

# Shape-changing tensegrity-membrane building skin

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**Abstract.** Building skins are persistently exposed to changes in the weather, including the cases of weather extremes, increasing in frequency due to global climate change. As a consequence of the advancements of digital design tools, the integration of the weather conditions into the design process is much smoother. The impact of the ambient conditions on buildings and their structures can be digitally analyzed as early as in the conceptual design stage. These new design tools stimulate original ideas for shape-changing building skins, actively reacting to the dynamic weather conditions. In the paper, a digital design method is introduced, leading towards the design of a building skin, able of the passive shape adaptation when subjected to the wind. The designed building skin consists of a tensegrity structure where the tensioned elements are substituted by a tensile membrane, creating a self-equilibrated building skin element. In the previous research, a small prototype of this wind-adaptive element was created. The computer simulations are employed to predict the adaptive behavior of a bigger, full-scale building skin element. The before-mentioned building envelope becomes an active player in its surrounding environment, passively reacting to the wind in real-time, thanks to the geometric and material properties. Due to the local shape changes caused by the wind force, the wind can be perceived unconventionally through the adaptive building structure.

## 1 Introduction

In the past decades, the topic of the nature-adaptive built environment has been actively discussed among architects [1-4]. This intriguing architectural approach blurs the boundaries between architecture and nature. The examples of adaptive systems found in nature inspire the geometries, as well as the material properties for designing the architectural passive (without the computer control) adaptive systems [3, 5, 6]. Adaptive architecture, instead of resisting the fluctuating, even extreme weather or external load conditions, can instantly react and adapt to them. This adaptive behavior implies the consequent optimization of material use, which leads to lighter structures [7]. Designing for dynamic, future climatic conditions,

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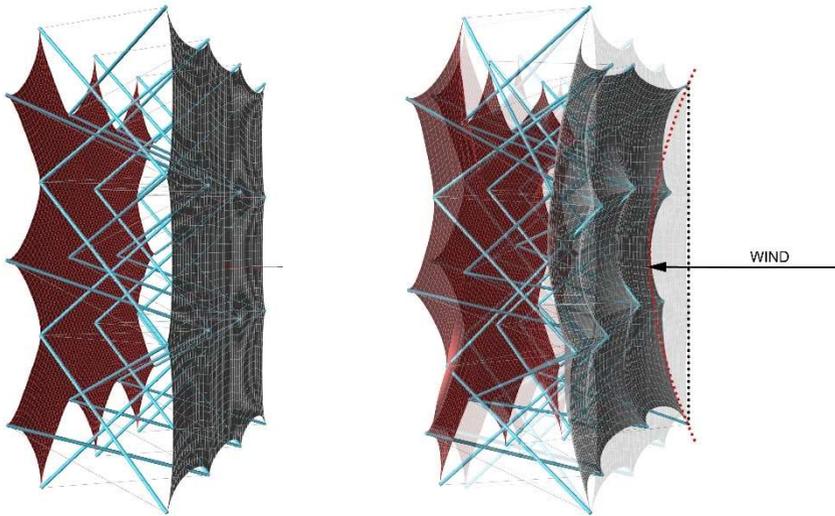
however, requires an interdisciplinary design approach already from the first ideas and concepts. With the progressive design tools, the interplay between architectural ideas, nature, and structural response of architecture itself can be observed interactively, early in the conceptual design stage. This paper presents a digital approach using Grasshopper for Rhino<sup>1</sup> and its extensions for developing, loading and consequently analyzing a wind-adaptive façade element.

## 1.1 Design method

### 1.1.1 Digital design of wind-adaptive building skins

Utilizing these popular digital design tools for architects, the influence of the wind, along with the real-time shape change of architecture exposed to the wind, can be observed and examined in the conceptual stage of architectural design.

The elements forming wind-adaptive building skin, proposed in this paper, consist of tensegrity (tensional integrity) [8] structure and tensile fabrics that replace some of the elements in tension. The shape change of one adaptive element is caused by momentary wind pressure. The structure responds passively, ergo without the computer control. The geometrical configuration of the tensegrity-membrane, as well as employed materials, enable the reversible shape adaptation under load (Fig. 1).



**Fig. 1.** Left – wind-adaptive element in the form-found state; right – wind-adaptive element subjected to the wind force (the deformation is exaggerated).

