Building envelope adapting from and to the wind flow

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The paper presents research for wind-responsive architecture. The main objective is the digital design methodology incorporating the dynamic, fluctuating wind flow into the shape-generating process of architectural envelopes. These computational studies are advanced and informed through physical prototyping models, allowing a hybrid method approach. The negative impacts of the wind at the building scale (wind loads), as well as urban scale (wind discomfort), can be avoided and even transformed into an advantage by incorporating the local wind conditions to the process of creating architectural envelopes with adaptive structures. The paper proposes a tensegrity-membrane system which, when exposed to the dynamic wind flow, enables a local passive shape adaptation. Thus, the action of the wind pressure transforms the shape of the building envelope to an unsmoothed, dimpled surface. As a consequence, the aerodynamic properties of the building are modified, which contributes to reducing wind suction and drag force. Moreover, the slight shape change materializes and articulates the immaterial wind phenomena. For a better understanding of the dynamic geometric properties, one unit of the wind-responsive envelope is tested through simulations, and through physical prototypes. The idea and material-geometric studies are subsequently applied in a specific case study, including a designed building envelope in an industrial silo cluster in Stockholm.

Keywords: *adaptive envelope, tensegrity, wind flow, digital designing, shape-change*

INTRODUCTION

Erasing the boundaries between the natural and the built environment, the fluctuating climatic fluxes in nature, such as solar radiation, thermodynamic flow, or wind flow can become an integral part of the design process leading towards environment-based, responsive architectures. The research of environment-responsive architectural prototypes stimulates new ideas and discovers the potential of such architecture (Foged and Pasold 2016; Nagy et al. 2016; Reichert et al. 2015). Amidst all the weather forces that affect architecture, the interaction of wind fluxes with building shape is the most perceptible in the building, as well as urban scale. Globally, as well as lo-

cally, wind fluxes are unevenly distributed. Therefore, the interaction of architecture and the wind flow can be aimed at different goals, i.e., enhancing natural ventilation, mitigating the wind, or even wind harvesting. Architectural design proposals, utilizing the wind phenomenon as a driving force for generating architectural shapes, as well as city layouts, have been emerging since Computational Fluid Dynamics (CFD) has become accessible to architectural practice (Alexander et al. 1997; Kuenstle 2001; Tsou 1998). Including the local wind conditions to design in the conceptual stage is suggested to contribute to creating a sustainable, as well as comfortable built environment (Jin et al. 2017).

Form-finding with the wind
The paper focuses on the wind-driven design method resulting in a design of an architectural envelope with a structure responding to the wind load. The form of a building or the relative position and orientation of building clusters in the urban layout typically change the microclimate in their vicinity (Blocken and Carmeliet 2004; Tsou 1998). The environmental fluxes, in general, are very complex, and relating them to architecture may produce interesting morphogenesis processes (Mazauric et al. 2018). However, the form-generating effect of wind fluxes in the broader urban context, such as the city planning configuration is not the subject of this paper. The aim is to propose a method which can lead the design process towards a wind-adaptive architecture. In the form-generating process, an advantage over other design techniques consists in utilizing digital design tools combined with physical prototyping. The spatial relations and various environmental constraints become a natural part of the design process (Pellitteri et al. 2009). The paper will present a case study, where the wind-formed envelope, along with the responsive tensegrity-membrane system, is developed by using computational and physical prototyping techniques. The potential is that the immaterial air fluxes are utilized into the transformation of environmentally tangible architecture.

Adaptive architectural envelope
The constant change in the wind speed and direction requires an evenly distributed dynamic architectural response. The tensegrity (tensional integrity) systems are used as a source of inspiration for creating lightweight structures since the invention of the principle and the creation of first patented structures by Kenneth Snelson or Buckminster Fuller (Motro 2003). Applied in the architectural context, the kinetic envelopes can either employ 'pure tensegrity' (Sterk 2003) or benefit from combining the tensegrity principle as a primary load-bearing system and other kinetic systems, for example tensegrity and folding (Abdelmohsen et al. 2014) or tensegrity and bending (Phocas et al. 2014). The tensegrity-membrane system proposed in this paper contradicts the standard idea of static architecture. Instead of the resistance to the wind load, the lightweight structure complies to the wind forces by slightly bending in the wind direction and thus changing the overall aerodynamics of the building by a local wind force. In this process, a dimple effect is caused by the wind to geometry relations, forming an undulating surface similar to that of a golf ball.

