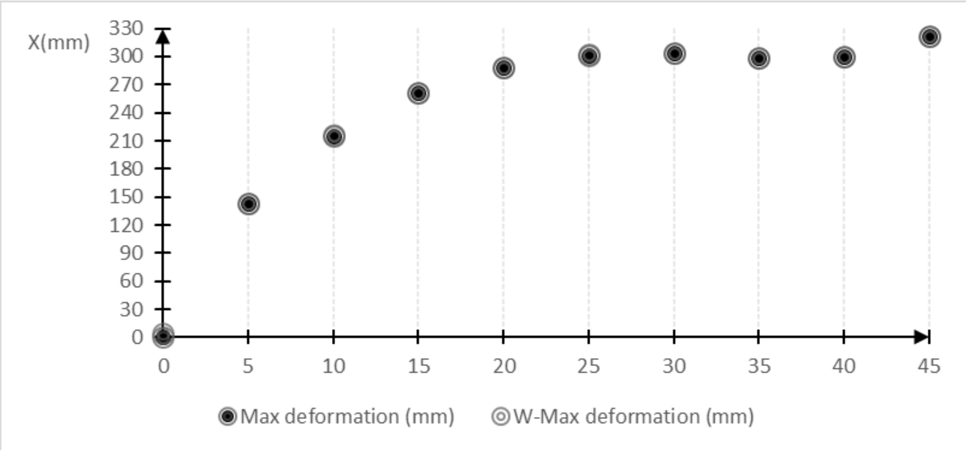

Fig. 3 Maximum plate's deformation for different relative opening angles of scissor-like elements

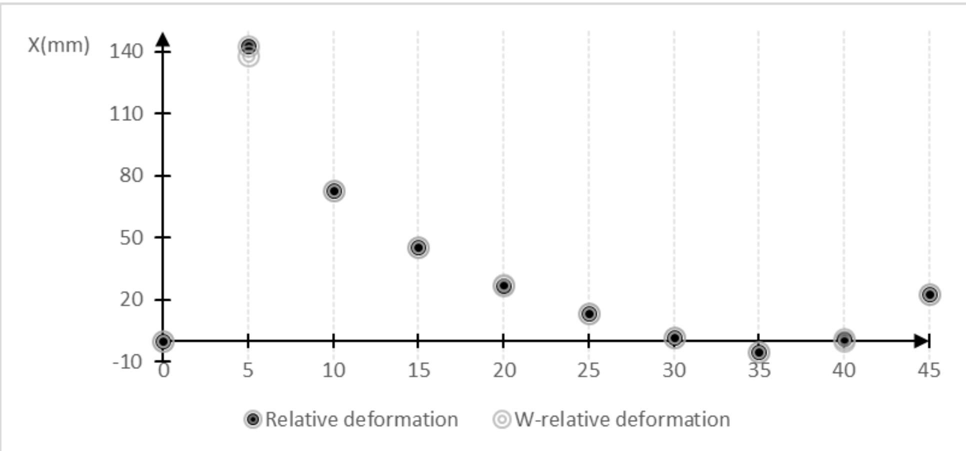

Fig. 4 Relative plate's deformation for different relative opening angles of scissor-like elements

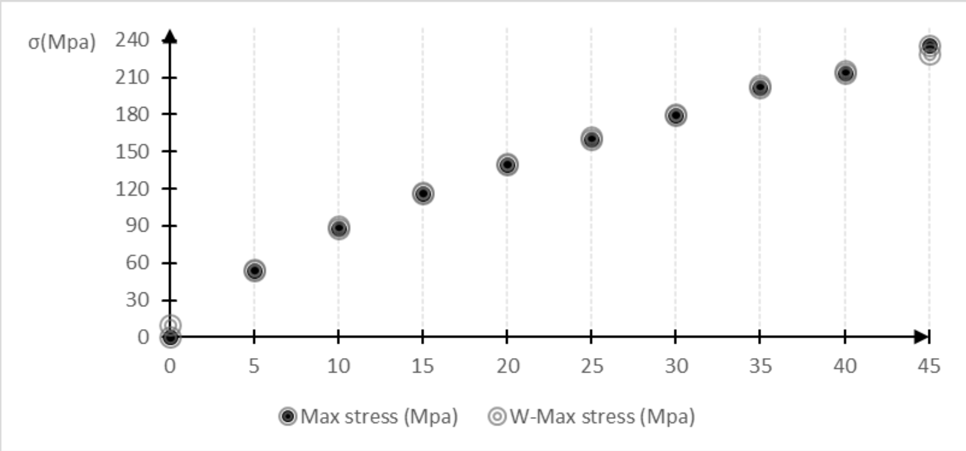

Fig. 5 Maximum plate's stresses for different relative opening angles of scissor-like elements

