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ADAPTABLE LIGHTWEIGHT STRUCTURES TO MINIMISE MATERIAL USE

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Summary. The optimal use of materials is highly necessary and a key issue for the near future. World's current demand on resources and waste production has an enormous impact on the environment, which will even dramatically increase when future's explosion on population takes place. The high contribution to this by the building industry gives it a big responsibility to reduce the concerning figures of material use.

This paper describes an approach in which structures are optimised with the use of adaptability. Structural optimisation is normally only done for static structures, while they are loaded in a dynamic way, meaning loadings which are changing in time, level and location. When structures are made adaptable to these dynamic environmental conditions the adaptability can significantly decrease the structural materials needed by increase of its efficiency.

Within this paper the structural adaptability is categorized in passive and active adaptability; passive adaptability using a higher deformation acceptance (flexibility) and active adaptability actively controlling the structure with actuators under different circumstances in a static or dynamic adaptive way.

The required higher deformation acceptance for passive adaptable optimisation, and the non-efficient influences of actuators for permanent loadings, like self-weight, does focus the research within the field of lightweight structures. Within the chair ISD of the Eindhoven Technical University 'adaptable lightweight structures' is one of the key research topics.

1 INTRODUCTION

The building industry must change. At the moment the building industry is responsible for more than half the mass waste production worldwide and uses a large percentage of the total used energy. Because of the increase of the number of people on this planet this problem of mass consumption will dramatically increase in the future. The population has grown in the last 80 years by a factor of 2,5 to about 7,5 billion people. Added to this the (additional) growth of world's population, the lifestyle of the current less developed countries will increase, claiming more space and luxurious materials. The impact of this increase of population and on the other hand the shortage of materials is critical to the environment and cannot become reality.

This means there is a big responsibility within the building industry to reduce these concerning figures of material use and mass waste. The current status however is, that in general buildings are build unsustainable and inefficient. Stiff and static objects are built with a lot of materials while the external environment acting on it is highly dynamic and changes in time and loading type, -level and -location. When structures are made adaptable to these variable environmental conditions the adaptability can significantly decrease the structural materials needed by increase of its efficiency.

The generally used optimisation of static structures is therefore extended by passive adaptive and active adaptive optimisation. Structures with higher deformation acceptance can react in a passive adaptable way which can reduce the load impact and the occurance of internal forces. With active adaptability the structural behaviour can be specifically controlled and further optimised. Combining the passive and active adaptability can result in an even further structural optimisation allowing the structure to deform in a controlled way as a reaction to avoid or absorb the impact of the varying external environment.

