Shape morphing wind-responsive facade systems realized with smart materials

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Abstract

This paper presents the opportunity to exploit the kinetic adaptation of the façade skin-roughness for enhancing the air-flow related characteristic of high-rise buildings. A conceptual design solution, in which the roughness adaptation is achieved by means of innovative shape changing materials, will be presented. Roughness elements located on the building envelope are able to modify the velocity field close to the façade; this modification has an effect on the natural ventilation and, primarily, on the heat exchange due to the wind convection. The study will deal with some simplified case studies of 3D geometries of round and square towers. Computation Fluid Dynamics (CFD) will be used to show how integrated roughness elements are able to affect the flow field along the building envelope. This paper contains some new ideas about wind optimisation of buildings and the opportunity to use shape changing materials for adaptive façade elements.

Intro

Wind is a phenomenon, which is highly dynamic by nature and thus is a challenging design driver for architecture. The aerodynamic performance-oriented optimisation of shapes is a rather common technique in the turbo machinery, aerospace, naval and automotive industries, where operating conditions of components and vehicles are characterized by a flow direction, which is constant or varying within a small range. In these cases, the optimization process, although a very expensive and time consuming operation, allows the real maximization of the aerodynamic performance. The same concept cannot be applied for the form finding process of wind-optimized architecture. The direction of the wind is in fact not constant. For each region of the globe, a predominant wind direction can be identified but if the shape of the building is optimized according to this, there is no guarantee on the good performance for other wind directions that might occur. A first challenging option for solving this problem is the usage of adaptive systems which are able to adjust the large scale geometry of the building to the external conditions [1-3]. Studies of geometrically morphing building skins for high-rise towers, which are wind responsive (i.e. the overall structural geometry can respond to external conditions), have already been carried out [4].

A second option for modifying the aerodynamics of the building is to act at a smaller scale, by changing the roughness of the envelope. It is demonstrated [5, 6] that effects of reduction of wind pressures are considerable for walls with surface roughness such as balconies, louvers, canopies and any kind of appurtenances. Adding external elements to the building envelope can reduce the local forces on the building façade and also damping the strong pressure oscillations due to vortex shedding at the upwind corners. Obviously, by actively modifying the external flow field it is also possible to act on the natural ventilation and the heat exchange between internal and external environments. In fact, the heat transfer coefficient from the building surface to the ambient is strongly correlated to the air velocity. External roughness elements, which are able to change orientation, can strongly modify the velocity field, for example, by making a more uniform pattern on the facade or canalizing the airflow and moving it in different zones. These external elements should be able to move and adjust themselves assuming different apertures and directions in different areas of the building façade according to the wind characteristic and the current needs (e.g. cooling energy demand).

In this paper the wind load of a high-rise building with a geometrically morphing façade is analysed by numerical simulation. The focus lies on the influence of the surface texture on the wind pressure and velocity fields. A design solution is presented of an adaptive building skin constructed of smart materials. Smart materials are capable of automatically and inherently sensing or detecting changes in their environment and responding to those changes with some kind of actuation or action [7]. In this project we focus on shape morphing smart materials, which are able to adapt the building texture by intrinsic material characteristics. Examples of mechanical driven kinematic systems are found [8, 9], but these will lead to large and heavy complex construction components. With smart materials it is possible to construct lightweight shape morphing elements.

Wind

The aerodynamic and hydrodynamic characteristics of a smooth body are not necessarily better than the ones of a rough body, as it could be naturally expected. Surface roughness does indeed increase the friction between the flow and body, but it has also a positive influence on other phenomena. Therefore, the final effect of an increase of the surface roughness could paradoxically be the enhancement of the aerodynamic characteristics of the body. Many examples of this apparent inconsistency, where the surface roughness is exploited for enhancing the aerodynamic characteristic of a body, can be found in different fields, like sport and nature. The extremely rough skin of a shark has been shown to reduce friction when it glides through water, which is why sharks are surprisingly quick and efficient swimmers [10] This is due to a multitude of V-shaped bumps that cover the shark's body, preventing eddies from forming as water passes over the surface by channelling the fluid along grooves in the skin fabric. These grooves allow the water to spiral in microscopic vortices, a hydrodynamic advantage. The random-looking bumps on the humpback whale's flippers have just inspired a breakthrough in aerodynamic design. This sort of tubercles are enhancing the hydrodynamics performance of the fins. The same idea has already been used in the aerospace and energy industry, and dramatically increased the efficiency and performance of wind turbines, fans, flippers and even wings and airfoils [11]. Also, in the design of golf balls roughness is used for reducing the drag force [12, 13]. The dimples on the surface of a golf ball cause the air flow on the upstream side of the ball to transit from laminar to turbulent (see Figure 1). The turbulent boundary layer is able to remain attached to the surface of the ball much longer than a laminar boundary and so creates a narrower, low pressure, wake and hence less pressure drag. The reduction in pressure drag causes the ball to travel further.

