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ACTUATION CONCEPTS FOR STRUCTURAL CONCRETE ELEMENTS UNDER BENDING STRESS

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Abstract. The population growth is a big challenge for the construction sector. Because of the limitation of resources, new radical approaches must be investigated. Werner Sobek states that only new methods of construction can overcome this challenge [1]. Especially concrete structures need to be reconsidered because concrete is the most common construction material and in some regions of the world there is already a scarcity of sand, the main aggregate of concrete. One possible method of construction dealing with this challenge is the implementation of adaptive structures. Adaptive structures are able to react to external loads. Therefore, actuators manipulate the structure to reduce stresses and deformations so that less material is needed. This paper will depict different actuation concepts to minimize the deflection of beams and slabs in order to significantly decrease the construction material used. In addition, the suitability of different actuator types for the use in this field of application will be discussed.

1 INTRODUCTION

The Collaborative Research Centre SFB 1244 “Adaptive Skins and Structures for the Built Environment of Tomorrow” deals with the challenge of applying the concept of adaptivity to building structures and façades. This concept means the ability to react to external loads by implementing sensors, actuators and control units into the structure. Its implementation in the built environment was first described in 2000 by Werner Sobek [2]. The components, their tasks as well as their interaction are shown in Figure 1.

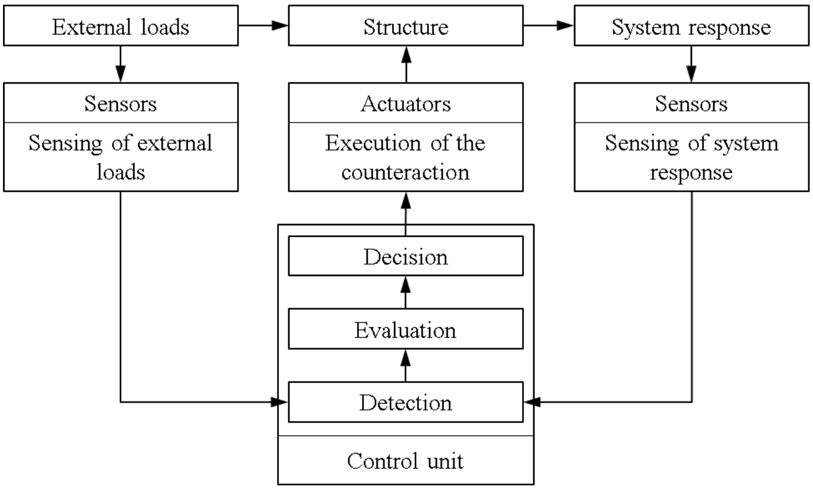

Figure 1: Components of adaptive structures and their interaction based on [5]

Whereas common sensors and control units can be used for adaptive structures, the requirements for actuators are more specific. Some of the following actuation concepts cannot be realized with state-of-the-art actuators. Therefore, new actuators have to be developed and tested.

In the context of adaptive structures the research project “Integrated Fluidic Actuators” investigates the resource saving potential of adaptive beams and slabs. The objective is to, develop new actuators and to investigate how these actuators can be integrated in concrete structures. The importance of this research field becomes clear when taking a closer look at the built environment. Nearly every residential and office building uses beams and slabs, with the latter usually accounting for nearly 50 % of the overall weight of the structure [3]. It is remarkable that the design load nearly never occurs during the lifetime of the construction, which leaves a high amount of material unused for most of the time. Therefore, the basic idea of adaptivity in the built environment is to use sensors to identify whether the design load takes effect and to have simultaneously a control unit cause a reaction by activating actuators.

2 LOADS

Since adaptive structures react to external forces, it has to be defined in advance which loads will be carried by actuators and which loads will be carried by the passive structure itself. The self-weight of the structure, additional dead loads and quasi-permanent loads should be carried by the structure without the need of actuators since they are temporally constant. Variable loads, such as payloads, wind loads, snow loads and earthquake loads are not constant over the lifetime of the structure and should be carried by the actuators.

Generally, contrary to mechanical engineering, in structural engineering one cannot predict the real loads acting on a structure; therefore, a highly conservative estimate is the basis of the structural design.

