From adaptive to high-performance structures

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Abstract

Multiple design aspects influence the building performance such as architectural criteria, various environmental impacts and user behaviour. Specific examples are sun, wind, temperatures, function, occupancy, socio-cultural aspects and other contextual aspects and needs. Even though these aspects are acknowledged to be variable, conventional buildings are conceived to provide one design solution, represented in a static configuration. Ongoing research includes several of the above mentioned environmental design drivers, amongst others wind, earthquakes, daylight, interior and exterior climate as well as user requirements.

In this paper two of these aspects shall be considered and discussed in more detail; namely wind and earthquakes, which are manipulated with shape morphing elements within the building envelope and / or active structural elements. Finally an outlook will be presented how the introduction of the idea of adaptive systems will have impact on the future of structural engineering.

Keywords: Adaptive systems, structural control, wind engineering, seismic design

1. Introduction

Multiple design aspects influence the building performance such as architectural criteria, various environmental impacts and user behaviour. Specific examples are sun, wind, temperatures, function, occupancy, socio-cultural aspects and other contextual aspects and needs. Even though these aspects are acknowledged to be variable, conventional buildings are conceived to provide one design solution, represented in a static configuration. Due to the changes in needs and context, a static building cannot guarantee the same level of performances over time. This will lead to a discrepancy between the building and the environment.

Ongoing research includes several of the above mentioned environmental design drivers, amongst others wind, earthquakes, daylight, interior and exterior climate as well as user requirements. In this paper two of these aspects shall be considered and discussed in more detail; namely wind and earthquakes.

Within this paper the possibility to utilize the adaptation of the façade in order to control its skin-roughness and thus manipulating the air-flow characteristics of high-rise buildings or wide span structures. Shape morphing elements, for example made out of smart composite materials, can be located at specific areas of the building envelope to modify the wind velocity field close to the façade to control the heat exchange between inside and outside the building. Further on to this adaptation, which takes place at building component level, a global shape changing system of the façade leads to new ideas about wind optimised buildings, which leads to high-performance aerodynamic systems

A second area of application of adaptive structural systems is seismic design: in this paper a study of an efficient seismic responsive adaptive structure will be presented. Using active elements the internal force pattern will be optimised to control the behaviour during a seismic event. Eventually the brought-in energy will be re-distributed within the structural system in a beneficial manner and this will allow the building to be truly an adaptive structure, instead of a passive structure controlled by active systems.

2. Design Drivers

2.1. Wind Loading

One of the key aspects for large-span or high-rise structures is the wind loading, which is a highly dynamic phenomenon and therefore a very interesting driver for adaptive architecture. While in other disciplines, such as aerospace or automotive industry, aerodynamic performance-orientated shape optimisation is a regular approach, in architectural design it is less common. Of course the major difference between these other disciplines and architecture is that for aerospace or automotive a clearly defined flow direction exists, while the design of buildings requires the consideration of variable directions (and velocities as well).

One possibility to deal with this is the shape morphing at a large scale [1-4], the second option is to handle it at a smaller scale, namely the roughness of the envelope [5-7].

The wind load of a high-rise building with a geometrically morphing façade is analysed by numerical simulation. In this paper the focus is 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, which are capable to sense automatically and inherently to detect changes in their environment and to respond to those changes with some kind of actuation or action. In this project the focus lies on shape morphing smart materials, which are able to adapt the building texture by intrinsic material characteristics, such as smart composite materials [7, 8].

2.2. Seismic Loading

There are two possibilities to design a structure to resist lateral earthquake loads: The first one is giving it enough dissipation capacity, in order to dissipate the energy introduced by seismic motion of the structure. The second one is to isolate it from the ground, avoiding energy that may be introduced in the structure.

The traditional strength based-design is based on a thorough selection of load-bearing components of a structure, in which the following properties of the chosen material are relevant: modulus of elasticity, ultimate stress and density, which must be taken into account. Besides geometrical configuration and function, these properties allow to determine the ultimate strength of the structure and to face predefined load cases. However, it is assumed that buildings will work in a "static" mode when its structure bears the dead and live loads from the roof or top story through the ground. In the other case, the building will work in a "seismic" or dynamic mode, dissipating through vibration or motion. In practice the same structural system is assumed i.e. a configuration for loads, which works in both modes: static and seismic.