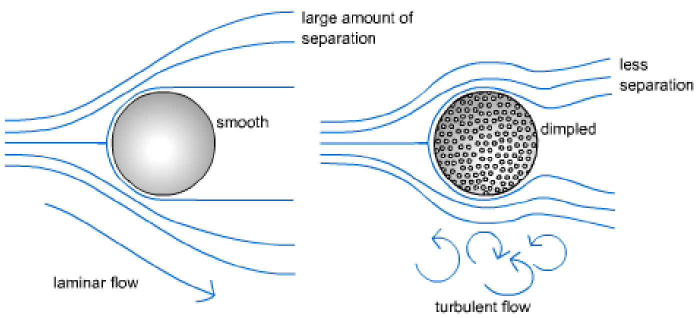

Figure 1: flow field around a golf ball.

In the field of architectural engineering research has been performed on how the roughness can affect the distribution of pressure on the building surface and therefore affect the wind loads on the façade and also modify the driving force of the wind-driven natural ventilation. Maruta [5] shows with experimental data for a 25 m square section high-rise building that wind pressures are remarkably affected by the surface roughness, particularly near the leading edge of the side wall on which local severe peak pressures decrease with increasing roughness. The increment of roughness restrains the development of conical vortices formed at the lower and higher zone of buildings. They demonstrate via wind-tunnel experiments that with an increase of the roughness length from 0 m to 1.2 m it is possible to reduce the under-pressure close to the building upwind edge of about 25% to 30%. It is shown that the surface roughness also has influence on the fluctuation of pressures produced by the disturbance of separated flows and separation bubbles; increasing the roughness length from 0 m to 1.2 m the power spectra of this oscillation can be reduced of about the 70%. Chand [6] measure how the pressure distribution on the windward wall of a low rise building is modified by balcony-like roughness elements. They demonstrate that large differences occur, especially close to the top and the bottom floors of the building. This phenomenon is of course affecting the overall driving force of wind-driven natural ventilation. Chand [6] executed experiments for calculating the different pressure distribution on the façade of a low rise building with and without balconies, which can be seen as very

large roughness elements. It is shown that provision of balconies alters wind pressure distribution on the downwind wall. Balconies produce a reduction of the wind pressure over the entire upwind wall on the ground floor and also at points covered by the balcony at the top floor. At the intermediate floors, wind pressure increases. This effect can be used for modifying the ventilation magnitude through openings located at opposite walls or for enhancing the stack effect of openings located at different heights above one floor.
In our research the opportunity to exploit the skin-roughness kinetic adaptation for enhancing the air-flow related performance of high-rise buildings will be investigated using computational fluid dynamics (CFD).

Case study

A series of CFD simulations has been performed on some simple case studies to analyse the actual influence of external roughness elements on the wind flow field close to the surface of a building. The code OpenFOAM 1.7x has been used for this purpose. This software has been chosen because it is a reliable general purpose code, completely open source and with some new applications and solvers especially suited for the wind analysis.
As a first step to assess the validity of the method and the tool, the case analysed by Chand [6] has been reproduced. Figure 2 shows the geometry of the low rise building with dimensions 10 by 7.5 by 15 meters. Balcony-like appurtenances are added on the front face (upwind facade). The following two cases have been simulated:

A1. smooth wall
B1 . wall with balconies

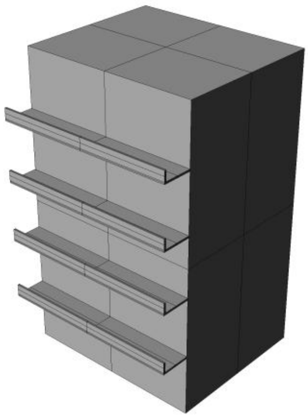

Figure 2: low rise building with balconies

The second case study is a simple square high-rise tower, which is 30 meters wide and 100 meters height. The roughness elements are chosen as balcony-like horizontal façade projections as long as the building side and as fin-like vertical projections as high as a floor (Figure 3). Thus the following cases have been simulated:

A2. smooth surface
B2. horizontal roughness elements on the side wall
C2. vertical roughness elements on the side wall

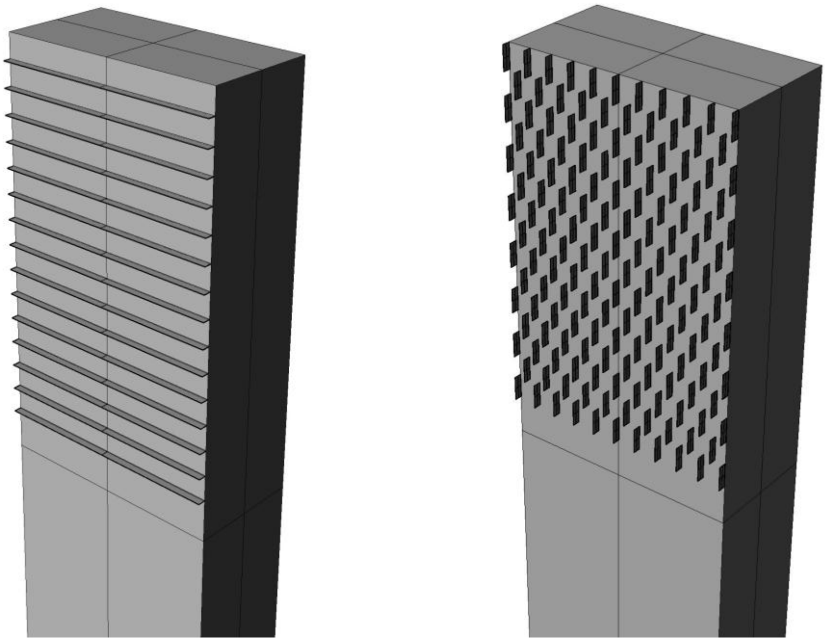

Figure 3: high-rise building with roughness elements (Left: case B2 and right: C2)