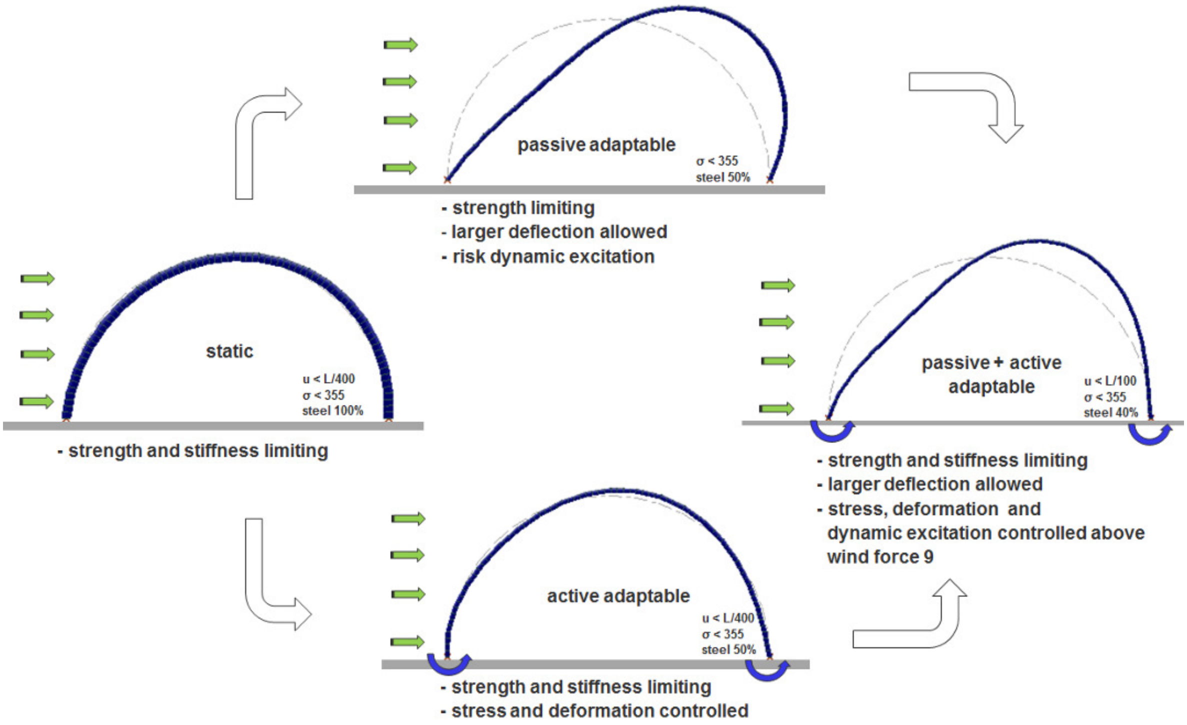

Figure 1: reduction in material use in an arch by passive adaptive, active adaptive and passive + active adaptive behaviour [2]

2 PASSIVE ADAPTIVE STRUCTURES

Structural deformation due to passive adaptable behaviour is often seen as undesired behaviour and in practice limited by building codes. But nature educates us about the advantages of flexibility. Loads are varying constantly. The wind's velocity, its direction and gust location changes and turbulence occurs, but even then organisms, such as plants, survive with minimum of damage despite their lightness. Important for their capability to survive is their flexibility and compliance.

But copying nature is not possible and not correct; there are other demands amongst deflections, isolation, cost, safety and many more. But by abstracting the main principles of the use of flexibility will result in better, lighter and more efficient design solutions.

By using this compliance passive adaptable structures can avoid the impact of the governing loading by adapting to it. Reduction of loaded surface, a better form factor and less friction are part of this principle. The so called Fluent Structural Interaction (FSI) plays an important role here.

Passive adaptability can also improve the efficiency of the material by changing its geometry and therefore its stiffness and/or the internal load-path (i.e. increase in curvature of a loaded membrane).

Allowing larger deformations in a structure will influence the dynamic behaviour. It can introduce dynamic absorption of forces and thus reducing peak loadings in time. For instance, this is the basis for the design of a bomb-blast resisting façade. But depending on the load spectrum and the vulnerability to excitation of the structural system, the dynamic behaviour can also increase the internal forces by resonance. For this reason active adaptability is researched not only as a static active adaptation, but also as a dynamic active adaptation to be able to control the dynamic behaviour (chapter 4 and 5).

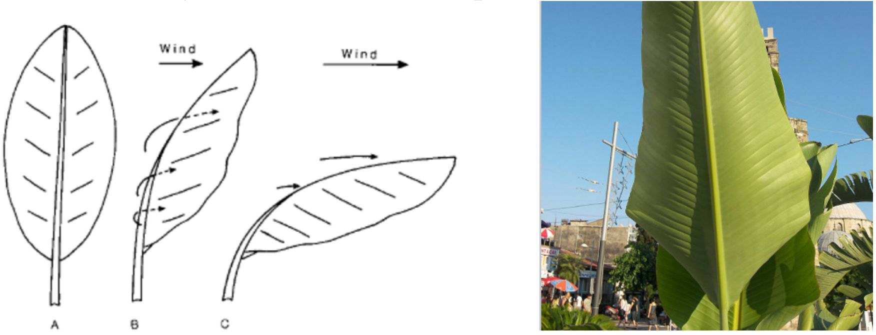

Figure 2: passive adaptive behaviour of a banana leave in the wind [7]

Roofs and (second) skin facades can play an important role in the study of flexibility within structures. The environmental loadings will act on this skin. When the skin will be designed in a way that larger deformation acceptance can be used for passive adaptable structural optimization the skin can improve the load absorption and transformation through the building to the foundation.

A brief study of the structural behaviour of the static and passive adaptable arch in figure 1 shows that the static tube arch of 2m in diameter spanning 67m with a height of 33m and a deformation limitation of h/200 can be reduced in weight by about 50% when the steel stress of 355 N/mm^2 is the limiting factor and not deformation.

3 STATIC ACTIVE ADAPTIVE STRUCTURES

In contrast with passive adaptability, active adaptability needs actuators and therefore input of energy to influence the structural behaviour. When using structural active adaptability, structures will mostly behave in a conventional passive way up to a certain level of loading or deformation. Above this threshold the structure will be active controlled by actuators, so called ‘active load-bearing capacity’.

