Adaptive and Lightweight

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Summary

In recent years adaptive systems, smart structures and “intelligent” building envelopes achieved great attention and these developments promise new prospects for architectural and civil engineering projects.

This paper will cover the latest research activities in the field of adaptivity as well as some of the results in this area. Key definitions of the basic terms and components of adaptive ensembles will be provided. Afterwards the design and optimization procedure of adaptive truss and surface structures will be presented.

The concept of load path management has been developed, in order to reduce the weight of the structure while maintaining stress and deformation criteria. The adaptation to different load cases is achieved using sensors, actuators and a control unit. Furthermore, surface structures can also be optimized by activating themselves or by using adaptive fibers, plasters or activated supports. Thus a reduction of stress concentrations under various load cases can be achieved, which exceeds the efficiency factor of passive measures of strengthening abundantly clear.

All these different aspects take into account the energy input for the activation of the system in comparison to the efficiency of the achieved adaptive ensemble. In contrast to Sullivan’s statement “form follows function”, one can restate it into “form follows energy”.

1 Introduction

Lightweight systems are necessary for wide span, high rise or mobile structures in order to exploit the potential impact in weight reduction, economic aspects and superior aesthetics. The design of new efficient lightweight structures and the enhancement of existing design concepts has been one of the most important research activities at the Institute of Lightweight Structures and Conceptual Design (ILEK) at the University of Stuttgart. The field of investigation on ‘adaptive systems’ enables a new understanding of lightweight structures and offers a breakthrough in a new dimension of minimalism.
Adaptive structures or systems as the authors understand them are load carrying systems which are able to react to variable external influences [Sobek and Teuffel 2001].
Three different states can be distinguished in such an adaptive system [Weilandt, Lemaitre, Sobek 2006]. The passive state is defined as the state where the system is without manipulation and

burdened only with external loads. The activated state as the condition where only the actuators are active and the third state is the adaptive state which is defined as the superposition of the passive and the activated state.

Passive + activated = adaptive

The system usually consists of four main components [Yao 1972]. The structural system which itself is equipped with sensors for monitoring on one side the external loads acting on the system and on the other side, the response of the system due to adaptive manipulation. The response can either be the deformation in defined points or the stress level in selected members depending on the design goal. The sensors transmit their informations to a controller unit i.e. a computer which calculates the necessary response in order to fulfill the requirements defined by the designer. The controller transmits this information to the actuators integrated into the structural system [Sobek, Haase, Teuffel 2000]. Actuators can be categorized in two main groups: the induced strain actuators and the stiffness actuators [Weilandt, Lemaitre, Sobek 2006]. Induced strain actuators are elements with varying lenghts and are therefore able to introduce a controlled stress scenario in the system which is superposed with the stress states from the external loads. The same effect can be achieved by changeable supports as part of the the induced strain actuators group. The second group, the so called stiffness actuators can be based on materials which can change their properties and therefore their stiffness resulting in a redistribution of the load paths within the structure which leads to a semi-active system [Teuffel 2004].

To demonstrate the application to a common structural engineering problem the ‘Stuttgarter Träger’ was built in 2001 [Sobek, Teuffel, Landauer 2002]. The ‘Stuttgarter Träger’ is a model of a railroad bridge under a single train loading. The structural system consists of a single span beam fixed on both ends on V-shaped supports. The distance between the supports is 1.60m and the depth of the beam is 3mm which results in a depth to span ratio of ~500. The system is designed in a way that at any given time the vertical displacement at the location of the train is zero. This is achived by applying an induced strain actuator, which in this case is located in one of the supports and the horizontal movement of this support is acitivated in such a way that it introduces a vertical deformation as the exact opposite of the vertical deformation resulting from the external loading. The result is a system whose weight is reduced drastically in comparison to a similar passive system. Additionally the vertical displacement in the critical loaded point is zero which is equivalent to an infinite rigidity, a state that is never achiveable in a passive reality.