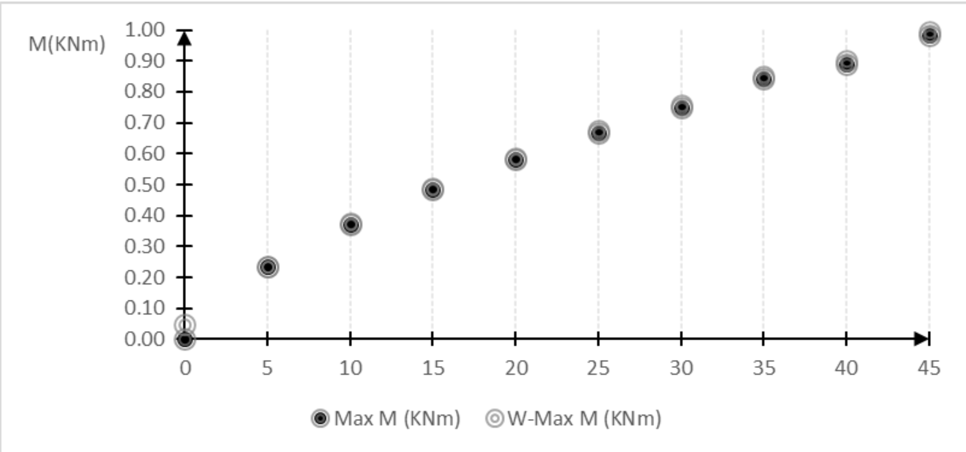

Fig. 6 Maximum plate's bending moments for different relative opening angles of scissor-like elements

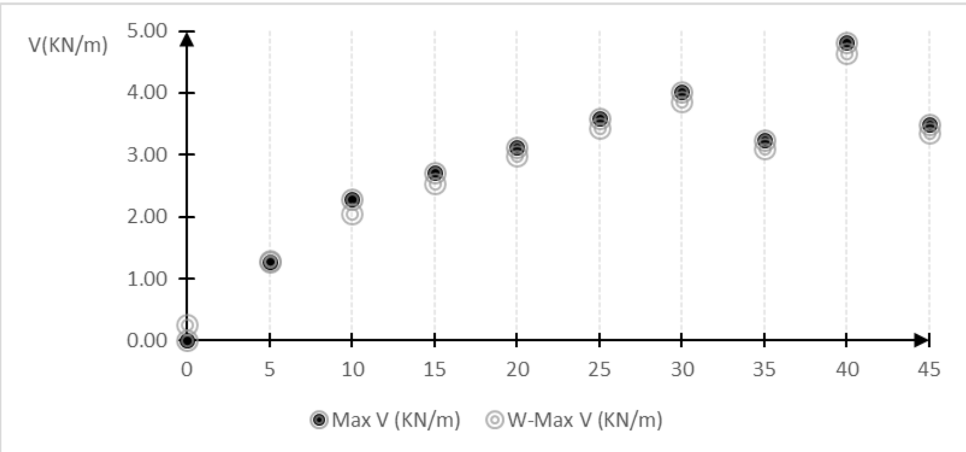

Fig. 7 Maximum plate's shear forces for different relative opening angles of scissor-like elements

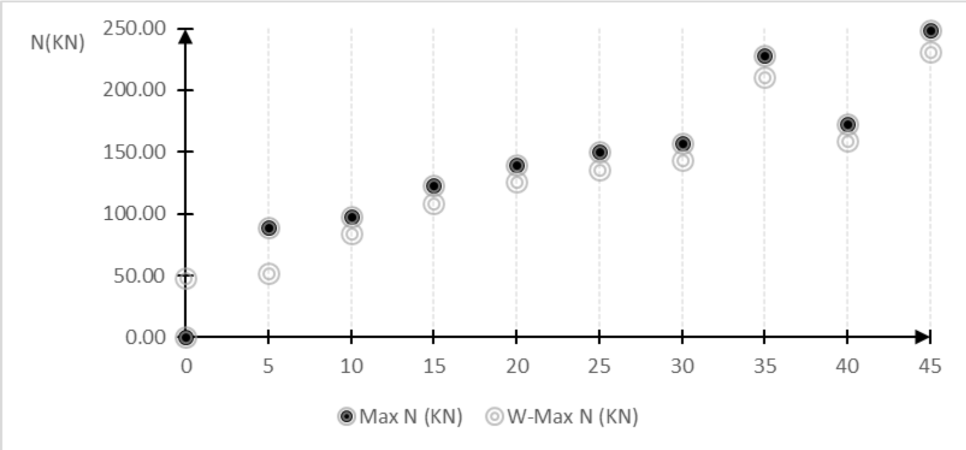

Fig. 8 Maximum plate's axial forces for different relative opening angles of scissor-like elements

3. CONCLUSIONS

The study presented the design concept for a unitized curtain wall system with integrated sun-shading units. The system utilizes bending-active plates made of glass-fiber reinforced polymer and supported by scissor-like elements on the corners. The Finite-Element Analysis of the structural behavior of a bending-active plate provided insight into its form-finding and load-deformation behavior under actuation and external wind loads. The results of the study showed that the maximum deformation of the bending-active plate occurs at an opening angle of 45 degrees, emphasizing the importance of considering the structural behavior of the element at its maximum operating conditions. Furthermore, the maximum stresses and bending moments experienced by the plate increase with the opening angle of the scissor-like elements. The self-weight of the plate has a minor impact on the deformed shape, and wind load partially relieve some of the forces acting on the plate. The study contributes to understanding bending-active structures and their potential applications in adaptive facades. Further research will focus on optimizing the design and exploring different nonsymmetrical forms of the bending active plate based on further combinations of relative opening angles of the scissor-like elements.

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