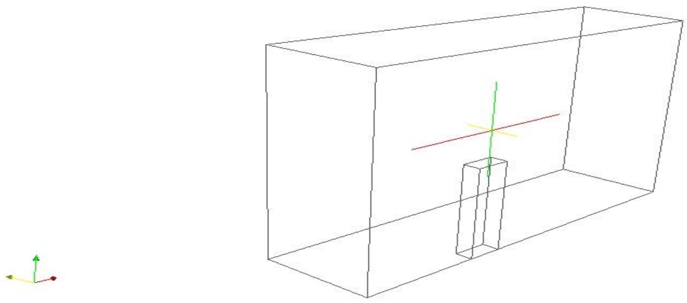

Figure 4: computational domain

Figure 4 shows the computational domain. It is a simple rectangular box 360 of meters long, 220 meters high and 100 meters wide, with the tower positioned 100 meters after the inlet. Due to the symmetry of the chosen geometry, only half of the domain has been taken into account and a symmetry plane boundary condition has been applied at the central wall. The mesh has 1,500,000 points. Each simulation has been performed with the Reynolds Average Navier Stokes method using the *k*-ε turbulence model. At the inlet a velocity profile with the classical shape of an Atmospheric Boundary Layer (ABL) has been introduced. The graph in Figure 5 shows the shape of the ABL and Eq.1 the mathematical formula:

$$U = \frac{u^*}{\kappa} log \frac{(z-z_0)}{z_0} \qquad \textbf{Eq. 1}$$

where:

$\kappa = 0.41$ is the Von Karman constant

$z_0 = 0.1\ m$ is the physical roughness length of the terrain

$u^* = 0.8\ \frac{m}{s}$ is the friction velocity

z is the physical vertical coordinate

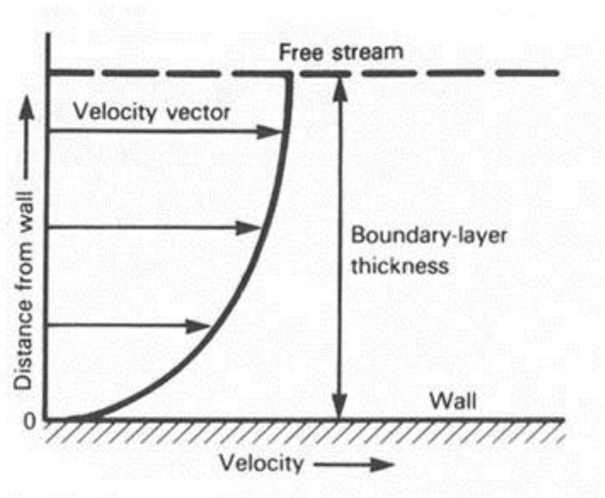

Figure 5: the Atmospheric Boundary Layer

Simulations results and discussion

The first simulation showed a rather good match between the Chand's case and the CFD results. The comparison between the two sets of data is shown in Figure 6. The matching between the two sets of data is not perfect but can be improved by further refinement of the mesh, but at this stage this is considered satisfactory.

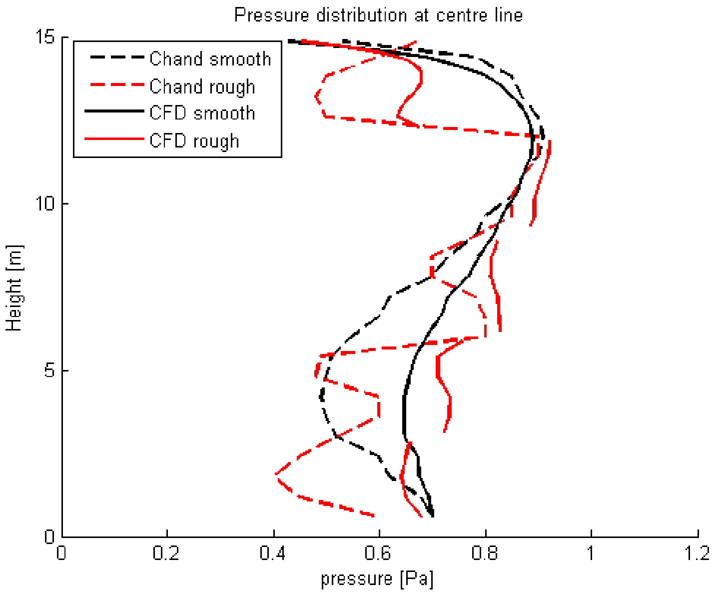

Figure 6: comparison between the simulation results Chand's experimental data.