The probability of occurrence, loading duration, intensity of load and distribution of load increase varies for different loads. The probability of occurrence directly determines the frequency of actuation. The more often a load carried by the actuators will occur the more often the actuators need to react. The influence of external loads on actuators is shown in Table 1.

Some variable loads occur only very rarely during the lifetime of a structure. The annual exceedance probability of wind and snow loads is 2 %, which leads to a statistical probability of occurrence once every 50 years. For earthquakes the probability is even smaller. An annual exceedance probability of 0.02 % leads to a statistical probability of occurrence once every 475 years. [4]

A prediction of the probability of occurrence of the payload is hardly possible since they vary greatly depending on the type of building, usage and user behavior. The payload is divided into a quasi-permanent part, e.g. the furniture, and a variable part, which accounts for people, cars, etc.

However, there are some examples where the payloads compared to the lifetime of the structure only rarely reach their maximum. Stands of sports arenas for example are rarely used, usually only during sport events. A standard football stadium for example will be used once every two weeks. But even during sport events it is not guaranteed that the maximum payload will be reached.

Moreover the duration of loading varies for the different types of loads. On the one hand the self-weight and the quasi-permanent payloads are constant and on the other hand the variable payloads appear only for a short time. Snow loads are seasonal loads in Europe and within the season they appear only for a period of a few days until several weeks. Wind loads appear only for several minutes or seconds but during the whole year. The duration of exposure for earthquakes is even shorter, which is in the range of seconds. Similar to the probability of occurrence, the change over time of the appearing payloads is hard to predict (see Figure 2). Coming to the already stated example, in sports arenas the sequence of loading is only a few hours and usually the load slowly reaches its maximum.

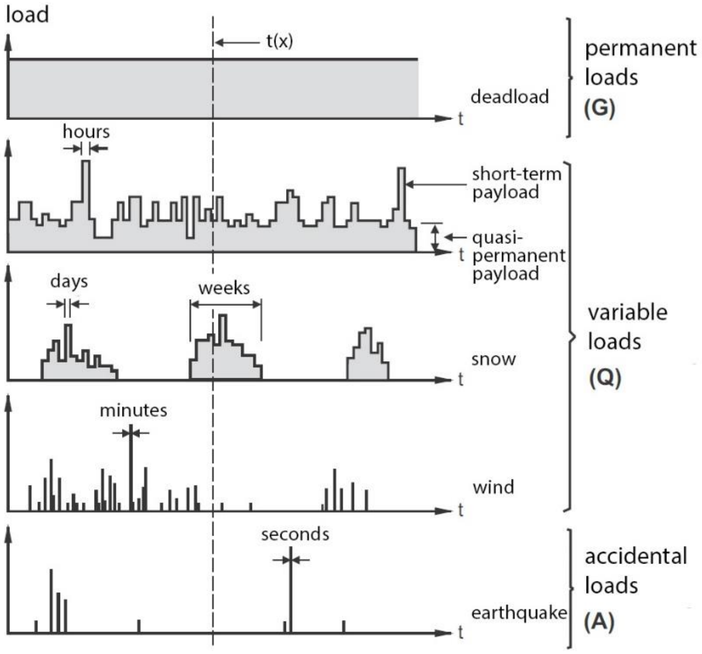

Figure 2: Change over time of loads based on [4]

The increase of the load up to its maximum is also important for the design and dimensioning of the actuators. On the one hand snow loads are characterized by their slow but linear increase, ordinarily increasing within several minutes or hours. On the other hand the maximum loads resulting from wind or earthquakes can be reached very fast.

Most of the loads that are acting on a structure are roughly simplified. For example payloads on slabs are idealized by uniformly distributed loads although this will be rarely the case.

The distribution of the load is particularly important when designing an actuation concept for downstand beams or slabs, since they are subjected to payloads. Because it is hard to predict, the real load-distribution must be captured by a sufficient number of sensors.