These high loadings, which are often the dominating design parameter, occur very rare, and cause the structure to be overdesigned for most of its working life. When these high loadings above the threshold occur these actuators modify the pattern of internal forces – ‘load path management’ - to optimize the internal load distribution towards a more homogenous stress pattern and/or reduce the governing deformation. This results in an active controlled design with minimised structural elements without losing structural capacity in strength or stiffness.

The actuators can influence different variables within a structure. They can introduce counter forces, change geometry or adjust the section or even material properties. The aim is to maximise the structural improvement while minimising the effort of required actuation. Studying variations within the different active adaptable variables will unveil their impact towards an increase of structural efficiency and their optimum under different circumstances.

Considering the active adaptable arch in figure 1, the active rotation of the supports can reduce about 50% of the steel weight within the same limitation in stress as well in deformation as the static arch.

3.1 Load path management

The Load Path Management procedure as proposed by Teuffel[1] consists of three principal steps. First, the load path is optimized while ignoring the geometrical compatibility equations. During this step the axial forces in the elements as well as their section areas are optimised for minimal volume. However, the optimised distribution of forces and section areas is non-compatible due to neglecting compatibility. The constraint forces that arise in the structure by applying the constraints and external loadings must be compensated by the actuators to induce the optimal load path. These constraint forces are calculated by performing a static analysis for all load cases on the optimised structure using the minimised cross sectional areas. The difference between the incompatible optimal load path and the constraint forces must be accounted for by the actuators (eq. 1).

$$\Delta N = N_{opt} - N_{lc} \tag{1}$$

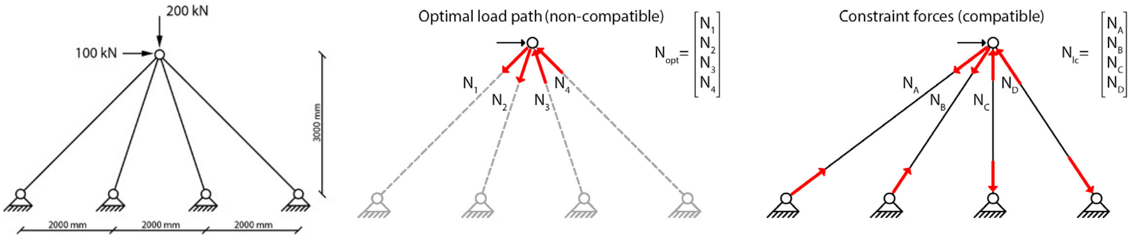

Figure 3: Four bar structure with optimal load path and constraint forces for the first load case.

As example a four bar structure[1] is taken (fig. 3). The first load case consists of a horizontal nodal force and the second load case consists of a vertical nodal force.

The minimum number of actuators needed to induce the axial forces ΔN in general is equal to the degree of indeterminacy of the structure. The optimal locations of the actuators are determined with the use of a sensitivity matrix Sn (eq. 2). Each element is subjected to a unity length change and the internal forces that arise in all elements due to the unity length change in the considered element are calculated. The vector e_i describes the efficiency of an element per load case (eq. 3), and E_i defines the efficiency of the elements considering all load cases at once (eq. 4).

$$\tilde{S}^{N} = \begin{bmatrix} \frac{\partial N_1}{\partial l_1} & \cdots & \cdots \\ \vdots & \frac{\partial N_2}{\partial l_2} & \\ \vdots & & \frac{\partial N_3}{\partial l_3} \end{bmatrix} \qquad e_{il} = \sum_{l=1}^{nLC} \left(\frac{\tilde{S}^{N} \cdot \Delta \tilde{l}_i^{a}}{\Delta N_l} \right) \qquad E_i = \Sigma_{i=1}^{ne} \left(e_i \right) \qquad (2)\ (3)\ (4)$$

During the adaptation process, the length changes of the actuators are determined while taking the compatibility equations into account. The length changes needed to control the load path and to create the optimal force distribution in structure follow from:

$$S^n \cdot \Delta L_{act} = \Delta N \qquad (5)$$

The adaptive four bar structure with the actuators marked in red is shown in figure 4.

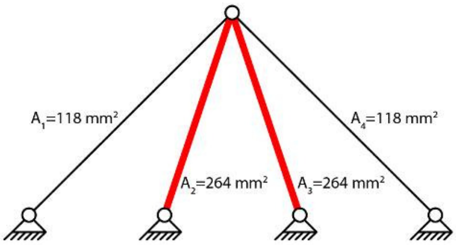

Figure 4: Adaptive four bar structure

In figure 5 the deformations and stresses due to external loading (load case 1) and the internal actuation are shown as well as the final optimal force distribution. The stresses in the adaptive structure in the passive state subjected to the external loading are higher than the allowable stress. However, by using the actuators the load path can be altered resulting in an optimal force distribution where all elements are 100% utilized in all load cases.