DESIGN METHOD
The wind-driven design method proposed in this paper has the following steps (Figure 1): (1) PRELIMINARY STUDY: site wind data, (2) SPECIFIC STUDY: wind-adaptive system creating a local shape change (dimples), (3) APPLICATION: local shape change applied on a fluid building envelope, (4) PERFORMANCE IN THE WIND: wind pattern, pressure, and drag force evaluation: aerodynamic properties and performance of the envelope in the wind.
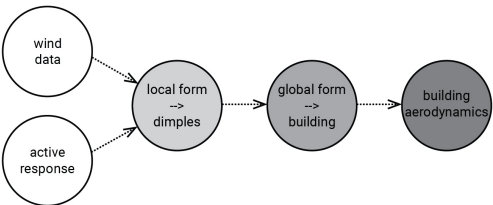

Figure 1
Design process scheme

Preliminary study

Wind conditions of the case study site are analyzed using Swift for Grasshopper [1] CFD tool. Swift utilizes the OpenFOAM CFD platform and can be set and controlled from the parametric design environment. The statistical wind data are obtained from EnergyPlus (the online weather database [2]). In the simulations, RAS (Reynolds-Averaged Stress modeling) and Standard k-ε turbulence models are used.

Virtual wind tunnel settings. The inlet wind speed 6 m/s at the reference height 10 meters above the ground is vertically distributed using power law wind profile (Emeis and Turk 2007). The wind tunnel size is 5H upwind, 15H downwind, 5H from both sides of the tested geometry, and 5H on the top of the geometry (H represents the highest tested building). Cell size is set to 2 meters with a refinement region around the investigated area, where the cell size is 1 meter. The simulation stops when the convergence criteria are met: final residuals in the calculations for velocity vectors are $1e^{-4}$, whereas the final residual for the pressure is $1e^{-3}$. It is important to note that Swift uses kinematic pressure units in $\frac{m^2}{s^2}$ (the pressure is divided by density) [3].

Specific study

The wind-adaptive structural system is developed using Kangaroo 2 [4] live physics for Grasshopper, along with K2 Engineering [5]. The plug-ins are used to integrate the material properties of the intended adaptive system, as well as to simulate the effects of the wind.

Material properties. (1) STRUTS: 250 mm long, 10 mm in diameter, natural beech wood struts, Young's Modulus of Elasticity ε is 46 MPa for the compression, in the direction of the fiber, the stiffness *k* is set to 14 444. (2) VERTICAL CABLES: 190 mm long, 0.3 mm in diameter, nylon cables, ε is 3000 MPa, the stiffness *k* is 1115, pretension is 0.9. (3) MEMBRANES: 0.5 mm thick fabric, ε is 0.6 MPa, stiffness *k* is 300, pretension is 0.8. The stiffness and pretension of the membrane are set based on the physical experiments with

the 60% viscose, 35% polyamide, and 5% elastane fabric. Same properties are considered for the warp and the weft direction, which implies that the strain is the same in both thread directions (Seidel 2009). The stiffness values for *k* are derived from Hook's law:

$$k = \frac{\epsilon A}{l}$$

where ε is the Modulus of Elasticity, *A* is the cross-sectional area in m^2, *l* is the length in m. In the case of the membrane, the stiffness is calculated with the thickness *h* of the fabric instead of the cross-sectional area *A*. The length *l* is the linear meter, i.e., 1. Simulations in Kangaroo have to have consistent units, whereas the most suitable is the use of SI units.

Wind. The wind pressure *p_w* is applied in Pascals. The value 22.5 Pa is calculated for the wind speed 6 m/s from the following formula:

$$p_w = \frac{1}{2}\rho v^2$$

where ρ is the density of air = 1.25 $\frac{kg}{m^3}$, *v* is the wind velocity in m/s.

Application

The passive shape change is examined on a designed fluid building envelope (an auditorium). First, streamlined shape with low resistance in the wind flow is created. Subsequently, a dimpled surface is created by applying the wind load 22.5 Pa on the surface in Kangaroo 2 for Grasshopper. The stiffness value *k* is set to 1000, which represents a 1 mm thick membrane with ε = 1 MPa.