### 1.1.2 Specific methods to create the tensegrity-membrane façade element

The basic geometric, as well as material relations, were tested on a small physical prototype in the previous work [9]. A hybrid design approach was used, combining the digital simulations with physical prototyping. The live physics engine for interactive simulations, Kangaroo 2 for Grasshopper, was used to set the geometric relations, as well as material properties of the adaptive element. Kangaroo 2 is a particle-spring system based on dynamic relaxation method<sup>2</sup>. The fabric material properties in the simulation, i.e., pre-tension and strength, were defined through the tests on the physical prototype of the same dimensions. The stretch

properties of the real fabric were compared to the behavior of the simulated fabric in Kangaroo 2.

The behavior of the full-scale adaptive element, presented in this research, is explored using Kangaroo 2, Kangaroo 2 Engineering<sup>3</sup>, and the parametric structural engineering tool, Karamba 3D<sup>4</sup>, which is based on the Finite Element Method. The tensegrity-membrane element consists of 1.0 m long wooden struts, 0.78 m long steel cables, and membranes, made of flexible fabric that covers the front and back of the adaptive element. The structure is lightweight, one element weights 9.1 kg. Tables 1 and 2 depict the material properties used in the simulations.

**Table 1.** Material settings in Kangaroo 2.

	Diameter $\Phi$ or thickness $h$ [m]	Stiffness $k$ [N/m]	Young's Modulus $E$ [Pa]	Pretension $0=\max.; 1=\min.$ [-]
<b>Struts</b>	$\Phi = 16e^{-3}$	2 110 080	$10.5e^9$	1
<b>Cables</b>	$\Phi = 2e^{-3}$	523 333	$130e^9$	0.99
<b>Membranes (isotropic)</b>	$h = 0.51e^{-3}$	84 150	$16.5e^7$	0.90

In Kangaroo 2 Engineering, identical settings can be used. However, instead of the percentual pretension, the pretension of the cables and tensile membranes is set in Newton. The value of 3 Newton is set to attain the equilibrium state, so the struts are in pure compression, whereas the cables, and the fabric are in pure tension (Fig. 2).

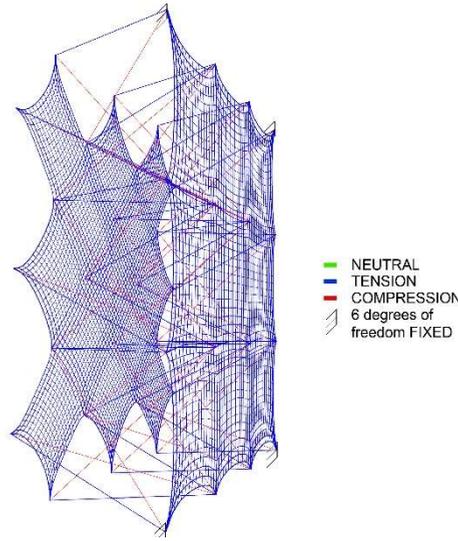
**Table 2.** Material settings in Karamba 3D.

	Diameter $\Phi$ or thickness $h$ [cm] (material)	Specific weight $\gamma$ [kN/m <sup>3</sup> ]	Young's Modulus $E_1, E_2$ [kN/cm <sup>2</sup> ]	In-plane Shear Modulus $G_{12}$ [kN/cm <sup>2</sup> ]	Transverse Shear Modulus $G_{31}, G_{32}$ [kN/cm <sup>2</sup> ]	Yield Strength $f_{y1}, f_{y2}$ [kN/cm <sup>2</sup> ]
<b>Struts</b>	$\Phi = 1.6$ (wood)	6	1050	360	360	2.5
<b>Cables</b>	$\Phi = 0.2$ (steel)	78.5	13 000	5000	5000	23.5
<b>Membranes (orthotropic)</b>	$h = 0.1$ (fabric)	5.7	$E_1 = E_2 = 16.5$	6.157	6.157	4.575

Table 2 depicts the overview of material properties set in Karamba 3D. The settings of stainless steel cables are based on [10], the properties of wood are derived from EN 338:2016 Structural Timber – Strength classes, while the material properties for membranes with orthotropic behavior are derived from [11]. A small drawback of Karamba 3D is that it does not use basic SI units.