Table 1: Influence of external loads on actuators

Characteristic of the variable load	Importance for the design of the actuators
Probability of occurence	Frequency of actuation, service life expectancy of the actuator
Size	Needed positioning force and positioning distance
Duration	Duration of actuation, therefore energy consumption
Velocity of occurrence	Positioning velocity of actuators

3 ACTUATION CONCEPTS

Beams and slabs have a non-constant stress curve in the cross section. Single-span beams, for example, have a compression zone above and a tension zone below the neutral axis. Actuators should counteract these stresses caused by external loads. In general, this can be achieved by one or more actuators which have the point of load application inside (internal) or outside (external) the structure. An external actuation can influence the whole structural element at once. Internal actuators can either manipulate certain sections of a structure or the whole element.

Actuators and their working principle will be presented in chapter 4. In very simplified terms, it can be said that actuators cause either a translation or a rotation. Some combinations can be derived from these general differentiations (Fig. 3).

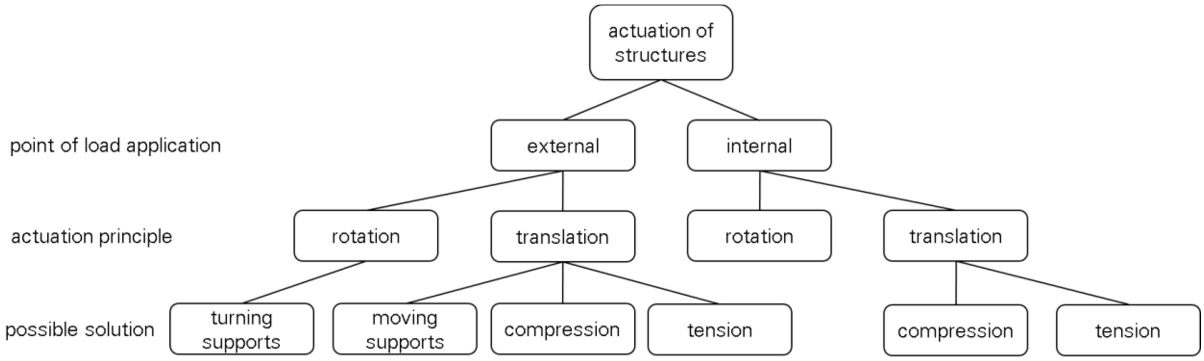

Figure 3: Basic considerations on adaptive structures (excerpt)

The advantages and disadvantages of some of those actuation concepts will be discussed in the following subsections.

3.1 External actuation

The external actuation takes place over supports, surfaces and edges. This can be done by linear and rotational motions. Possible solutions to counteract deflections caused by external loads are shown in Figure 4.

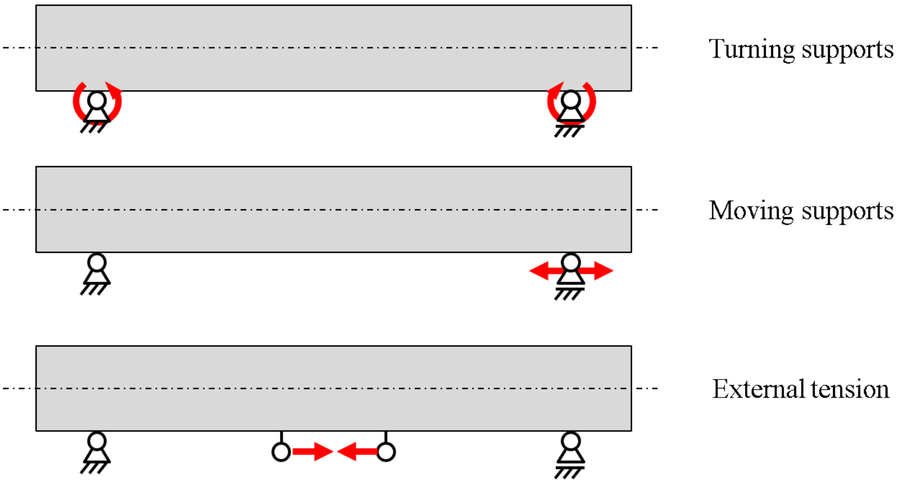

Figure 4: Concepts for external actuation

The general advantage of external actuation is the accessibility of the actuators, which allows easy maintenance, repair or exchange in case of failure. For this application, common actuators can be used. On the other hand, if the actuators are visible the acceptance for this kind of actuation is questionable due to aesthetic reasons.

