

STRUCTURAL DYNAMIC FAÇADE

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Summary: Second skin façades are used to improve the building physics of a façade not for structural reasons. This research at the Eindhoven University of Technology focuses on the structural advantages of form-active lightweight second skins façades using their dynamic structures behaviour.

By detaching the form-active façade from the rest of the building, larger deflexions are possible. Their flexible behaviour and the dynamic structural response to (wind)loading reduces the internal forces and optimizes the efficient use of material. The second skin takes a global stabilizing role as a main structural element

1 INTRODUCTION

Façades play a very important role in the quality of a building. It forms the barrier between the internal space and the outside climate. In this role of building physics, second skin façades are designed to make use of the natural energy sources as wind- and solar energy.

Structurally the façade line is the most efficient line for placing the main structural elements. Therefore high-rise building have often a tube structure integrated in the façade. It is interesting to see how a second façade can be active as a structural element.

These two technical aspects must be designed in line with a third very important role of the façade, the architectural quality. The façade is the medium through which the interaction takes place between the activities inside and outside. The image of a building, and therefore also of the users, is reflected through the design of the façade

The danger of the combination of all three - building physics, structure and architecture - will lead to a compromised design instead of fully optimizing all three aspects. Often the technical requirements of the façade will restrict the architectural wish of transparency.

At the Eindhoven University of Technology several studies are done in which the second skin façade is part of the main structural system and takes a global stabilizing role. The function of the façade is focussed on absorbing wind energy. This limitation in function allows us to use form-active lightweight façade structures that reshape under different load patterns.

Because of allowing these movements two major advantages can be obtained:

- forces are transferred by axial forces, resulting in higher efficiency and less use of material,
- forces are absorbed in a dynamic way resulting in lower internal forces and therefore less use of material.

After describing both issues, two projects will be presented with a form-active lightweight second skin façade.

2 FORM-ACTIVE FAÇADE STRUCTURE

Membrane structures, pneumatic structures and cable net structures are typical form-active structures. They can only support loads by deformation. Without external loads, the internal prestress forces are balanced by a form-finding process. When the structure is loaded externally the shape must change to find a new balance in forces.

The structural elements are flexible and cannot take bending moments. Internal forces are only axial forces or forces in plane of the membrane. These internal forces will activate and use the full sections of the material efficiently, reducing the amount of material used.

Minimising structural material by increasing its efficiency is the key of the behaviour of lightweight structures. Form-active structures can be very efficient but because they adjust in shape to resist loading their stiffness is often not sufficient for certain usages. Form-active structures are therefore often used where stiffness and the related deformation is less critical, as in large span roof structures.

Looking at this in another way, does it mean that when we allow higher deformations that we can reduce the amount of material? Maybe this is not an overall correct statement but in many cases this could be correct. For instance, compare a concrete floor with a trampoline. A concrete floor is often more than 200mm thick with a heavy weight to provide the comfort in limiting the deflexions and vibrations. A trampoline is a lightweight structure from a few millimetres thick membrane with a high flexibility. To support the load it must deform largely. They both serve their purpose.



Figure 1: Stiff and heavy concrete floor⁷



Figure 2: Flexible, lightweight form-active trampoline⁸

It is therefore most important to find the optimal link between the requirements of a structure and its capacity / behaviour. Depending on the requirements it could be that the solution is not to resolve all issues within one structure. Combining the best characteristic of multiple structural systems can result in a more optimum result.

3 SPLIT OF STRUCTURAL FUNCTIONS

There is often an architectural wish of high transparency in the façade, but with high rise buildings structural requirements often restrict this. To stabilize a building, the façade is the best location to place the construction. This so called “tube structure” build up from façade columns and beams can stabilize the building by moment-stiff connections or introducing bracing between them.

Buildings need to be stabilized in a way that no unpleasant horizontal movements occur. This is not only governed by the amount of movement in millimeters, but mainly by the acceleration a person will feel from the moving floor the person is standing on. This restriction has a high impact on the structural sizing of the stabilizing structural elements in the façade.

The loading on buildings we can split in functional loading (live load) and non-functional loading (wind- and snow load). Live load, as of people standing on a floor slab, need strength and stiffness for the above mentioned comfort reasons. For wind loading strength is needed in a structure but stiffness could be interpreted differently. The wind loading however is transferred via the same stiff structure as the live load to the foundation that could result in an interference of requirements. The wind loading can accelerate the structure that supports functional loading in an uncomfortable way. This way the wind load is a governing load case, requiring to strengthen the structure to meet its primary requirements.