## 1.2 Application on building façade

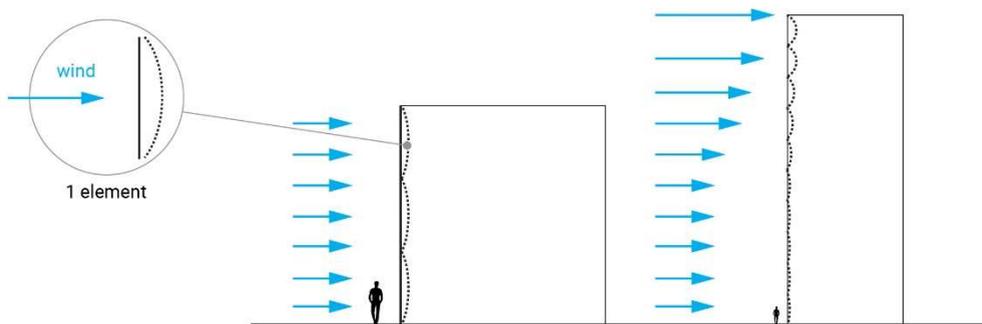
The wind flow pattern in the built environment is shaped by the configuration at the urban and the local building scale. Other factors that have an impact on the wind flow are i) the rotation of buildings towards the wind; ii) their size; iii) the global building shape; iv) the building façade's surface roughness.



**Fig. 2.** The scheme of the forces in the tensegrity-membrane element in the equilibrium state.

The application of the wind-adaptive tensegrity-membrane elements to the upwind building façade creates a shape-changing skin, which morphs into a textured, rough surface depending on the power of the acting wind (Fig. 3). The motivation for investigating the effect of dimpled surface in architectural scale is the research of wind drag force reduction in the automotive industry [12], the sharkskin contributing to the water drag force reduction in biology [3], and suggestions of implementing this effect on building skins in architecture [13].

The influence of the adaptive building envelope on the wind pattern around the buildings, the wind drag force, and the wind surface pressure was investigated in the previous research. The adaptive skin was applied to two basic shapes and an aerodynamic shape. The dimpled building skin, created as a consequence of the acting wind pressure, can lead to the reduction of drag force, as well as reduction of wind suction on the leeward side of the building. The particular results are dependent on the global shape of the building [9].



**Fig. 3.** The principle of the adaptive behavior of the proposed adaptive building skin in the wind.

Using digital simulation and analysis tools that are interconnected in one working environment, the proposed, full-scale adaptive element is sequentially assembled, form-found, and analyzed.

## 2 Design experimentation

### 2.1 The synergy of architecture and structural engineering

The design intent is to interconnect the benefits of digital designing, simulations, and analyses with the architectural designing to invent a lightweight, shape-changing wind-adaptive building skin that positively affects the surrounding wind conditions. The shape change of one element is caused by material-embedded characteristics and tensegrity geometry.

The development of the digital model of one wind-adaptive element in full scale is based on the previous tests with a smaller model. The proposed design method of the full-scale digital model can be divided into three steps:

(1) The material properties, geometric relations, and boundary conditions of the tensegrity-membrane element are set in Grasshopper for Rhino. Kangaroo 2 calculates the equilibrium state, taking into account the given parameters (Table 1).

(2) Kangaroo 2 Engineering calculates the resulting axial stresses and axial forces.

(3) The resulting axial forces from Kangaroo 2 Engineering are subsequently used to calculate the inputs for the initial strain of the membranes and cables in Karamba 3D [14]. The following equation is used to obtain the initial strain value  $\varepsilon_0$ :

$$N = -\varepsilon_0 AE \tag{1}$$

where  $N$  is the axial force in kN,  $\varepsilon_0$  is the initial axial strain imposed on the element (positive sign = elongation),  $A$  is the cross-section of the element in cm, and  $E$  is Young's modulus of elasticity. The distribution and the value of stresses in the tensegrity-membrane element in the equilibrium state can be seen in Fig. 4.