Actuating supports (turning and moving supports in Figure 4) allow to influence the whole structure at the same time. This also means that it is impossible to manipulate one point without affecting the rest of the structure. In addition, supports are areas with one of the highest stresses. Inducing forces here results in further loads and can lead to a very complex construction for the load introduction. This has to be considered for the dimensioning as well as for the design.

Examples for an external actuation via supports are the Stuttgart Smart Shell (moving supports) [6] and the Stuttgarter Träger (turning supports) [2].

Inducing forces over surfaces and edges in certain areas only (for example tension in Figure 4) allows a more specific manipulation of the structure. Especially for bended structures, less energy is needed due to the great lever between force transmission points.

3.2 Internal actuation

Internal actuation has one or more actuators integrated in the load bearing section. Figure 5 shows three possible solutions with one actuator in the compression zone, one in the tension zone and one example with both.

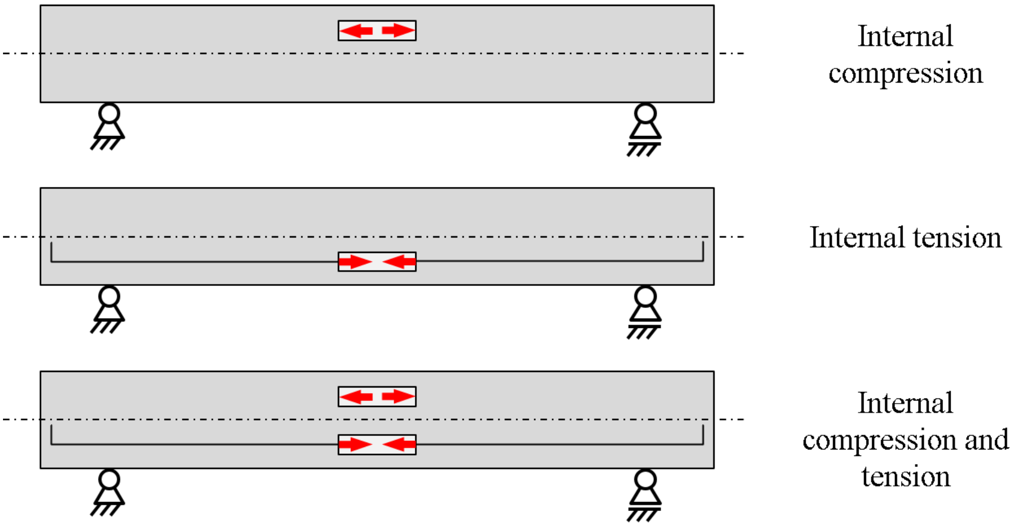

Figure 5: Concepts for internal actuation

The upper part of figure 5 shows an actuator that generates a compression force. The actuator is embedded in the compression zone of a beam and counteracts the deformation caused by external forces. Depending on the external loads, there could be one or more actuators along the component axis. The advantage of an internal actuation is the possibility of a targeted local manipulation of the deformations and stresses of the supporting structure; especially when there are several actuators. The use of several actuators allows load-appropriate actuation and thus selective influencing of the structure. Analogously, the tensile force introduced in the middle part of figure 5 also counteracts the load. The actuator can be connected to a frictionless reinforcement as a load introduction. The reduction of the component deflection can also be achieved by using this method but is more complex. This concept looks similar to a state of the art (passive) prestressing, but allows to react specifically to a high variety of load cases. A limitation of the prestressing, when only the dead load takes effect, is no longer necessary. A combination of the compression zones and tension zone actuation can be seen in the lower part of figure 5. The main advantage of a combination is its ability to better reduce vibrations.

For components manufactured in a precast factory, the actuators can be positioned precisely during the manufacturing process without disturbing environmental influences. The external shape of the beams and slabs is not affected, contrary to external actuation. Integration protects the actuators from vandalism and other external influences.