Would it be a good solution to design an independent form-active façade structure for wind loading and allow larger deflections to increase the efficient use of the materials? In this way the independent façade protects the internal space in an efficient way, prevents horizontal wind forces and acceleration to act on the internal structure, making it possible to design the overall stability structure in a different way.

In 1971, a feasibility study called “City in the Antarctica“ showed us an air-supported building over a city. The building, a climatic shell spanning 2km, protected the buildings underneath from rain snow and wind. At the same time, it also functioned as a first physical plane.



Figure 3: 'City In Antarctica'; study of Frei Otto, Kenzo Tange en Ove Arup & Partners²

Although this is a futuristic design, imagine a building placed within a protected space, embraced by a structural independent film. The scale is reduced, but the principle stays the same.

The protection against external influences will reduce the structural requirements of the building within, and increase both the efficiency in use and the architectural freedom. Structural requirements have moved towards the embracing structure. Because of the structural independency between the building and the embracing skin, the horizontal movement of the embracing structure is not limited by the value of acceleration that is acceptable to people. Consequently, the allowable deflections and accelerations in the embracing structure can be much higher. This opens a whole new field of structural possibilities, especially within the field of using lightweight structures.

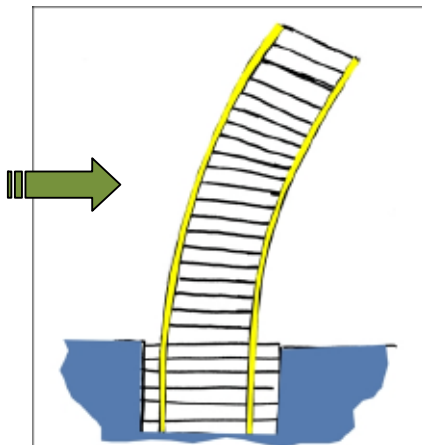


Figure 4: Tube structure³

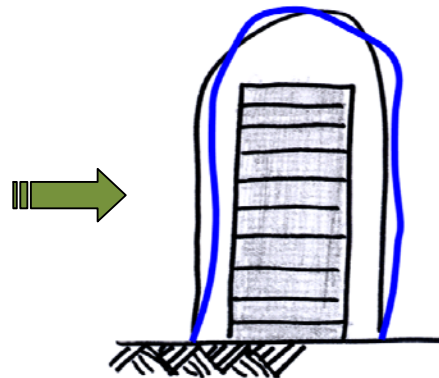


Figure 5: Independent second façade structure³

Limiting the stability requirements of the internal structure will put earthquake resistance in a different perspective. The more flexible the building, the less energy it attracts. The link to earthquake resistance is part of the research at the Eindhoven University of Technology.

3 DYNAMIC BEHAVIOUR

Wind is often calculated as a static load on a static structure. In reality it is a dynamic wind spectrum acting on a dynamic structure. This raises the questions “How is the dynamic load transferred to a static load?” and “What difference in impact does a loading have on a static or a dynamic structure?”.

When a constant force is pushing against a fully encastre mast, the properties of the mast does not influence the internal forces and the foundation forces. When a dynamic loading is acting on the mast the properties of the mast does make a difference. A more flexible mast will reduce the internal loading and therefore the foundation forces. You can take grass moving in the wind as a reference. It would break if reality would be static.

This can be explained by hitting your hand against a concrete wall, this hurts. But when you place a pillow between it makes a big difference. In both cases the energy in your movement (kinetic energy) is the same and is transferred to the concrete wall. Without the pillow this energy transfer is done in very short amount of time. With the pillow the time in which your energy is transferred is longer, therefore the force is lower.

Beneath we compare the internal forces, the foundation forces and the deformation of a 10m high mast with different stiffness. At the top of the mast an impact of a mass of 15 kg with a speed of 10m/s is modelled. The following results are found.

Model	Mast A	Mast B
Mast length	10 m	10 m
Mast profile	Round 150x5 steel tube	Round 250x5 steel tube
Section area	2277 mm ²	3848 mm ²
Moment of Inertia	600 cm ⁴	2900 cm ⁴
Displacement top by 1 kN	271 mm	56 mm
Spring stiffness	3690 N/m	17860 N/mm
Kinetic force load – 15 kg at 10 m/s	750 J	750 J
Period	0,4 s	0,182 s
Frequency	2,5 Hz	5,49 Hz
Maximum displacement at top	640 mm	290 mm
Maximum force at top	2,35 kN	5,18 kN
Maximum bending moment in mast	23,5 kNm	51,8 kNm
Maximum stress in mast	294 N/mm ²	224 N/mm ²
Maximum reaction force	23,5 kNm	51,8 kNm

Table 1 : comparison impact on two different mast profiles

The deformation of model A is larger, allowing to transfer the kinetic energy of the mass in a longer period to the mast, resulting in a lower force impact, a lower internal bending moments and lower foundation forces.