Figure 7 shows the comparison between the pressures fields of the smooth building (case A1) and the building with appurtenances (case B1). Only the values of the front side (the one facing the wind) are reported. The differences between the two fields due to the presence of the balconies are rather evident, especially at the top and the ground floors.

After validating the methods and demonstrating the possibility to modify the pressure field by mean of facade projections, the second case study has been analysed. It has been noticed that the difference in the pressure fields for the case of a smooth and a rough facade are much less evident for high rise buildings. However, the influence of the roughness elements is much stronger on the velocity field.

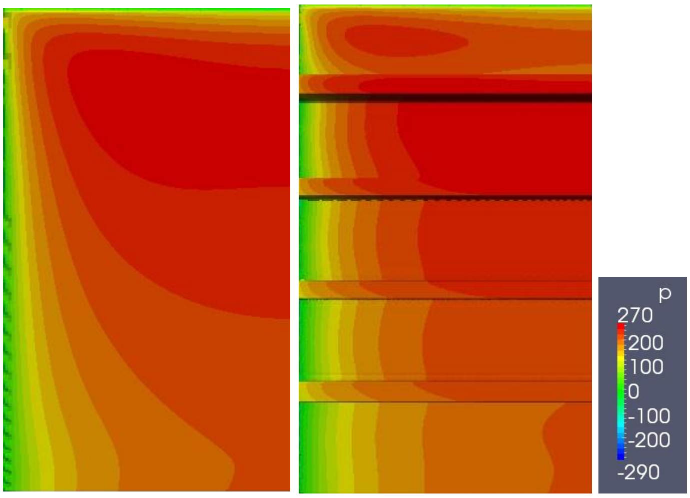

Figure 7: pressure field on the upwind façade of the low-rise building (Case A1 and B1)

In Figure 8 the velocity fields of case A2, B2 and C2 are compared (wind coming from the right hand side of the picture). The values of velocity are taken along a plane located at 0.5 meters away from the façade surface; this corresponds to the plane which intersects the roughness elements at their centre point. It is possible to notice how much the flow field is affected by the presence of the roughness elements. Along the smooth facade (case A2), velocities are mostly within the range 5 – 9 m/s and up to 15 m/s close to the top and the upwind corner. Right after this corner, there is an area where the velocity is almost equal to zero. Moving the roughness elements in a vertical direction (case C) provides a larger uniformity of the flow field. As a matter of fact, they offer a big resistance to the wind, decreasing the air velocity close to the façade. This effect can be exploited when there is need to decrease the heat exchange between the indoor and outdoor environment, for example at winter time in the case of strong wind. Turning the roughness elements into a horizontal direction provides a sort of canalization of the air that can be exploited for moving the zone at a higher velocity where desired. For example the areas of the building at higher insolation, where there is need to enhance the natural heat exchange.

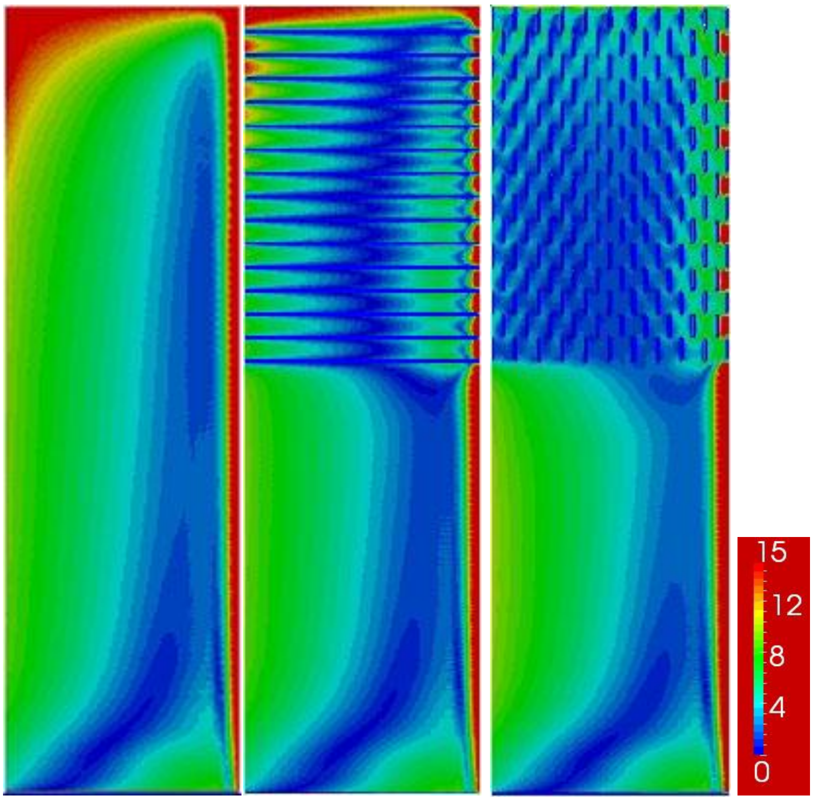

Figure 8: velocity field on the side wall of the high-rise building (case A2, B2 and C2). The wind is coming from the right-hand side.