One challenge of internal actuation is the wear of the actuators; since maintenance, repair or replacement are difficult, the lifetime of the actuators must correspond to that of the encapsulating structure.

So far, the approach of internal actuation for the targeted manipulation of deformations, stresses and vibrations has not yet been implemented and is the subject of further research. New actuators are needed and have to be developed. Due to the variety, different actuator working principles as well as their suitability are discussed in the next section.

4 ACTUATORS

At least one actuator is necessary to manipulate deformations, stresses and vibrations of the structural element regardless of the implemented actuation concept. The main task of the actuator is to generate required forces and strokes. As shown above, the actuator is controlled by a control unit and can be considered as the counterpart to the sensor system [7]. There is a great variety of actuators for very different applications. But using actuators in adaptive structures is a new field of application. Due to the novelty of this field, the general actuator working principles as well as their advantages and disadvantages will be introduced in the next section.

4.1 Actuator working principles

In general, an actuator has to convert a non-mechanical auxiliary energy to a mechanical energy by using a low energy control signal. The classification of actuators can be done by the type of the resulting movement: linear or rotational actuators. A more differentiated classification takes place according to the auxiliary energy used [8]. Examples for linear and rotational actuators can be found for nearly each category. A classification of selected actuators by the auxiliary energy used is given in Table 3. The individual working principles are also shown.

Table 3: Classification of selected actuators and their working principles based on [8]

Auxiliary energy	Actuator type	Working principle	Examples
Electrical energy	Electromagnetic	Force effect on object in a magnetic field	Lifting magnet, rotary and oscillating magnet
	Electrodynamic	Lorentz force on electrical conductors in a magnetic field	DC or AC motor, plunger coil, linear motor
	Piezoelectric	Change of piezo crystal dimensions by electrical voltage	Piezo motor, inject printer, fuel injection valve
	Magnetostrictive	Ferromagnetic volume change in a magnetic field	Setting unit
	Magnetorheological	Change in viscosity in an electrical/magnetical field	Clutch, shock absorber, pump drive

Auxiliary energy	**Actuator type**	**Working principle**	**Examples**
Flow energy (fluidic)	Pneumatic	Fluidic pressure difference, displacement flow	Linear propulsion motor, diaphragm actuator
	Hydraulic	Fluidic pressure difference, displacement flow	Linear and rotational motors
Thermal energy	Thermobimetal	Differential thermal expansion of a material composite	Thermal switch
	Thermomechanical actuators (shape memory alloy)	Microstructure transformation	Positioning elements
	Expansion material	Volume change	Setting unit, thermostat
Chemical energy	Electrochemical	Pressure difference by an electrochemical reaction	Gas dosing unit, expansion setting unit

4.2 Actuators for adaptive structures

The requirements for the actuators implemented in adaptive structures are versatile depending on the actuation concept. Considering the variety of different actuator types (type of movement, auxiliary energy used), the most fitting actuator has to be chosen. The universally valid advantages and disadvantages of the different actuator types are shown in Table 4.

Table 4: Advantages and disadvantages of different actuator types based on [7][9],[10]

Type	Advantages	Disadvantages
Electromagnetic	• simple mechanical construction • no transmission element • high dynamics with short strokes • good integration possibilities	• low power density • short strokes • non-linear behavior • hysteresis characteristic
Electrodynamic	• good control characteristics • high dynamics • versatile drive concepts • high total efficiency	• limited power density • energy demand for stationary tasks • limited thermal operating range • high proportion of moving parts
Piezoelectric	• high forces • high material rigidity • high power density • short response time • hardly no energy demand for stationary tasks • versatile ceramics usable • practically non-wearing	• hardly lifetime assessment • small strokes • temperature and ageing dependent characteristic • hysteresis characteristic • piezoelectric effect can be lost by high temperature, high field strength or mechanical shock • heating through dynamic tasks