Performance in the wind

Swift for Grasshopper is used for testing the smooth building envelope, and the dimpled variant. The turbulence models and the wind tunnel settings are the same as for the preliminary wind tests. However, the cell size 3 m is used to speed up the simulations, while the refinement region cell size is kept to 1m. The post-processing of the results is performed in Paraview [6].

DESIGN EXPERIMENTATION

The following case study introduces a process of designing and investigating a building envelope formed by the wind fluxes, alongside the digital, and physical development of actively adapting tensegrity structure, interacting with the wind. The local airflow around building envelope and their reciprocal interaction become a trigger and an inspiration in the architectural form-finding process. The method leads the design process in successive steps towards the reduction of wind loads on buildings, suction, in particular, and therefore lightweight structures. An added aesthetic value is the articulation of wind phenomena through building envelopes.

Preliminary study

A part of an unused industrial area in Stockholm docks serves as a case study site. The preliminary westerly wind flow between densely distributed, 30 meters high cylindrical silo clusters, is turbulent and accelerated due to the Venturi effect. Figure 2 shows the wind flow around the selected silo cluster at 1.8 meters above the ground.
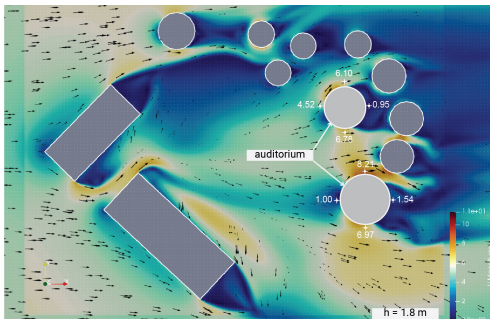
The zone in-between and around the silos marked as 'auditorium' is turbulent, in some areas the wind speed is exceeding 8 m/s. With the wind gusts that can reach 15 m/s 0.25% of hours per year, the situation would be even more unpleasant for the pedestrian wind comfort.

Specific study

A tensegrity-membrane system proposed in this paper consists of nine 4-strut units, in the counter-clockwise rotation, ergo some of the struts meet and create a rigid 3-dimensional space structure. Tensile membranes replace the upper and bottom tension cables.

Digital simulation. After the form-finding, the wind pressure 22.5 Pa is applied to the system. The self-weight of wooden struts equal to 0.6 kg is added using K2 Engineering extension. Four corner points of the front membrane are anchored when the system is subjected to the wind load (Figure 3). The combination of the material properties and the tensegrity geometry allows for the slight shape change in the wind.

Physical experiment. The prototype of one unit is created in the same scale as the virtual model and consists of natural beech wood struts, nylon vertical cables, and stiff, yet elastic fabric made of 60% viscose, 35% polyamide, and 5% elastane. For achieving the pretension, the fabric is reduced to 80% of the size and laser-cut to smaller parts. The fabric parts are subsequently stitched together, which creates stiffer connections. The pretension of the fabric stabilizes the structure. During the wind testing, it is anchored in 4 corners of the front side and placed in the wind flow. The 'WeatherFlow' anemometer is used to record the wind speed and direction. Several measurements were performed, whereas the one with the strongest wind gusts is published here. During the 1-minute measurement, the outer conditions were the following: temperature = 13.2°C, humidity = 50%, average wind speed = 4.6 m/s, maximum wind gust = 7.8 m/s. The wind direction was from the west, although the wind has a chaotic and unpredictable behavior, the wind gusts are random, as is the wind direction. The structure exposed to one of the wind gusts is depicted in Figure 4.