3. Case Studies

3.1 Wind-adaptive facade system

On simple case studies a series of CFD simulations have been performed 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 [7]. Figure 1 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

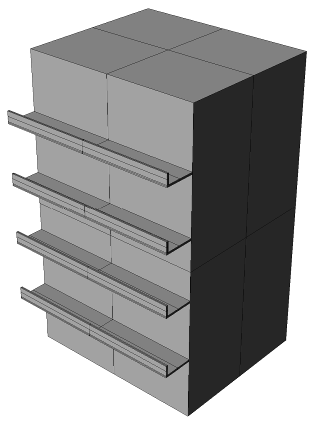

Figure 1: Low rise building with balconies

The second case study is a simple square high-rise tower, which is 30 m wide and 100 m high. 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 2). The following cases have been studied:

A2. Smooth surface
B2. Horizontal roughness elements on the side wall
C2. Vertical roughness elements on the side wall

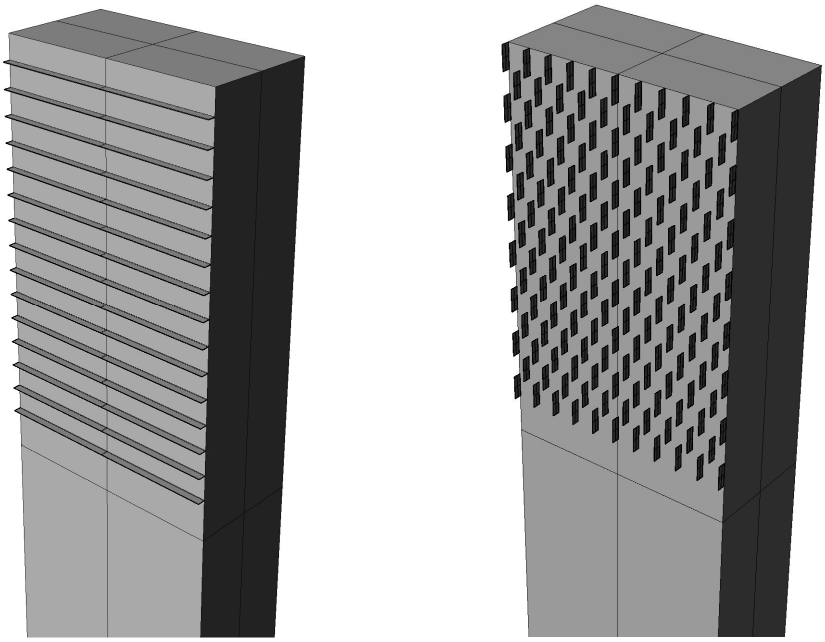

Figure 2: High-rise building with roughness elements (Left: case B2 and right: C2)

Simulations results and discussion

Figure 3 shows the comparison between the pressure 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 are rather evident because of the presence of the balconies, especially at the top and the ground floors.

After validating the methods and demonstrating the possibility to modify the pressure field by means of facade projections, the second case study has been analysed. 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.

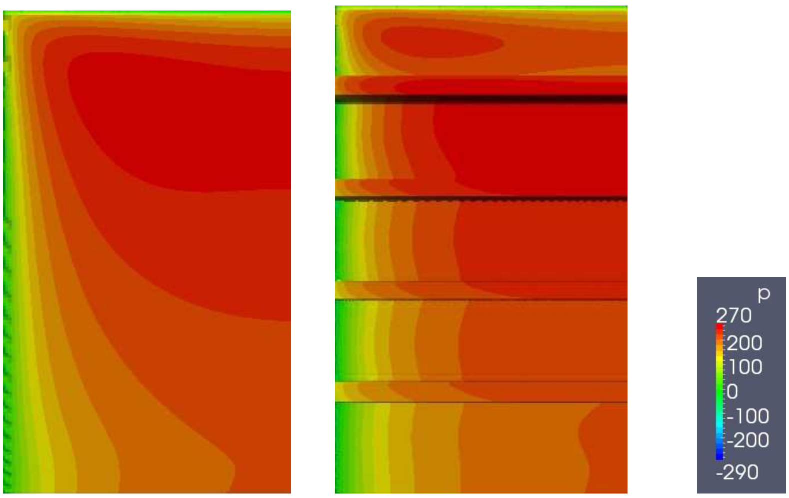

Figure 3: Pressure field on the upwind façade of the low-rise building (Case A1 and B1)

In Figure 4 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 facade surface, which corresponds to the plane. This 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) a larger uniformity of the flow field will be provided. They offer a big resistance to the wind, decreasing the air velocity close to the facade. This effect can be exploited when there is need to decrease the heat exchange between the indoor and outdoor environment. Turning the roughness elements into a horizontal direction, provides a sort of canalization of the air which can be exploited for moving the zone at a higher velocity where desired [7].