Another minor, but still positive effect obtained by adding roughness elements on the façade is the decrease of vorticity close to the upwind corner. Figure 9 shows the different pressure distributions on the lateral side of the building (wind coming from the right hand side of the picture) with (case A2) and without (cases B2 and C2) the roughness elements on the side wall. The zones characterised by a strong under-pressure and therefore by a strong suction on the façade elements (e.g. windows or double skin elements) are coloured in red. It is evident in Figure 9 that close to the building corner in the upwind zone there is a strong under-pressure area. This is due to the presence of a corner vortex which is almost completely eliminated

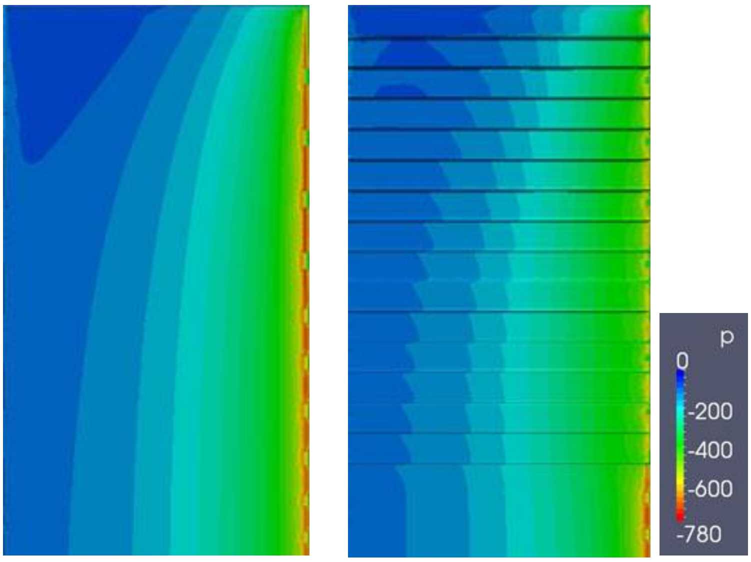

Figure 9: pressure field on the top region of the side wall of the high-rise building (case A2 and B2). The wind is coming from the right-hand side.

Design

As described earlier, the wind load on a building is under constant change, therefore, an adaptive façade system is presented based on the executed simulations. It is proven that the surface texture of a body can manipulate the aerodynamics of a body. We use this principle for the design of a building envelope, which has the property of changing the surface texture for the control of wind pressure and velocity. Large wind forces are found on high building levels, which make it difficult to use natural ventilation. These large wind forces are used as a design constraint to create an adaptive façade, which enables the use of natural ventilation. In this case, the morphing envelope can control the ventilation of the building, by changing its surface roughness. This is general principle, which can be found at the fur of mammals and the feathers of birds.

As is shown is figure 10, the design proposal is based on a building envelope with small deflecting elements, which can be open and closed according to the wind velocity and direction. Every element can be controlled individually, leading to a diverse surface texture, optimized for every height and wind velocity. The purpose of these elements is to steer the wind on the building envelope for secure control of the wind-flow. It might be possible to conduct wind from shadow parts of the envelope to parts where sun radiation can lead to a high heat load. In order to generate such behaviour, the texture elements should be able to deform both in horizontal as vertical direction (figure 11).