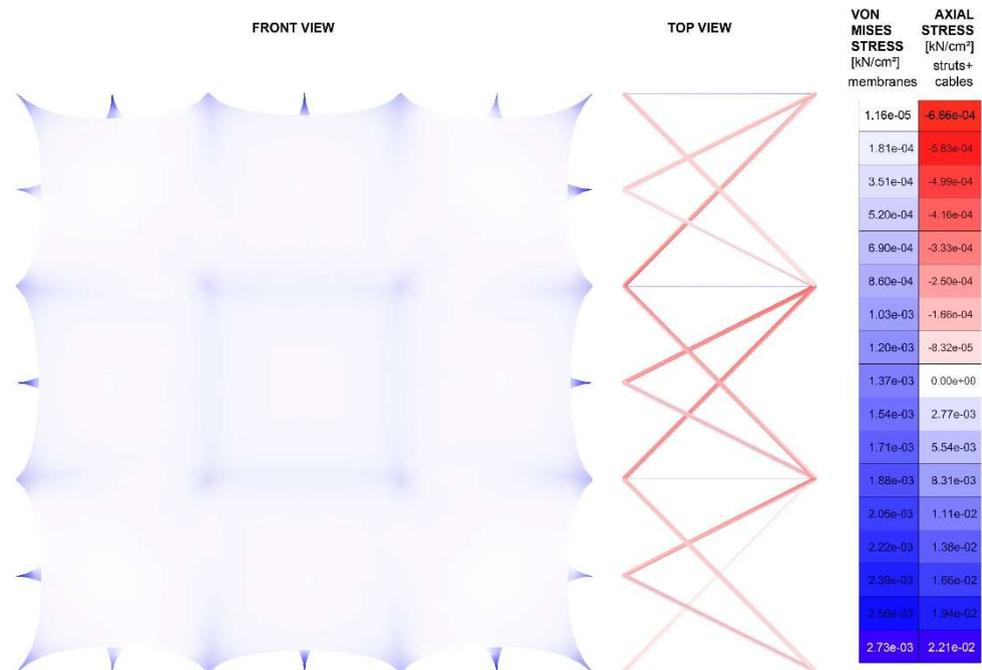


Fig. 4. The stress distribution on the membranes, struts, and cables.

Two load cases are set and examined in Karamba 3D:

1) The initial strain of the membrane and the steel cables. The input value for  $\epsilon_0$  is calculated from Equation 1. The resulting axial forces  $N$  for membranes and cables are taken from the Kangaroo 2 Engineering simulations.

2) The wind speed of 24 m/s. The corresponding value of the wind load in  $\text{kN/m}^2$  is derived from the Bernoulli equation, with a value of  $1.25 \text{ kg/m}^3$  as the density of air [15]. The distribution and the values of stresses in the wind-adaptive tensegrity-membrane element under the wind load can be observed in Fig. 5.

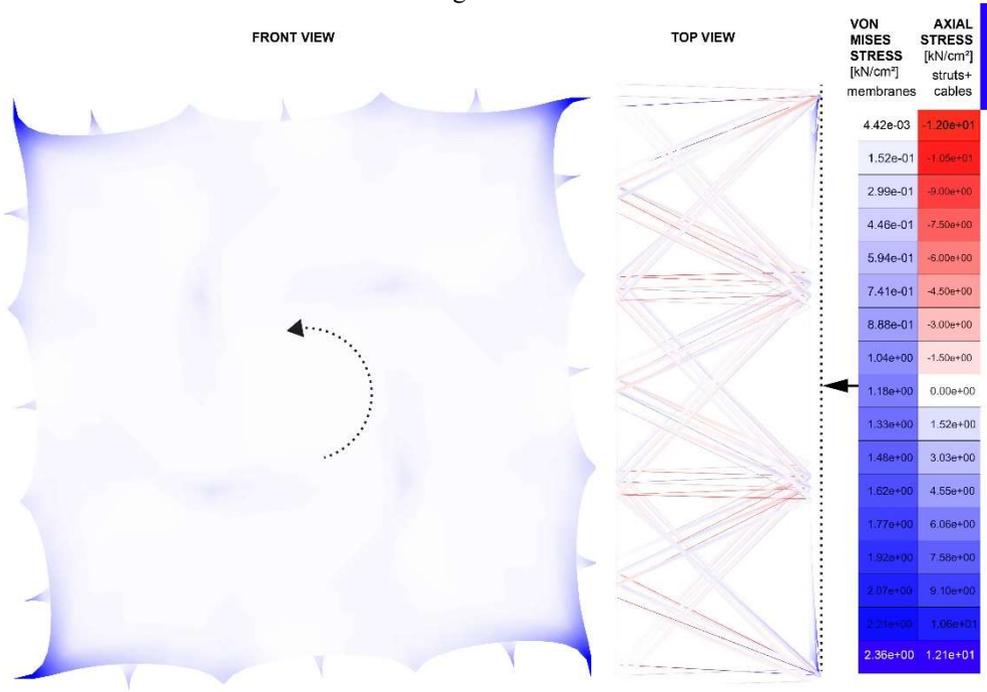


Fig. 5. The stress distribution on the membranes, struts, and cables under the wind load.