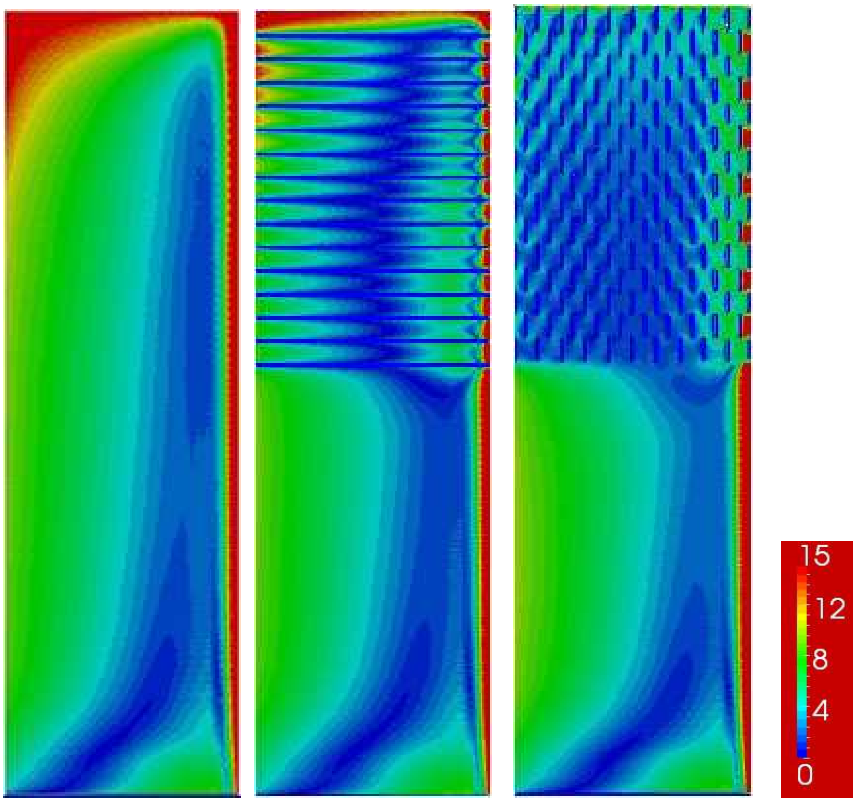

Figure 4: Velocity field on the side wall of the high-rise building (case A2, B2 and C2). The wind is coming from the right-hand side.

A minor positive effect obtained by adding roughness elements on the facade is the decrease of vorticity close to the upwind corner. Figure 5 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 facade elements (e.g. windows or double skin elements) are coloured in red. It is evident in Figure 5 that close to the building corner in the upwind zone there is a strong under-pressure area. This is because of the presence of a corner vortex which is almost completely eliminated.

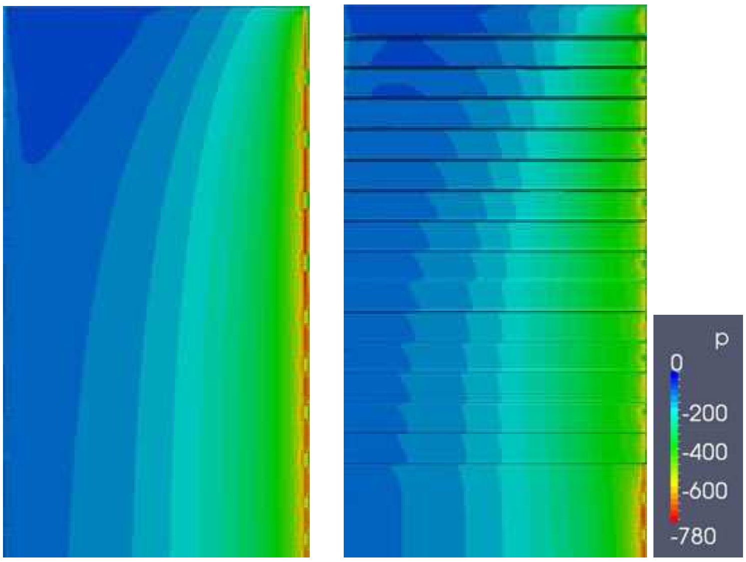

Figure 5: Pressure field on the top region of the side wall of the high-rise building (case A2 and B2). The wind is coming from the right-hand side.

3.2 Earthquake-adaptive structural system

A typical example based on a 5-story building will be used to study the optimal stiffness distribution of a vertical structure faced to earthquake motion. The final aim is to analyse the adaptiveness or capacity of the structure to adapt itself to the very significant loads that change in time.