Application

The digital simulations, as well as the physical prototype, exhibit the same behavior when subjected

Figure 2
Westerly winds 6 m/s around the selected silo cluster 1.8 m above the ground

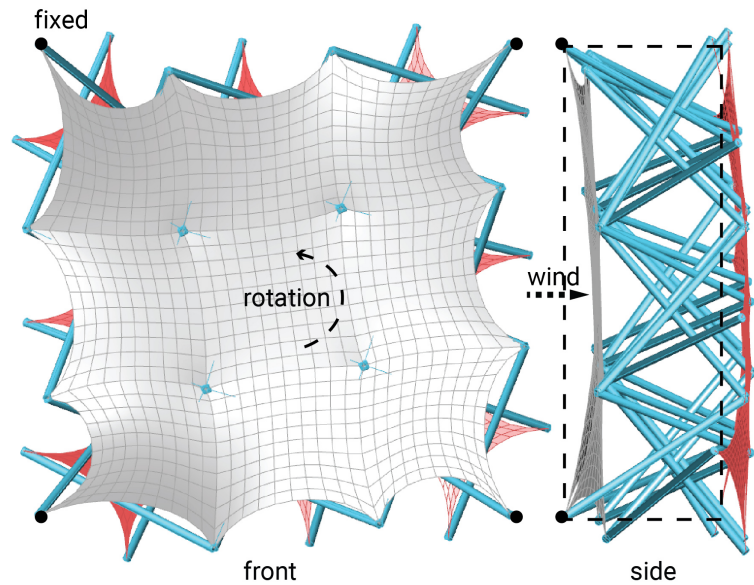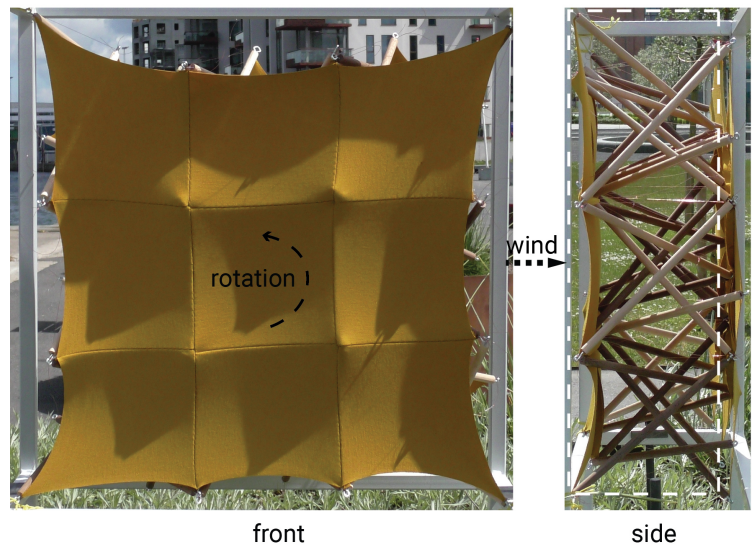Figure 3
Tensegrity-
membrane unit
subjected to the
wind load

fixed

rotation

wind

front

side

Figure 4
Physical prototype
tested in the
exterior conditions

rotation

wind

front

side

to the wind load. The structure bends in the wind load and rotates counter-clockwise as a result of the tensegrity geometry. The real-time shape response of one unit inspires the application of wind-adaptive units on the scale of the building envelope (Figure 5). The surface is divided to a grid, with the maximum size 2.2 x 2.2 m (representing 1 tensegrity-membrane structure). The leeward side of the surface is smooth, i.e., no dimples are applied. The shape of the dimples created on the surface is directly proportional to the magnitude and the direction of the acting wind.
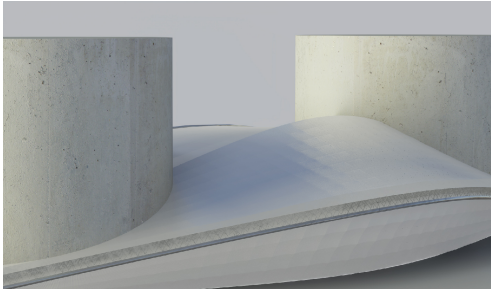
RESULTS
According to the simulations, the wind speed 6 m/s, acting as the wind pressure 22.5 Pa on the prototype structure in the +x direction causes maximum displacement of the tensegrity-membrane structure in the +x direction equal to 46 mm. By the double wind speed 12 m/s, represented by the pressure equal to 90 Pa, the maximum displacement of the structure is 78.4 mm.