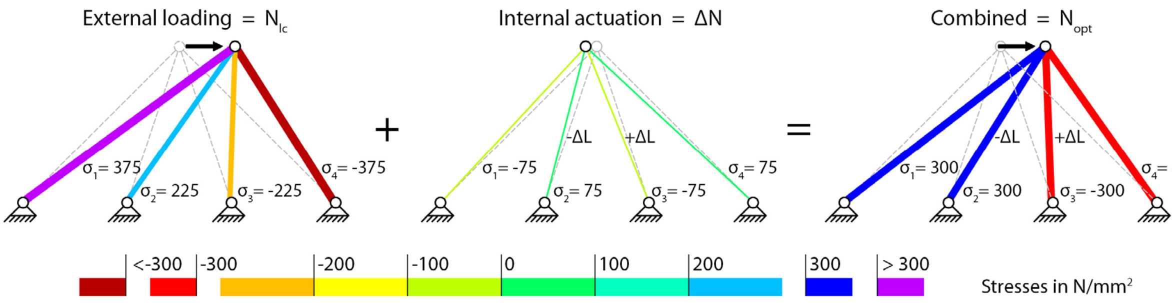

Figure 5: Static results of the adaptive four bar structure for the first load case

The same goes for the adaptive structure subject to the second load case.

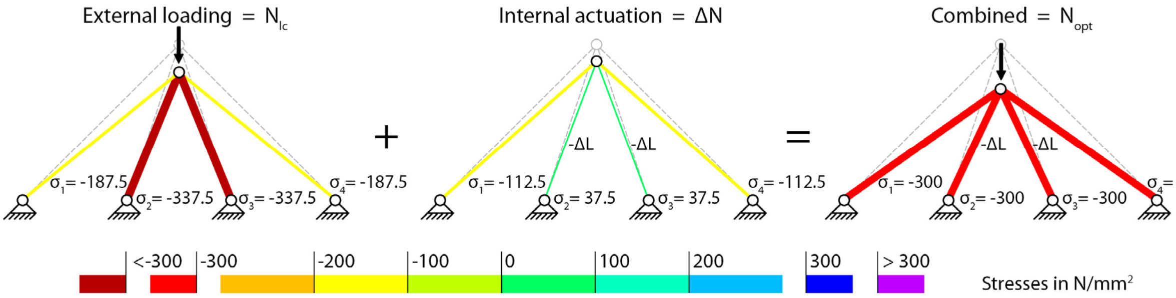

Figure 6: Static results of the adaptive four bar structure for the second load case

4 DYNAMIC ACTIVE ADAPTIVE STRUCTURES

When reducing structural material by optimisation its vulnerability to dynamic excitation can increase. This can limit the desired level of structural optimisation or will demand additional dynamic control systems.

For this reason, the same actuators used for static adaptive optimisation are used to control the dynamic excitation by superimposing additional small length changes based on the nodal velocities. This requires the actuators to be designed in such a way that they can sustain high static loadings while at the same time producing smaller but highly dynamic loadings. So by using the actuators not only for internal force control but also for control of deformation and dynamic excitation, the structural optimization can be highly efficient and further extended towards all boundaries set for strength, deformation and acceleration. Active adaptability will control the internal load path, deformation and dynamic excitation, while passive adaptability can increase the structural efficiency by increasing the threshold level of active interference.

5 CASE STUDIES OF DYNAMIC ACTIVE ADAPTIVE STRUCTURES

To accomplish a better understanding on how the dynamic behaviour can be actively controlled by actuators, two case studies are presented. The first study presented is a dynamic analysis on the adaptive four bar structure shown before which is followed by a dynamic study on a trussed arch structure.

5.1 Case study 1: Dynamic analysis of the four bar structure

For comparison a static and dynamic active adaptable four bar structure is analysed. They are subjected to harmonic resonance loadings corresponding to the two static load cases used before (horizontal and vertical nodal loading).