The elastic response of the structure to lateral forces is depending on the stiffness properties of the system. In order to determine the base shear, most procedures are defined by seismic design codes in which the final value is obtained from different parameters: acceleration and main features of the ground, structural system of the building and weight of the structure. These parameters (among others as the importance factor depends on a building's function) are used to define a factor that multiplies the total weight in order for the base shear to be a percentage of the total mass of building, see figure 6.

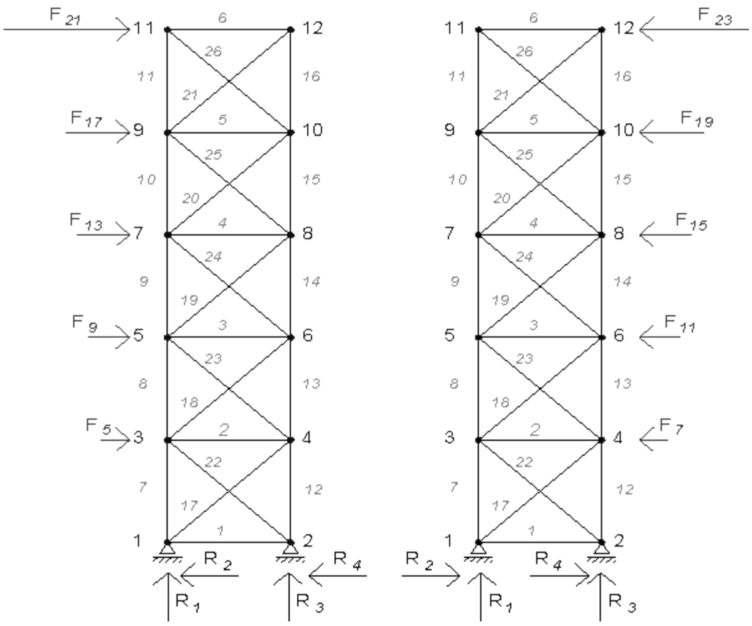

Figure 6: Load cases 1 and 2 (left and right) for lateral loading equivalent to base shear in 5-story truss [10]

Load Path Management

Load path management (LPM) [9] aims at optimising the performance of the load bearing system, while minimising its weight, by manipulating the properties of the structural elements, in order to control its response. In the context of dynamics various properties, such as moving masses, damping and/ or stiffness, can be used to control the structural behaviour. For instance if the displacements can be controlled to zero, it is possible to reach a virtual infinite stiffness of the structure supported by means of input of energy but without additional mass.

The first step of LPM is the optimisation of the force paths for a fixed geometry and neglecting of compatibility constraints, see fig. 7. This results in an optimal cross section distribution with a 100% stress utilisation.

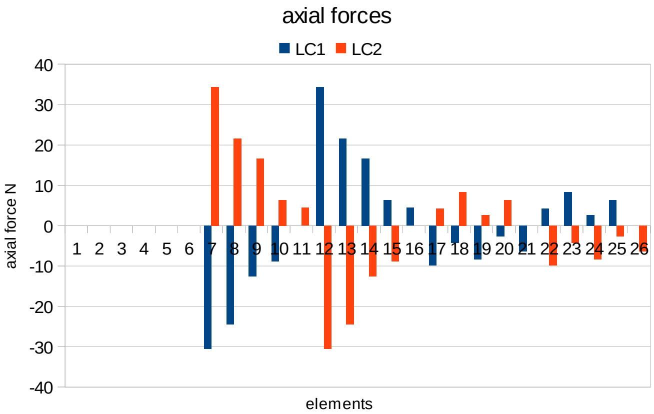

Figure 7: Passive optimized stress distribution

Displacement Control and Adaptation

Based on the force path optimisation a conventional FEM analysis is carried out to determine the forces and displacements of the given system. The difference between this analysis and the aimed optimal force path defines the required active response of the system, including the number and location of active elements.