Form-active structures like pneumatic structures have a low stiffness. The impact of their dynamic behaviour can therefore be substantial. The internal forces and the forces on the foundation due to peak wind speed will reduce because of their large deformation and the longer period of kinetic energy transfer.

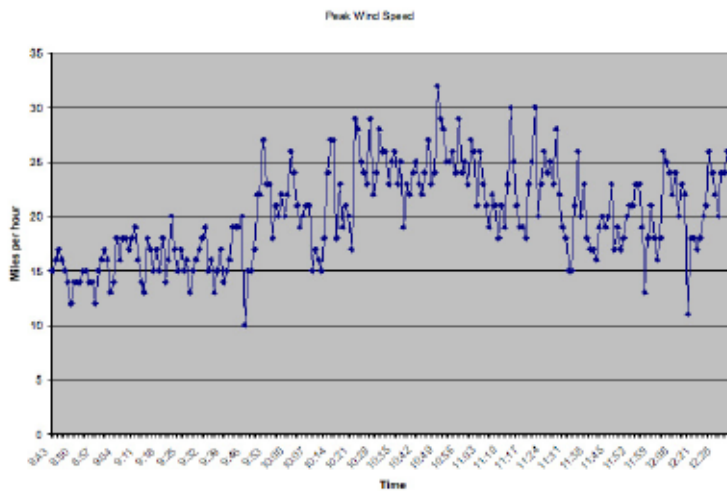


Figure 6: wind speed measurements with peaks of wind speed ⁶

3 PROJECT 1 – HYPERBOLIC OFFICE TOWER

A hyperbolic office tower is embraced with a structural second façade, that protects the building in a structurally independent way. The second façade is made from a hyperbolic cable net structure with a central mast, clad with pneumatic membrane elements.

The cable-net structure is a form-active structure that will deform when loaded by wind. This deformation will limit the impact of peaks in wind speed. Internal forces are axial forces only. Together with the high material strength of the cables and its dynamic behavior this results in a high transparent façade.

Figure 7 shows impressions of the design of the building. Columns are only located along the inner floor edge, although the main stability structure is located in the façade.

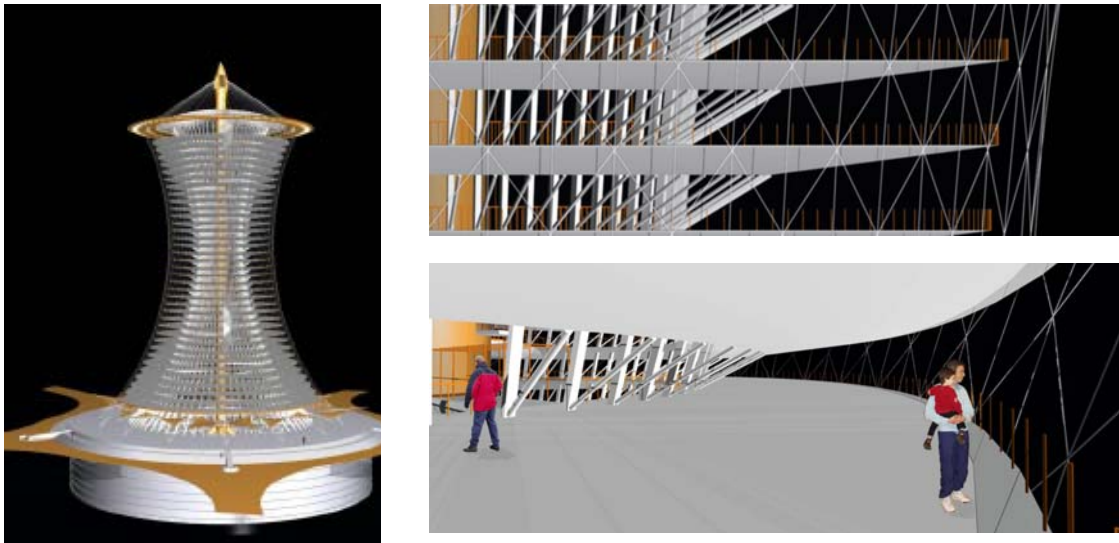


Figure 7: Impressions of the building design ³

The internal space within the cable-net can be used freely for the design of the independent internal building.