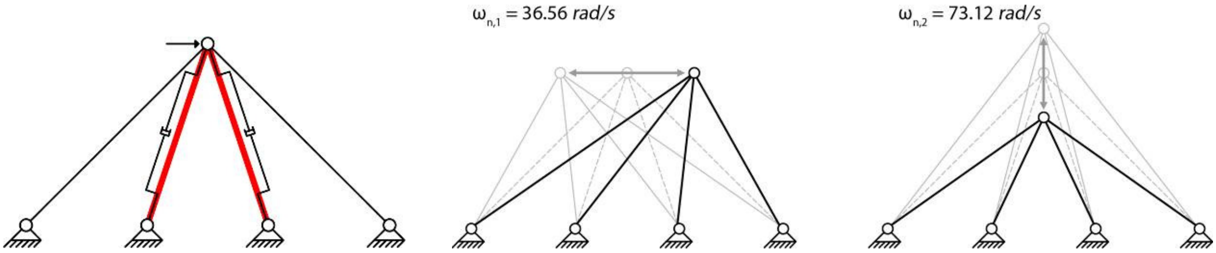

Figure 7: Actuators used to control the relative nodal velocities and natural frequencies and mode shapes of the adaptive four bar structure

First the natural frequencies and the corresponding mode shapes are determined by solving the eigenvalue problem (eq. 6). Where M is the mass matrix, K is the stiffness matrix and $\underline{\omega}_n$ is a vector containing the natural frequencies of the structure. The natural frequencies and corresponding mode shapes of the four bar structure are shown in figure 7.

$$-\underline{\omega}_n^2\left[M\,\ddot{\underline{x}}-K\,\underline{x}\right]=\underline{0} \tag{6}$$

During the dynamic analysis energy dissipation due to various mechanisms, such as friction and material damping, must be taken into account. Therefore, a damping matrix is defined by performing a modal analysis. Modal analysis is a method to rewrite the mass and stiffness matrix in a new modal basis by using the orthogonality conditions so that the system of equations is decoupled.

Once the equations are decoupled the modal damping parameters can be defined using the modal mass and stiffness parameters (eq. 7). Where m_j is the modal mass parameter, ω_j is the corresponding natural frequency and ζ_j is the desired damping ratio. In this case a damping ratio of 2% is used considering that both the passive and adaptive structures are made from steel. Rewriting in the real basis again the matrix becomes full resulting in the damping matrix C which is used during the dynamic analysis.

$$c_j = 2m_j \cdot \omega_j \cdot \zeta_j \tag{7}$$

5.1.1 Dynamic analysis of the four bar structure with static active adaptability

First the static active adaptive four bar structure is loaded with a horizontal harmonic loading while imposing the desired length changes of the actuators for the static load case. The excitation frequency of the harmonic loading is equal to the first natural frequency of the structure corresponding to the first mode shape where the structure is vibrating horizontally. The magnitude of the horizontal harmonic nodal loading ranges between 90% and 100% of the static horizontal loading.

In figure 8 the horizontal displacement of the upper node and the stresses in the four elements are plotted against time. Initially, the amplitude of the horizontal displacement increases very fast but after a couple of seconds a dynamic equilibrium establishes due to the applied 2% damping. Clearly, the weakly damped structure is resonating. Also the amplitudes of the stresses increase very fast initially until equilibrium establishes. The stresses increase up to 700 N/mm^2 which is much higher than the allowable stress of 300 N/mm^2.

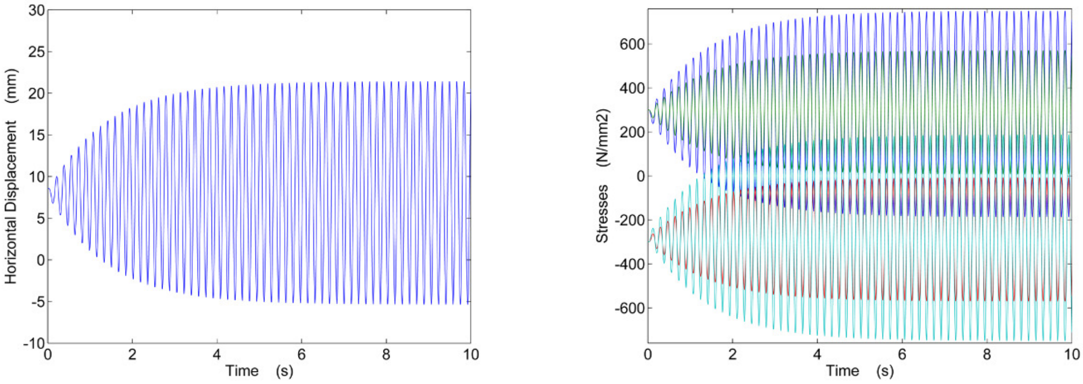

Figure 8: Results of the static active adaptive four bar structure subjected to a horizontal harmonic resonance loading

5.1.2 Dynamic analysis of the four bar structure with dynamic active adaptability

Again, a dynamic analysis is performed on the adaptive four bar structure subject to a horizontal harmonic resonance loading, but this time the actuators are used to control the structure dynamically. The desired length changes of the actuators for the static horizontal load case are imposed and 2% damping is applied. The dynamic control is introduced at each time interval by superimposed additional length changes based on the current relative velocity of the start and end nodes connected to the actuators.