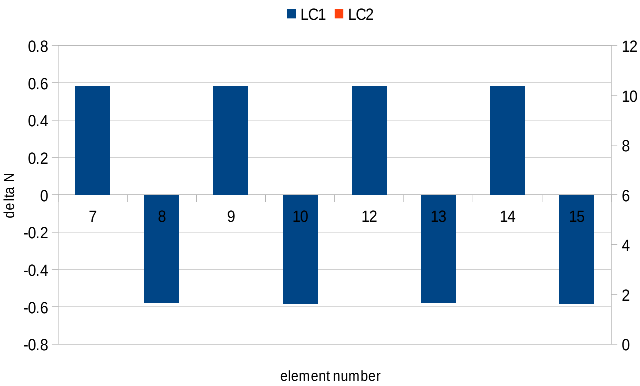

Figure 8: ΔN = Optimized – FEM axial forces

The selection of actuator and sensor numbers and locations is carried out through a sensitivity analysis, which tests the effects in nodal displacement and axial forces respect to the length extension in one unit for each element of the structure. The iterative process output is the selection of the most efficient positions, i.e., how far this variation in length will allow achieving the desired state of forces or deformation. Figure 9 shows the configuration of the structure with the most efficient actuators.

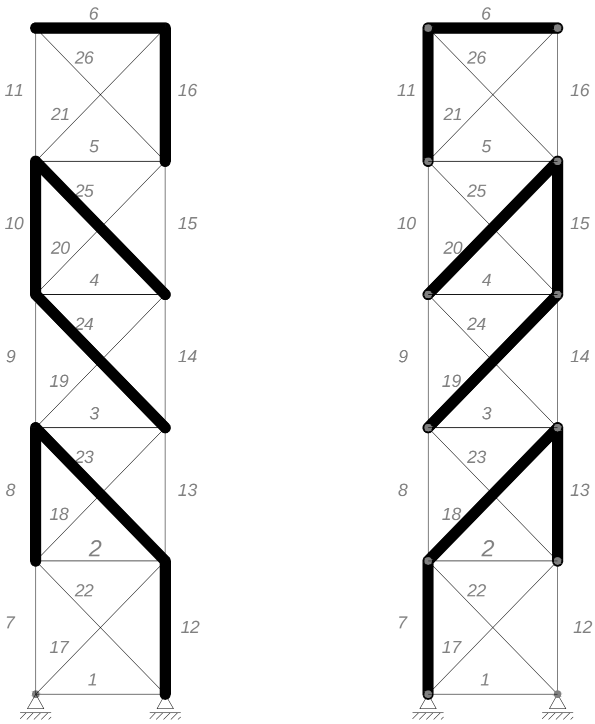

Figure 9: Distribution of eight most efficient actuators for each load case

For dynamic case, it is more likely that the sensors and actuators will be at different locations on the structure, although a regular configuration permits some simplifications [11].

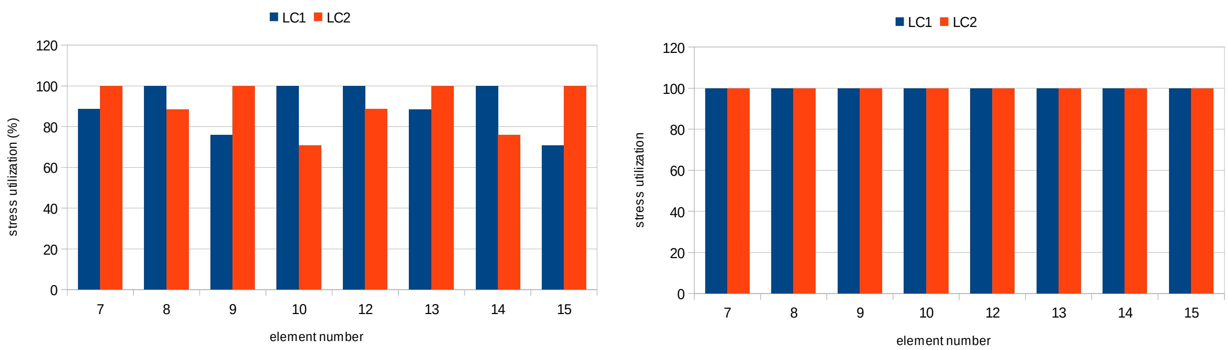

Figure 10: Stress utilization in passive (left) and adaptive force path optimized (right) system, for LC1 and LC2 in the most stressed elements in the structure

Finally, the determination of the optimal force paths takes place after a comparison between the passive optimized structure and the adaptive solution. The adaptive structure considers active elements in the location predefined. In figure 10 it can be seen that the passive force path optimization achieves a stress utilization of 100% for only some elements of the structure, while a stress utilization of 100% in all elements in all load cases can be achieved for the adaptive system.

4. Conclusion

The presented case studies demonstrate the potential of adaptive systems in the built environment. Any future constructed building system or its components should be evaluated on their potential to react flexible and adaptive to future changes of user requirements or variable environmental conditions. The introduction of smart materials and control systems into architectural and engineering systems will provide new possibilities to achieve new levels of performances.

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