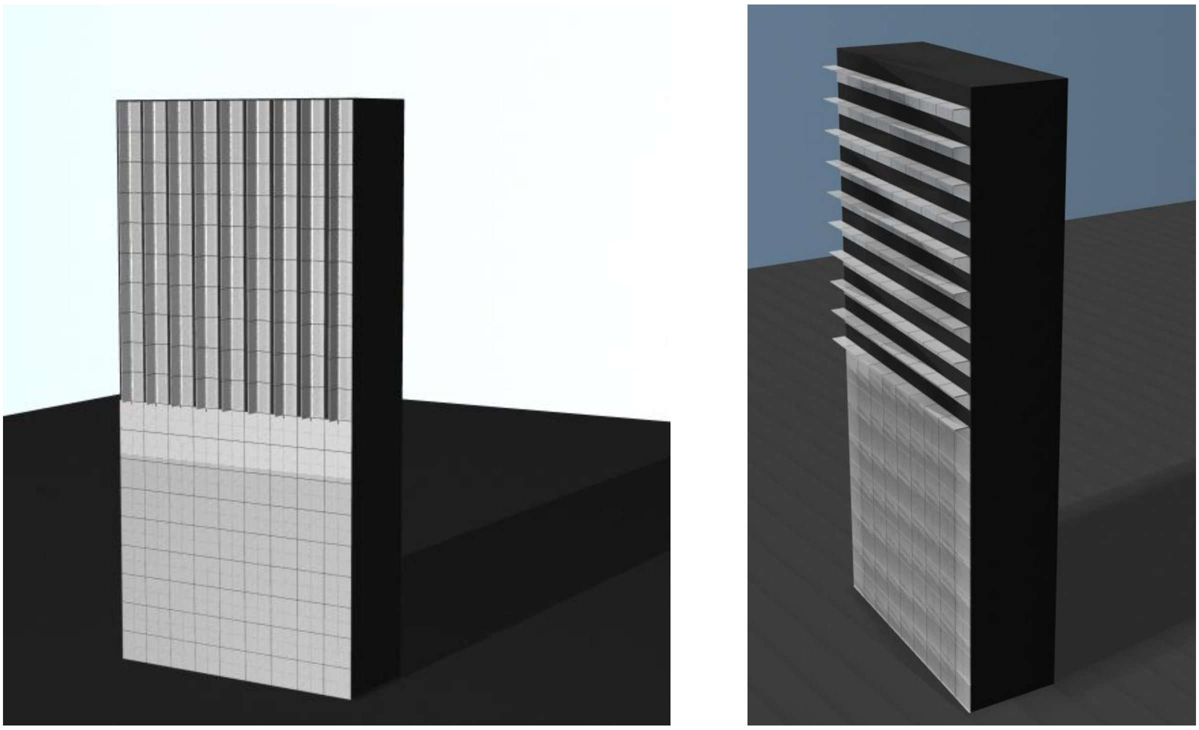

Figure 10: model of adaptive façade texture, vertical and horizontal deformation of the smart elements.

Within the same adaptive system, different configurations if the building envelope can be found, which is shown in figure 12 and 13. By changing the configuration of the façade elements according to the wind direction and speed, an optimized situation can be created on the building surfaces.

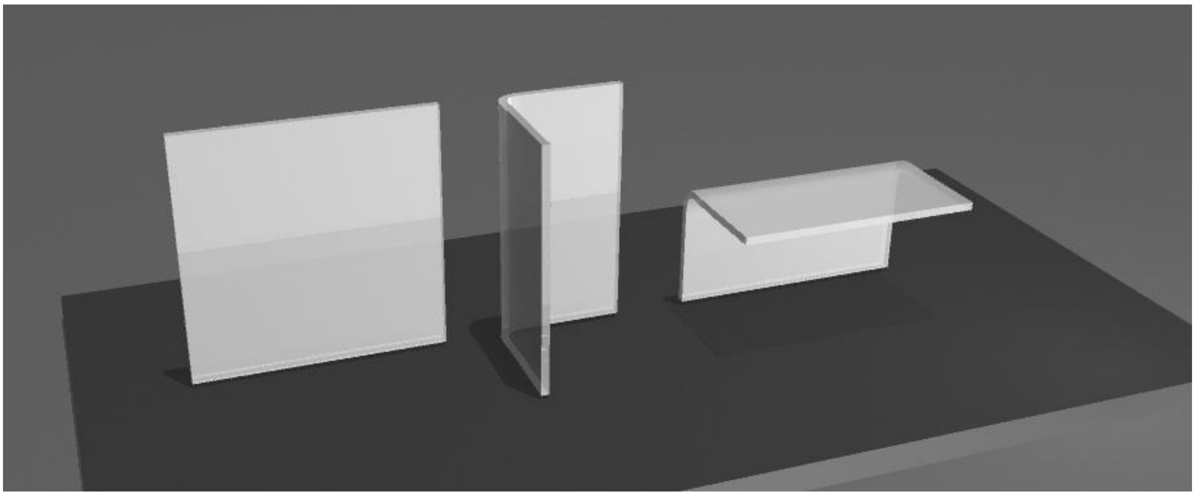

Figure 11 schematic drawing of shape morphing facade element. Left: smooth surface, middle: vertical deformation, right: horizontal deformation