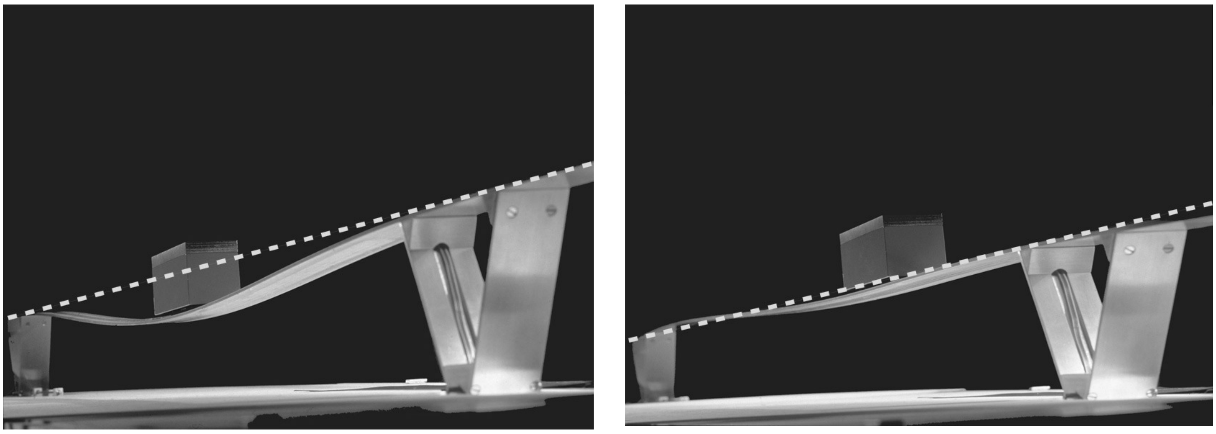

Figure 1: ‘ Stuttgarter Träger’: comparison between passive and adaptive state

The following two paragraphs will present two different approaches for the design and optimization of adaptive systems.

2 Load path management (LPM)

Already Louis Sullivan stated in 1896 "Form follows functions", but what happens, if the function varies over time [Teuffel 2006] ? This novel approach leads to two new considerations, on the one hand side one can think of re-configurable systems, or one can incorporate the intensity of various load cases into the design process, which leads to the aspect "form follows energy" [Teuffel 2004].
The aim of the Load path management (LPM) concept is to minimise the weight of the structures while maintaining stress and deformation criteria [Teuffel 2004]. The adaptation to different load conditions can be realised using elongation and stiffness actuators. In this context, a concept is developed, where the potential of the adaptation of the structures can be considered from the beginning, i.e. the active elements are not only additional elements of a passive structure, but form an integral component of the overall system. This proceeding is called load path management and is defined as follows:
"Load path management considers the controlled and temporally variable adaptation of the characteristics or properties of a structural system and a manipulation of the structural response in real time."
The goal of this manipulation is the minimization of the structural weight by means of cross section and form optimisation and the employment of adaptive elements, with consideration of stress and deformation criteria.
Apart from the necessary limitation of permissible stresses also deformation criteria can be treated in the context of this concept. Thus it is possible to limit the deformations of individual degrees of freedom to "zero" - this corresponds to a virtual infinite rigidity, which actually contradicts all known laws of physics. This points out that by the introduction of adaptation not only a quantitative improvement can be achieved, but qualitative new possibilities arise: mass is replaced by energy.
Numerical and experimental examples to show the great potential of adaptive structures are described and discussed in detail in (Teuffel 2004). This relates to stress and deformation control of these structures, considering shape optimisation as well.
The concept will be briefly presented as follows:

Achieving (LPM) essentially consists of 3 steps:
- determination of the optimal force path for different load cases
- determination of the number and location of the necessary sensors and actuators
- adaptation process

The optimal force path for different load cases is determined using mathematical programming: The goal is it to minimise the weight of the structure (taking nodal equilibrium and permissible stresses into account). Contrary to a "conventional" static analysis, geometrical compatibility equations are neglected. Apart from the cross-sectional optimisation, a shape optimisation of the system can be accomplished as well. As a result of ignoring the geometrical compatibility equations constraint forces arise in the real system, which can be compensated by the adaptive elements. After selecting the number and position of the adaptive elements their necessary reaction can be determined. The necessary extension respectively shortening is determined on the basis of the geometrical compatibility equations. The force and deflection adaptation can be achieved in two different ways, either via a direct length variation of the element (e.g. by elongation actuators) or indirectly by an adjustment of the rigidity (e.g. stiffness actuators).

Another important aspect for the design of adaptive structures is the evaluation regarding energy aspects and therefore the study of realistic load assumptions. Various studies show, that in most cases only 20-30% of the maximum loads are frequently applied. This leads to the conclusion that it is reasonable to develop adaptive system, which are not overdesigned for most of their life time.

3 Adaptive Planar Structures

Within the research activities, adaptive planar structures have been subject of investigation as well. As an example of these structures a shell with active supports will be presented in this paragraph. Planar structures are characterized by a high bearing capacity in case of evenly distributed stresses. But in case of interferences the bearing capacity will be reduced significantly, therefore the aim of adaptivity in planar structures is the reduction of stress concentrations.

As shown by Sobek in 1987 [Sobek 1987] the distribution of stresses in concrete shells constructed on formworks is not uniform, as it could be expected at first. The strains of the shells which appear due to the dead loads when the formwork is discharged could not be compensated in the border areas by adjusting to the form of the formwork. Hence in these border areas, the stress distribution is already disturbed under dead loads and high tensile stresses have to be dealt with. By introducing an adaptive approach to these shells, the occurring tensile stresses under dead loads can be reduced to zero with simultaneous limitation of the occurring compressive stresses.