Figure 8: Model of a hyperbolic cable net structure ³



Figure 9: Sketch of a hyperbolic shaped building embraced with an independent cable net structure ³.

The cable net structure can be calculated separately. The structure is prestressed to prevent cables to go slack and to reduce the deformation. In figure 10 the deformation is calculated to be maximum about 900mm. between the second façade and the building flexible connections are made capable of bridging these differences in movement, but to control the air movement within the cleft.

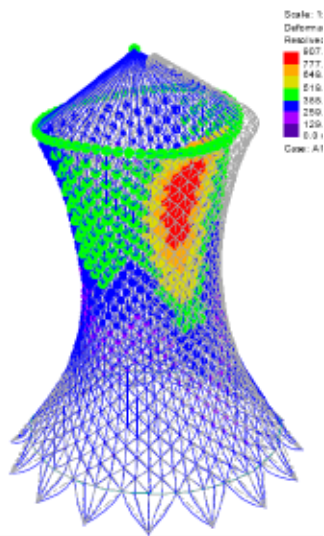


Figure 10: deformation because of windloading ³

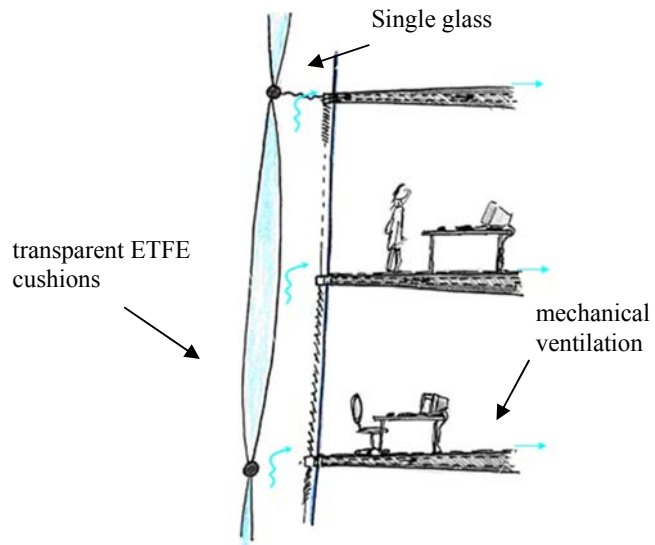


Figure 11: Structural second skin façade as a cable net with pneumatic cushions infill ³

Together with the basement and foundation structure the cable net is designed as a structurally closed system. The tension forces in the cable net balance the compression forces in the pylon by connecting them in the basement. This excludes pre-stress forces on the foundation. Figure 3 shows that the internal forces balance in a 3-dimensional way.

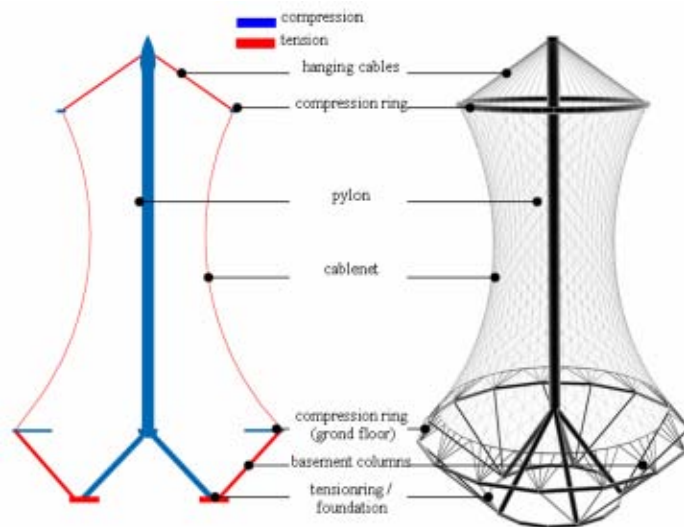


Figure 12: Structurally closed system of the embracing hyperbolic cable net skin structure ³

3 PROJECT 2 – PNEUMATIC SOUND BARRIER

Occupants of Hoofddorp in the Netherlands experienced for many years noise nuisance from the low frequent sound produced by planes during their start at Schiphol.

Natrix is a design for a pneumatic sound barrier that symbolizes the particular Dutch relation between land and water. The noise barrier is a fluent arc of water carried by air referring to the high sea level and air as the supporting medium of airplanes.