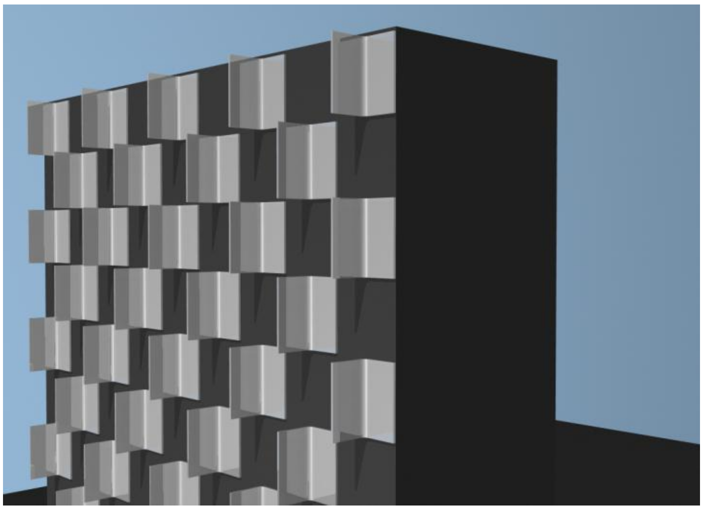

Figure 122 vertical deformation detail as tested in CFD

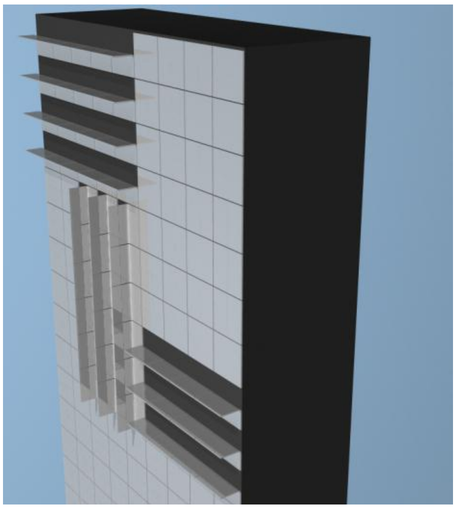

Figure 11 deformation variation for wind conduction

Materialization

Shape deforming smart materials are implemented for the realization of the adaptive façade elements. A smart composite is developed within this research project which provide the requested adaptive behaviour. The advantage of smart materials can be found in the fact that small and light construction sizes can be reached, as the shape deforming properties are based on the intrinsic characteristics of the material. Furthermore, due to the sensoric properties of smart materials a secure control is can be achieved. Currently, these materials are mostly applied in other fields than architecture, like robotics and medics.

The focus lies on shape morphing smart materials which have the characteristic to maintain the deformation without constant energy input. Next to that, the material should be able to return to its original shape. The proposed adaptive element is applied as a façade tessellation, which is under constant influence of external forces. This means that the element should contain a certain level of stiffness. Likewise, the material should be able to deliver a considerable size of deformation, which should influence the surface on architectural scale. As a start, we concentrate our interest in a single curved surface (figure 14).

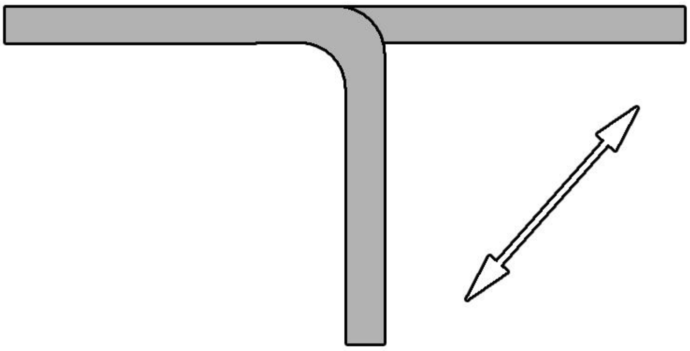

Figure 13: Schematic drawing of single deflection

After an inventory of shape morphing smart materials, a composite of Shape Memory Alloys and Shape Memory Polymer met the design constrains [14]. Shape Memory Alloys (SMA's) are implemented in a Shape Memory Polymer (SMP) matrix, where the SMA's are applied as an actuator material and enable the deformation of the element [15]. SMP provide the fixation of the deformation, as constant energy is needed to maintain the shape of the SMA, when external forces are applied. SMP is considered rigid in ambient temperatures, but by heating the material above its activation temperature, the material becomes rubbery, and can be deformed rather simple. By cooling the material to ambient temperatures, the material regains its rigid properties. Additionally, SMP has shape memory properties, and will return to its original shape by subsequent heating after deformation. Both materials are thermally activated, in our prototype we apply resistive heating for local activation.

In figure 15 a prototype of the proposed smart composite is shown. The initial shape of the composite is in flat configuration, the two outer SMA's (1) provide deformation upon bending, after the SMP (2) is heated with the integrated resistive heating wires (3) and became fully rubbery. When the acquired deformation is met, the composite is deactivated and will cool down, which will lead to the fixation of the composite. For the recovery of the composite, the SMP is subsequently heated, after which the SMA (4) located in the centre of the composite will recover the composite upon activation. As the polymer disposes of memory properties, SMA (4) is only implemented in the composite to deform the two antagonists SMA's (1).

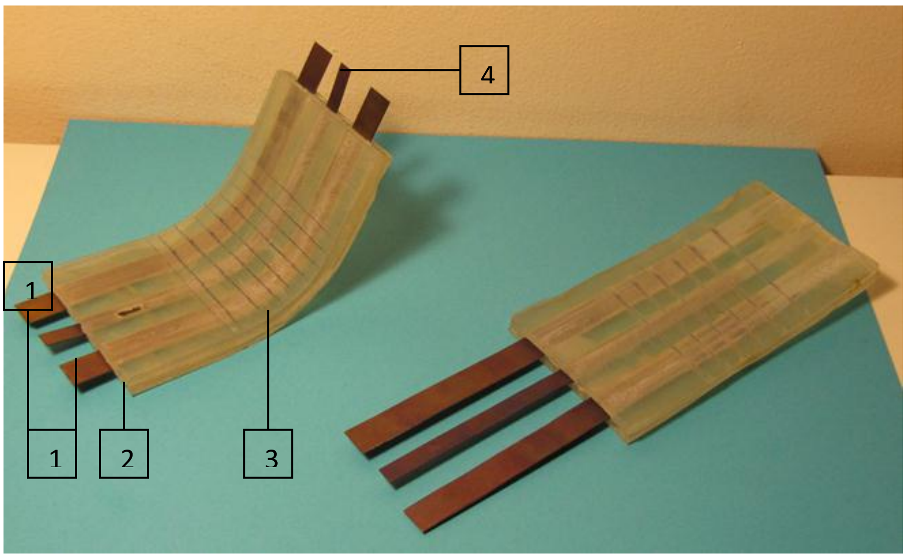

Figure 14: Smart composite, left in deformed configuration, right the integrated SMA strips are exposed.