In figure 9 the horizontal displacement of the upper node and the stresses in the four elements are plotted against time. Now, there is no increase in the amplitude of the displacement nor in the amplitudes of the stresses. Immediately a dynamic equilibrium is established and no resonance-effects occur. The dynamic active adaptive structure behaves more like a critically- or over-damped structure.

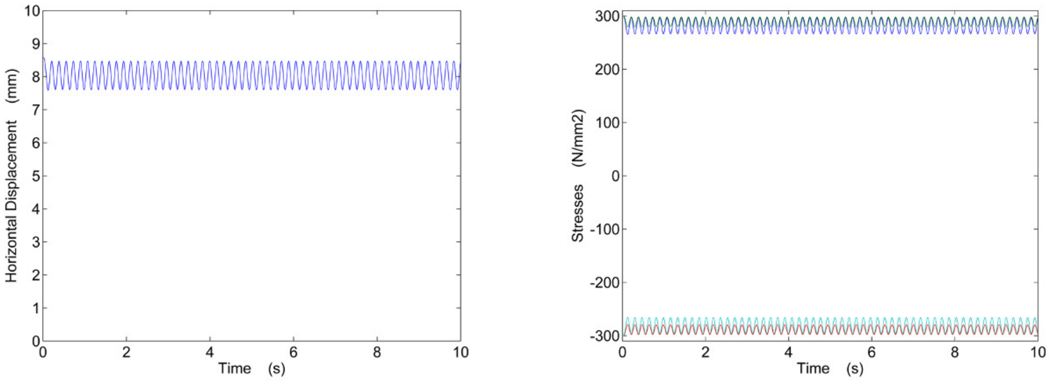

Figure 9: Results of the dynamic active adaptive four bar structure subjected to a horizontal harmonic resonance loading

5.2 Case study 2: Dynamic analysis of a trussed arch structure

A more complex trussed arch structure is studied (fig. 10). The trussed arch is 8 meters high and spans 40 meter with a structural height of 1 meter. The considered load cases are dead load combined with a static symmetric or asymmetric snow load or a harmonic wind load.

5.2.1 Load path management trussed arch

The adaptive trussed arch structure is designed according to the Load Path Management procedure outlined in 3.1. In this case 13 actuator locations are selected and the desired static length changes of the actuators for each load case are calculated.

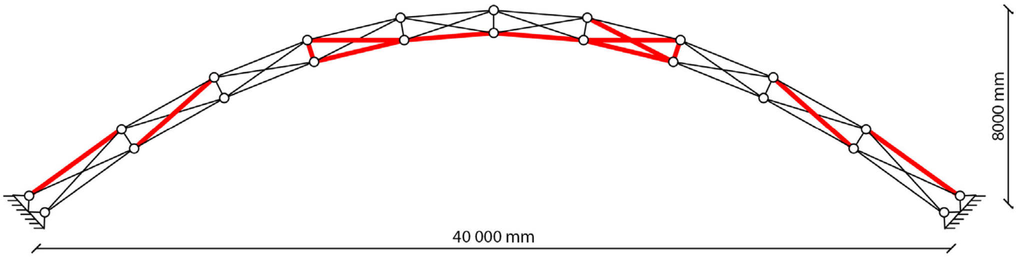

Figure 10: The adaptive trussed arch structure with 13 actuators

5.2.2 Static analysis of the trussed arch with static active adaptability

A static analysis is performed on the adaptive trussed arch structure subject to the static load combination of dead load with wind, while imposing the corresponding length changes of the actuators. The results of the static analysis are shown in figure 11.