The 1800m long Natrix has the shape of a snake, built-up with an inner and outer skin. The inner skin consists of pneumatic air arches spacing 6m with in between PVC-coated polyester membrane. On top of the inner membrane water tubes with a diameter of 28mm are placed side by side for sound absorption and as medium to store and transport sun energy.



Figure 13: 3D-visualization birds eye ¹

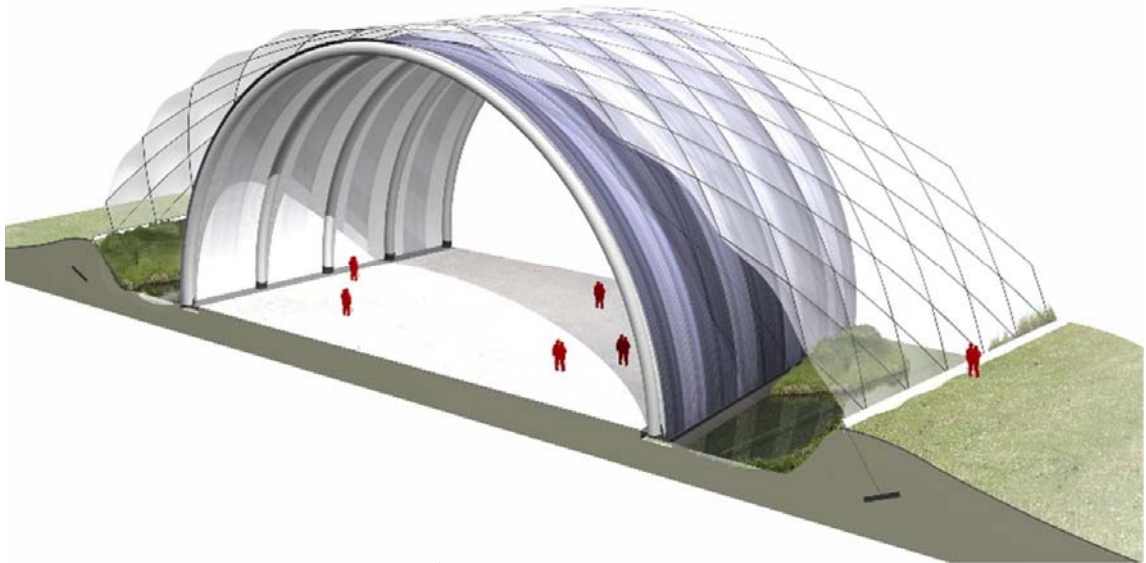


Figure 14: 3D-visualization – section part ¹

The outer skin exists from transparent foil called ETFE strengthened by a cable net and stabilized by an overpressure between the ETFE-foil and the PVC-coated polyester membrane. The cable net has a varying grid pattern to change its absorbing frequency along

the length of the runway according to the change of sound frequencies of an airplane during his take off.

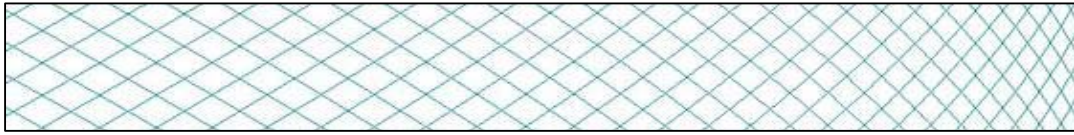


Figure 15: Optimized sound absorption by changing the pattern in the diagonal network ¹.

The inner and outer skin are fully disconnected from each other. By the application of the two layers, a cleft is created that acts as an insulation layer. Also the overpressure is only between the outer and inner skin, meaning the inside area is not under overpressure and available for all functions.

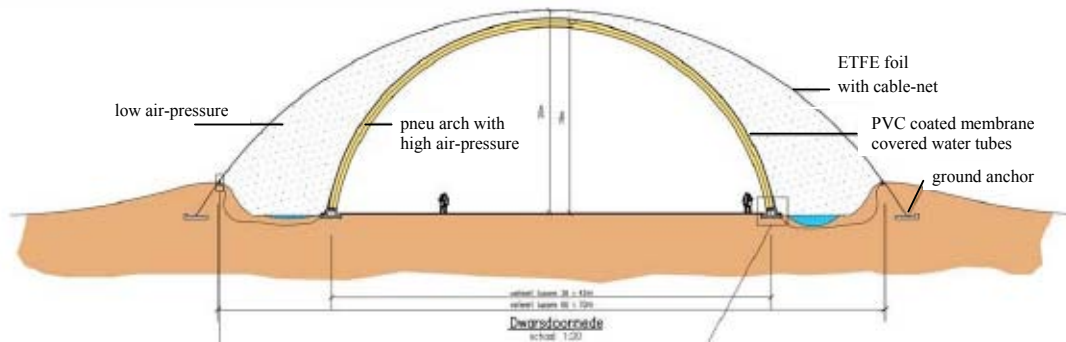


Figure 16: Cross section ¹.