### 3 Results and discussion

#### 3.1 The pre-stressed adaptive element in the equilibrium state

Von Mises Stress observed in the membranes, as a result of the initial stress load, ranges from  $1.16 \times 10^{-5}$  to  $2.73 \times 10^{-3} \text{ kN/cm}^2$  ( $11.6 \times 10^{-5}$  to  $27.3 \times 10^{-3} \text{ MPa}$ ). The maximum axial stress (compression) in struts is  $-6.66 \times 10^{-4} \text{ kN/cm}^2$  ( $-66.6 \times 10^{-4} \text{ MPa}$ ) whereas the maximum tension in cables reaches  $2.21 \times 10^{-2} \text{ kN/cm}^2$  ( $0.221 \text{ MPa}$ ) (Fig. 4).

#### 3.2 The adaptive element under the wind load

The actions of the wind on the proposed structure are displayed in Fig. 5. Under the effects of the acting wind, the tensegrity-membrane element bends and rotates in the counter-clockwise direction. The rotation is caused by the counter-clockwise configuration of tensegrities. The displacement of the tensegrity-membrane structure in the 24 m/s wind equals to 7.26 cm and generates elastic energy of 0.032575 kN·m.

The wind speed 24 m/s is used to test the designed adaptive structure. The value is obtained from Eurocode EN 1991-1-4:2005 Action on structures [15]. This extreme wind speed is used in Slovakia for the structural design of buildings, as well as civil engineering works. The equivalent value of wind load used in the simulations acts in the direction perpendicular to the wind-adaptive element. Because the wind speed and direction fluctuates, the passive adaptation (without computer control) of the proposed adaptive element, which instantly reacts to the acting force and its direction, is a benefit. The reaction is reversible, which means that the structure returns to the original position once the wind velocity decreases.

The maximum value of Von Mises Stress in membranes is  $2.36 \text{ kN/cm}^2$  (23.6 MPa) (Fig. 5). The yield strength  $f_{y1}$  is  $4.575 \text{e}^{-1} \text{ kN/cm}^2$  (4.575 MPa), which means the membrane can withstand relatively high wind speeds. The maximum value of the Axial stress in cables is  $1.21 \text{e}^1 \text{ kN/cm}^2$  (12.1 MPa) and in struts  $-1.64 \text{ kN/cm}^2$  (-16.4 MPa). The yield strength  $f_y$  of cables is  $2.3 \text{e}^1 \text{ kN/cm}^2$  (230 MPa), whereas for wooden struts, it is  $2.5 \text{ kN/cm}^2$  (25 MPa). The axial stress in cables, as well as struts is within limits. However, it is observed that some cables are under compression, instead of functioning as tension elements. On the other hand, the structure as a whole can distribute high loads without breaking. Once the structure is not loaded, the adaptive element can recover to the original state.

## 4 Conclusion

Designing architecture with the wind as one of the fundamental design parameters leads to the desired interaction of architecture and the wind, even in its extreme forms. The wind speed and wind flow patterns are influenced by urbanism, architectural shape, as well as texture, or roughness of the building envelope. This study presented a wind-adaptive building skin developed and tested using computer simulations. The building envelope consists of tensegrity-membrane elements. Thanks to the material and geometric relations, the adaptive skin reacts real-time to the acting wind load and locally adjusts its shape, according to the intensity and the direction of the wind. The architecture that reacts real-time to various load situations enables designing lighter structures, compared to the conventional, stiff architecture.

### 4.1 Advantages of the proposed approach

- (1) Architectural designing from the original idea to the structural analysis in one working environment thanks to the progressive digital design tools.
- (2) The parametric approach enables quick changes in geometric and material properties of the design, adding new load cases, and changing the load magnitude and direction.

### 4.2 Disadvantages of the proposed approach

- (1) The unit problem between different plug-ins. The future research will examine the option of basic SI units in Karamba 3D.
- Since some of the cables are unused when the structure is exposed to the wind force, the optimization of the elements and their cross-sections will be addressed in future research.

This research was funded by the Grant Agency of the Slovak Republic. The project numbers are VEGA 1/0674/18 and VEGA 1/0374/19.

## Notes

<sup>1</sup> <https://www.grasshopper3d.com/>

<sup>2</sup> <https://www.food4rhino.com/app/kangaroo-physics>

<sup>3</sup> <https://github.com/CecilieBrandt/K2Engineering>

<sup>4</sup> <https://www.karamba3d.com/>

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