At the building scale, the wind flow pattern, the pressure, and the drag force are primarily influenced by the overall form of the building. However, the dimples created on a building envelope by the wind, contribute to the surface pressure and drag force reduction, as well as to the change in the wind flow pattern. The responsiveness of the proposed system does not rely on additional, externally applied energy. On the contrary, the cause of reducing the building surface wind pressure is the wind itself. The power of this fluctuating climatic element is trans-

formed into the shape adaptation of the building envelope.

Performance in the wind
The wind flow pattern around the smooth building envelope and the dimpled variant are examined, focusing on turbulence reduction. The surface wind pressure values p, and the drag force values F_d are compared for both options. The pressure range for the smooth building envelope is from - 52.5 $\frac{m^2}{s^2}$ to +19.0 $\frac{m^2}{s^2}$, i.e. -65.6 Pa to 23.8 Pa, whereas the pressure range for the dimpled surface is from - 41.4 $\frac{m^2}{s^2}$ to +19.4 $\frac{m^2}{s^2}$, i.e. -51.75 to 24.3 Pa. The drag force in the case of the smooth surface is 6127.72 N, and in the case of the dimpled surface, it is 5876.54 N. The dimples on the windward side of the building, as well as on the building roof are efficiently decreasing the negative wind pressure. It is decreased by 21%. The drag force is closely related to the overall building form, as was already mentioned. Dimples contribute to the drag force reduction and complement the streamlined shape. The comparison of the wind flow pattern on the case study site without the architectural intervention and with the dimpled auditorium envelope is depicted in Figure 6.

DISCUSSION AND CONCLUSION
Discussion
The next step of the research is to investigate the properties of the system in 1:1 scale, whereas material properties will be different. The steel cables will be used instead of nylon cables and a thicker fabric with higher stiffness will substitute the fabric from the prototype. This will undoubtedly lead to the different behavior of the system in the wind. On the other hand, the shape change is not only based on material properties, but also on the tensegrity-membrane geometry.

Figure 5
Visualization

Figure 6
CFD tests

Figure 6
CFD tests
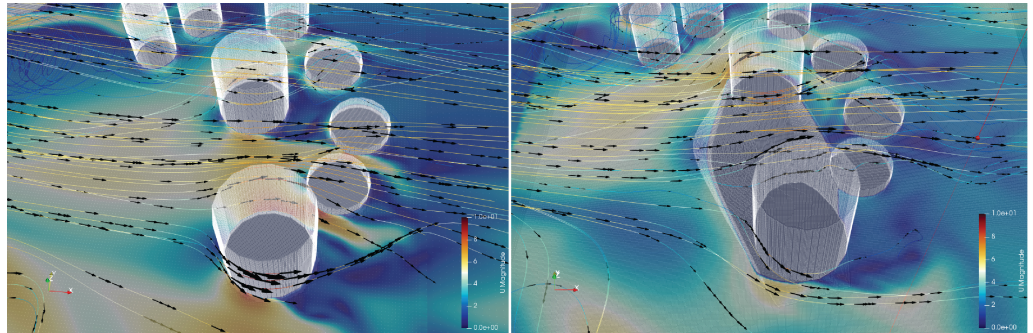
Conclusion

The paper proposed design steps, including digital design and prototyping, leading towards an envelope, able to morph real-time in the wind. This dynamic, fluctuating element is incorporated into the shape-generating process of wind-adaptive architectural envelopes. Such architecture can conversely alter and regulate the wind forces. The case study site in Stockholm serves as a demonstration case for illustrating the wind-driven design. Firstly, the wind situation is analyzed using CFD simulations. Subsequently, a lightweight, wind-adaptive tensegrity-membrane is developed as a scaled model. The physical model informs the material settings in the computer simulation. Wind load acting upon the proposed adaptive structure is distributed within the structure, resulting in the slight shape change of the system. This structure is applied to a fluid shape, an auditorium, which is designed between the concrete silos in Stockholm. The building envelope adapts according to the wind pressure and direction, and, as a consequence of the created dimples, it is able to change the wind flow in its vicinity. Moreover, the created dimples reduce the wind suction on a building surface and the drag force, which can contribute to designing lighter structures. The responsive changes of a building, which is adapting to this natural dynamic force, represent a potential new reading of this dynamic phenomenon by the architecture users. Hence, from a design-

phenomenological perspective, the immaterial moving air not only generates the shape of the envelope but also transforms into the physical motion mirrored in architecture.

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