Figure 17: Testing the screen of water tubes in the sound lab ¹

The maximum deformation with an internal air pressure of 0.3 kN/m² and a wind speed of 9 on the scale of Beaufort is 2.5m. The maximum deformation with an internal air pressure of 0.6 kN/m² and maximum wind force is approximately the same. The construction manages larger deformation, but it has been limited to 2,5m so that the external skin - with sufficient safety – never contacts the internal skin.

The pneumatic build-up of the structure will result in an external membrane that will deform by wind loading, while the internal membrane hardly moves. This is because the outer and inner skins are structurally not connected and deformation differences will be absorbed by air movement in the cleft. Studies at the Eindhoven University of Technology confirm this behaviour.

Because the people inside do not experience the deformation of the outer skin, there is no need for too low deformation limitations, resulting in a higher efficiency of material governed by strength.

Fluctuated wind acts on the outer skin. The outer skin deforms in a dynamic way. The larger the deformation the longer it takes to transfer the energy of a wind gust to the structure, the lower the impact force, the lower the internal and foundation force.

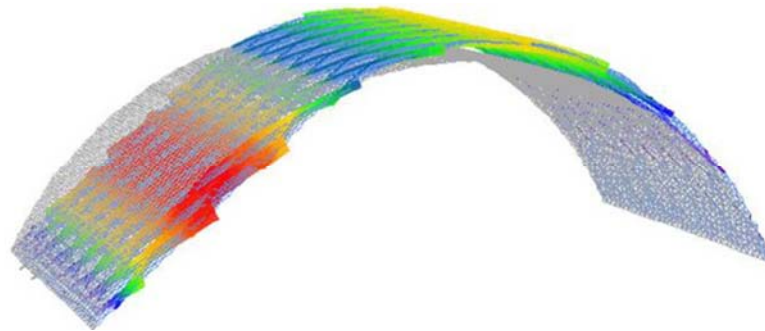


Figure 18: Deformation of external skin loaded on wind loading ¹.

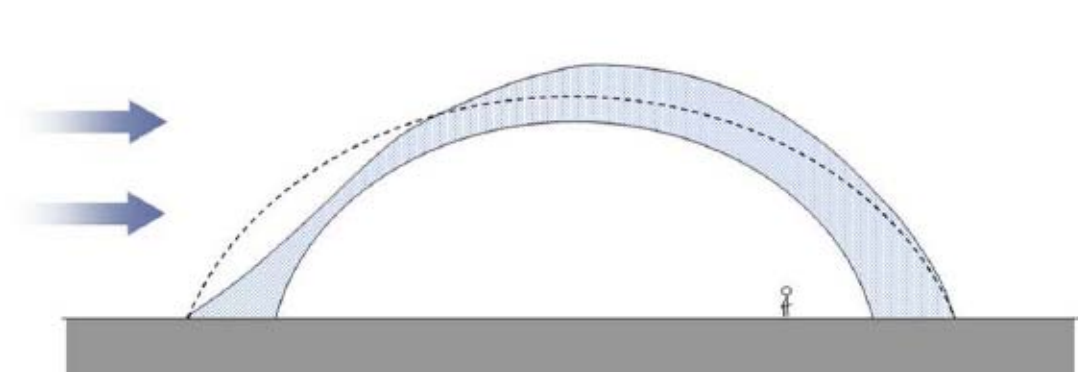


Figure 19: Outer skin deforms because of wind loading, but inner skin hardly moves ¹.

Because of the independent behaviour of the external and internal skin and the air movement in the cleft the varying external loading has limited influence on the internal skin. The pneumatic arches, supporting the internal skin, therefore are mostly loaded with permanent equal divided loading: self weight, internal skin, the water tubes and the air pressure in the cleft. When the differentiation of the loading pattern on an arch structure is limited, the arch can be designed as an optimum compression arch with limited bending moments. This will make it possible to use slender arch profiles.

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