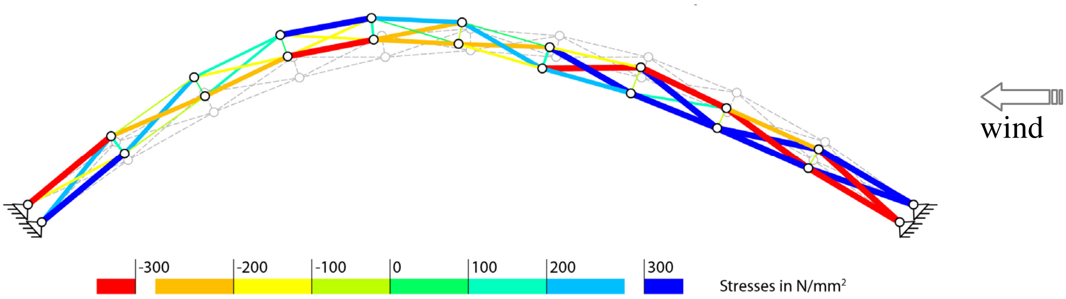

Figure 11: Static stress results of the adaptive trussed arch structure under dead- and wind loading

From figure 11 it can be concluded that the adaptive trussed arch structure is not capable of fully utilizing all cross-sectional areas as not all elements are fully stressed. Unlike the adaptive four bar structure the adaptive arch is unable to fully exploit all elements, because the trussed arch structure does not satisfy equation 8[1]:

$$n_{el} - n_{lc} \cdot \left(n_{DOF} - n_{bc} \right) \geq 0 \tag{8}$$

where n_{el} is the number of elements, n_{lc} the number of load cases n_{dof} the total number of dof and n_{bc} the number of constrained dof.

5.2.3 Dynamic analysis of the trussed arch with static active adaptability

Following the same procedure as before, the natural frequencies of the adaptive trussed arch structure have been found by solving the eigenvalue problem (eq. 6). In this case there are 36 eigenmodes as there are 36 unconstrained degrees of freedom. In figure 12 the first and second mode shapes of the adaptive trussed arch structure and their corresponding natural frequency are given.

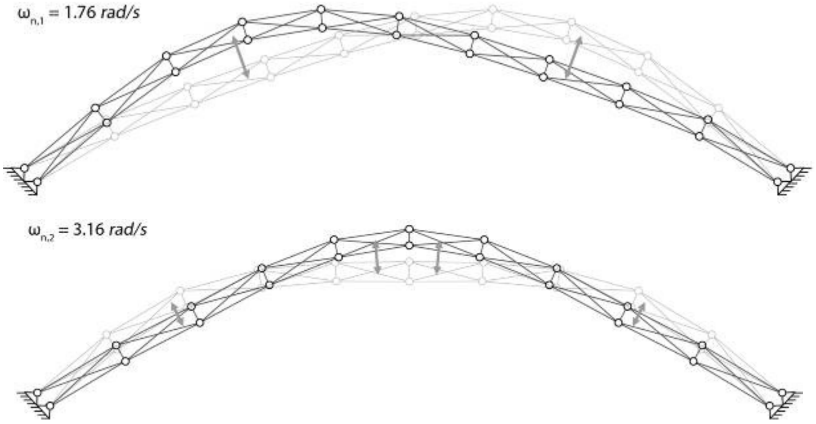

Figure 12: First and second natural frequencies and mode shapes of the adaptive trussed arch structure

A dynamic analysis is performed while applying 2% damping. First, the static adaptive structure is subjected to a harmonic resonance wind loading while imposing the desired length changes of the actuators for the static load case. The excitation frequency of the harmonic wind loading is equal to the first natural frequency of the structure where the arch structure is swaying horizontally. The magnitude of the harmonic wind loading ranges between 90% and 100% of the static horizontal wind loading.

In figure 13 the horizontal displacement of the unconstrained nodes and the stresses in the elements are plotted against time. The amplitudes of the displacements and stresses increase very fast due to resonance. Ater 120 seconds equilibrium establishes due to the applied material damping limiting stresses to 719 N/mm^2.