Conclusion and discussion

It has been demonstrated either via past wind tunnel tests and via CFD simulation that the texture of a building façade has a strong effect on the wind flow field. This phenomenon can indeed be exploited for modifying the natural ventilation inside the building, and the heat exchange through the envelope, as well as for reducing the effect of strong vortexes on the façade elements. It has been found out that the difference in the pressure field are much more evident for low rise buildings, whereas for high-rise buildings the velocity field is much more affected by the presence of facade projections. The research is still at an early stage; further research is needed for assessing the effect of other orientations, apertures and shapes of the roughness elements and the effect of different wind directions. Also, an interesting development would be to assess the possibility to decrease the overall drag force on round-shaped buildings by incorporating roughness elements on the building facade, which are used as vortex generators. The bumps on a golf ball perform the same function on a smaller scale. Further research is needed to understand if the same phenomenon can be exploited at a large building scale.

It is recognized that the adaptive building systems meet large wind forces, especially on higher altitudes. The current performance of the smart composite components is solely tested in lab environments. When the components are subject to large wind forces during transition to another configuration, the performance of the components might change. Further research is needed to test these adaptive components in wind situation. The relation between the deflection size and the effect on the wind velocity needs further analyses.

The current prototype is limited to single directional deformation, although, in the design proposal a element is presented which can be deformed in two directions for an optimal regulation of the wind flow field. Never the less, the shown prototype elucidates the application of the smart materials as a façade tessellation. Further development of the smart composite element will show the feasibility of the proposed design concept for wind conduction purposes. It is proven that it is possible to manufacture adaptive components without the use of large and heavy mechanical constructions. Smart materials have shown promising results in the application of adaptive architectural elements. By performing research on the edge of material science and architectural design, knowledge diffusion will lead to innovative solutions on this subject.

References

1. Irwin, P.A., *Wind engineering challenges of the new generation of super-tall buildings.* Journal of Wind Engineering and Industrial Aerodynamics, 2009. **97**(7-8): p. 328-334.
2. Tse, K.T., et al., *Economic perspectives of aerodynamic treatments of square tall buildings.* Journal of Wind Engineering and Industrial Aerodynamics, 2009. **97**(9-10): p. 455-467.
3. Teuffel, P., et al., *Computational Morphogenesis Using Environmental Simulation Tools*, in *International Association for Shell and Spatial Structures (IASS)* A. Domingo and C. Lazaro, Editors. 2009: Valencia, Italy.
4. Teuffel, P. and D. Ajdarpasic, *Development of a Shape Morphing Building Envelope*, in *IASS 2007 Structural Architecture; Toward the Future Looking to the Past*. 2007: Venice, Italy.
5. Maruta, E., M. Kanda, and J. Sato, *Effects on surface roughness for wind pressure on glass and cladding of buildings.* Journal of Wind Engineering and Industrial Aerodynamics, 1998. **74-76**: p. 651-663.
6. Chand, I., P.K. Bhargava, and N.L.V. Krishak, *Effect of balconies on ventilation inducing aeromotive force on low-rise buildings.* Building and Environment, 1998. **33**(6): p. 385-396.
7. Ansari, F., A. Maji, and C. Leung, *Intelligent civil engineering materials and structures a collection of state-of-the-art papers in the applications of emerging technologies to civil structures and materials*. 1997, New York: ASCE. 299.
8. www.hyposurface.org. *dECOI*.
9. www.flare-facade.com. *Flare Facade*.   2010-04-07]; Available from: www.flare-facade.com.
10. www.sharkskincoating.com. *Shark Skin Coating*.   2011-02-10].
11. www.whalepower.com. *Whale power*.   2011-02-10].

12. Aoki, K., K. Muto, and H. Okanaga, *Aerodynamic characteristics and flow pattern of a golf ball with rotation.* Procedia Engineering, 2010. **2**(2): p. 2431-2436.
13. Smith, C.E., et al., *Numerical investigation of the flow over a golf ball in the subcritical and supercritical regimes.* International Journal of Heat and Fluid Flow, 2010. **31**(3): p. 262-273.
14. Lelieveld, C.M.J.L. and A.I.M. Voorbij (2008) *Dynamic Material Application for Architectural Purposes*. Advances in Science and Technology **56**, 595-600.
15. Lelieveld, C.M.J.L. and P. Teuffel, *Smart Composite for Architectural Applications*, in *International Association for Shell and Spatial Structures (IASS)*, L.Y. Qilin Zhang, Yuyin Hu, Editor. 2010, China Architecture & Building Press: Shanghai, China.