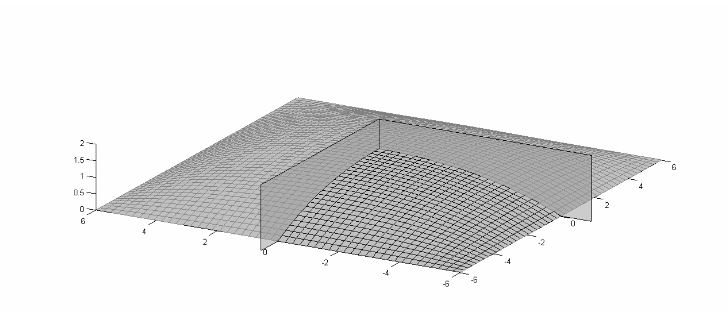

Figure2: finite element model of the investigated shell on pneumatic formwork

The necessary adaptive displacement of the induced strain actuators, in this case active supports can be determined by an optimization procedure, which was developed within the research activities at the ILEK in the past few years [Weilandt 2006]. To avoid discontinuities this optimization procedure approachs the distribution of the active relocation of the supports by methods of computer aided geometric design. The investigations have shown that already with the simplest geometric form - a straight line - the tensile stresses under dead loads can be reduced to zero. Using more sophisticated geometric forms such as B-Splines leads to an improved approach to the optimum distribution of the support relocation. In this case not only the tensile stresses can be reduced to zero but the maximum compressive strength in the shell is minimized as well.

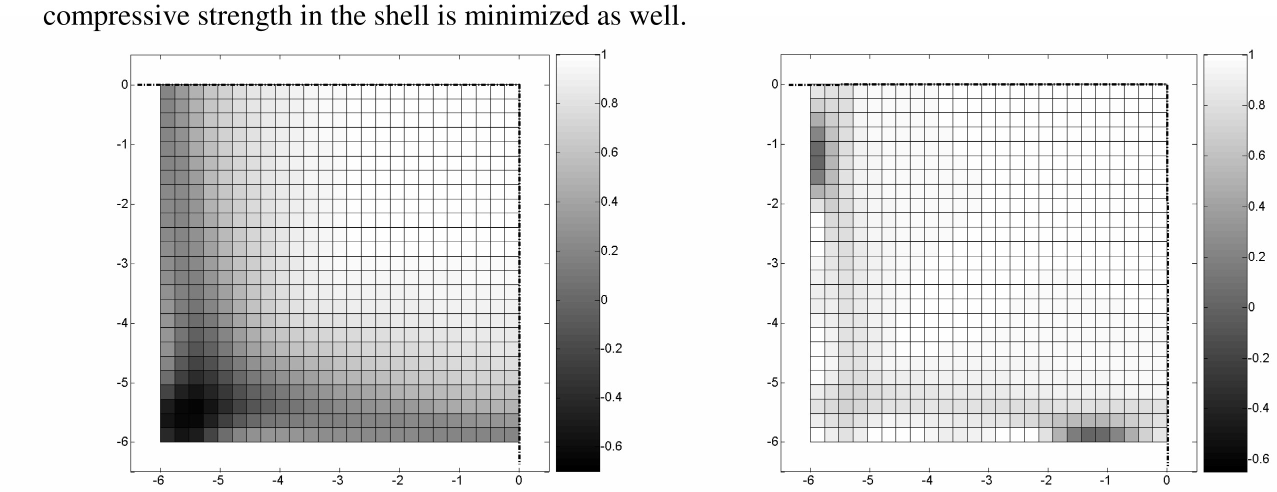

Figure 3: Principal tensile stresses related to the compressive stress in the center of the shell (σ_I/σ_∞) in the passive (left) and adaptive (right) state For one quarter of the shell as shown in figure 2.

The use of adaptivity leads to a significant higher possible loading of shells or planar structures by reducing interferences in stress distribution. Therefore making these already lightweight structures lighter.

4 Conclusions

As shown in this paper, the use of adaptivity opens a new area in the design of lightweight structures. It is described, that it is possible to design efficient structures due to deflections and stress criterias by manipulating the load paths. The target function contains the minimum weight under consideration of stress and deformation criteria's as well as the controllability under various load cases using actuators. Beyond these presented approaches, the next step is to consider topology optimization of adaptive truss structures. Safety issues and reliability considerations have to follow to convert these promising systems into practical engineering solutions. These questions will be a great challenge for interdisciplinary research activities in the next years.

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