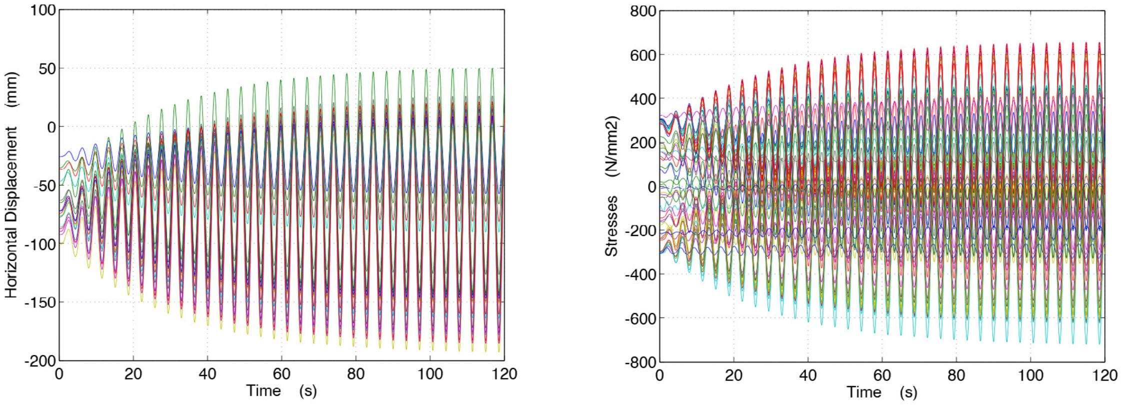

Figure 13: Results of the static active adaptive arch structure subject to a harmonic resonance wind loading

5.2.4 Dynamic analysis of the trussed arch with dynamic active adaptability

The dynamic analysis of the trussed arch has been performed again under the same conditions, except this time not only using the actuators in a static way to alter the load path, but also in a dynamic way to control the dynamic excitation of the adaptive arch structure. Though, controlling the relative nodal velocities - in which the velocity of the start node relative to the end node of the actuated element is controlled - is inefficient in this case. In case of the four bar structure the absolute velocities of the unconstrained degrees of freedom are controlled indirectly because one node of the element is supported, but this is not the case for the trussed arch structure. Therefore the actuators are now used to control the absolute nodal velocities instead of the relative nodal velocities.

The dynamic analysis on the trussed arch structure is performed under the same conditions, in which all unconstrained degrees of freedom are controlled by superimposing additional length changes based on the absolute nodal velocities. Considering the results in figure 14 one can see that resonance effects have been reduced. This time the displacements are smaller and the stresses are limited to 403 N/mm^2. Using the actuators to control the unconstrained degrees of freedom seems effective.

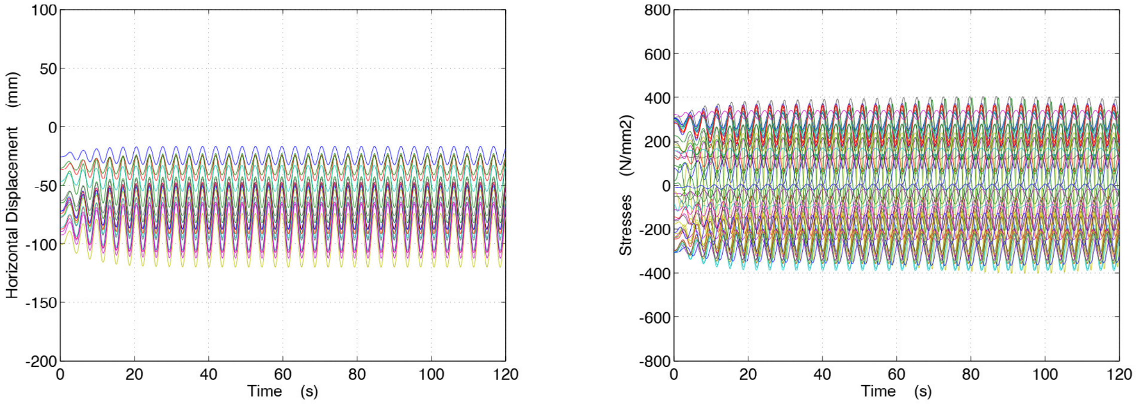

Figure 14: Results of the dynamic active adaptive arch structure subject to a harmonic resonance wind loading (controlling all degrees of freedom)

The control system needs time to collect and process the gathered information, to determine the response and to activate the actuators. This will introduce a delay in the response. A first preliminary study in which a short delay of 250 ms is taken into account, shows similar results as in figure 14 for the active adaptive structure with no time delay. But the delay time relates to the equipment used and the impact of the delay will relate to the structural behaviour of the system, to the dynamic loading acting on it and to the excitation frequency.

6 CONCLUSION

Adaptable structures can optimize the structural behaviour by adjusting to varying environmental conditions. This direct relation between loading and structural performance shows strong possibilities towards structural material savings.

Active adaptability is presented for static and dynamic load cases. The static Load Path Management shows strong opportunities towards a more homogenous distribution of internal forces reducing the often governing peak loading in all elements. Depending on the goal of the activation, also the deformations can be controlled. The reduction of the used structural material by using passive and static active adaptability can result in structures more vulnerable to dynamic excitation. By not only using the actuators in a static way but also in a dynamic way to control the dynamic behaviour of the structure, the structural optimization can be highly efficient and further extended towards all boundaries set for strength, deformation and acceleration.

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