Type	Advantages	Disadvantages
Magnetostrictive	• high forces • high power density • high energy efficiency • very short response time • high dynamics • high positioning accuracy • high thermal range of application • practically non-wearing	• small strokes • low availability and expensive materials • energy demand for stationary tasks • non-linear and temperature dependent characteristic
Magnetorheological	• easily adjustable viscosity • short response time	• sensitive to contaminants • temperature dependent characteristic • critical sedimentation • low material availability • no direct forces generation
Pneumatic	• high range of application • high power density • high reliability and safety • no energy demand for stationary tasks • robust design	• auxiliary energy supply needed • low positioning accuracy and difficult control characteristics due to the compressibility of the fluid • air-treatment system needed
Hydraulic	• high range of application • high dynamics • high power density • no energy demand for stationary tasks • robust design	• auxiliary energy supply needed • complex system structure • oil purification sometimes needed
Thermobimetal	• good availability • cheap materials • easily configurable • linear temperature-stroke behavior • application up to 650 °C • high mechanical stability	• small forces • only one change of shape (bended shapes) • low power density
Thermomechanical actuators (shape memory alloy)	• high power density • different change of shape (lengthening, bending, torsion) • abruptly change of shape	• expansive materials • low energy efficiency • limited thermal operating range • material degradation and fatigue
Expansion material	• high forces	• low response time • limited thermal operating range
Electrochemical	• low energy consumption • no energy demand for stationary tasks • quiet operation	• low response time • limited stroke • leakage • unknown long-term stability

Most important for choosing the actuator type to be used in adaptive structures is the consideration of the mechanical requirements like forces and strokes or rather torque and rotation angle.

Regardless of the actuation concept, the actuator has to compensate static loads as well as dynamic excitations. As shown in section 3, static or quasi-static loads often occur for long periods of time with an almost constant and average value (for example snow load or payload). The energy demand of the actuator can be reduced if there is no need for quasi-static tasks. Considering dynamic loads, vibrations must be compensated. For example, pedestrians generate excitations between 1.6 and 2.4 Hz [11]. The actuator response time must be correspondingly short. High forces must be generated emerging from the dead weight of the structure and the reaction forces of the moving mass. Used for an external actuation, the stroke must be high enough to compensate the movement of the surrounding structure as well as the elasticity of the structural elements. An internal (integrated) actuator, on the other hand, manipulates primarily the structural element itself. Therefore, only the deformation of the element must be considered. The stroke needed for an external actuation is higher than for an internal actuation. Especially in the latter case, a reliable and preferably maintenance-free actuator type should be preferred. Possibilities for maintenance or reparation are not given or require a great effort.

As shown in Figure 3, there are applications that need rotational or linear drive systems. It is possible to convert rotational into linear motion and vice versa by using transmission elements, but a direct force and motion generation is generally preferable. The advantages are a less complex system with higher total energy efficiency because of less friction contacts. In addition, each part is a potential failing element. If there are fewer parts, the reliability of the overall system increases [12].

Due to the variety, a promising working principle for actuators can be found for rotational and linear motion that also meets the requirements of the construction sector. It should be noted that there are mainly linear applications except for turning supports. Rotational applications in adaptive structures are special cases.

For linear motion hydraulic actuators seem to be the most suitable for adaptive beams and slabs (Table 4). Actuators for rotational applications should be considered separately. Whereas an external actuation can be realized with existing actuators, manipulating structures with integrated actuators is a new field of application. Suitable actuators do not exist. Therefore, structure integrated actuators should be the subject of further research and development activities.

12 CONCLUSIONS

Adaptive structures offer an approach for dealing with the challenge of material and energy optimized structures. In this paper, different actuation concepts as well as their advantages and disadvantages are discussed. While are already implemented external actuation concepts, the use of actuators for an internal actuation of structures is a new and promising approach. Internal actuation concepts allow a more direct and efficient way to manipulate a structural element. Currently, however, there are no actuators that can be integrated in the load-bearing section of the structure. Therefore, different actuator working principles are discussed as well as their advantages and disadvantages. Considering the requirements for integrated actuators, the hydraulic working principle seems to be the most appropriate for this new field of application. Actuators for this usage do not exist. Therefore adaptive structures with integrated hydraulic actuators are the object of further studies.

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