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FULL PAPER

Investigation of a large-scale adaptive concrete beam with integrated fluidic actuators

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Abstract

As the world population keeps growing, so does the demand for new construction. Considering material resources are limited, it will be unfeasible to meet such demand employing conventional construction methods. A new resource-saving approach is provided by adaptive structures. Using sensors, actuators and control units, structures are enabled to adapt to loads, for example, to compensate for deformations. Since deformations are dominant in the design of bending-stressed load-bearing structures, adaptivity enables such structures to be realized using less material and achieving the same load-bearing capacity in comparison to conventional designs. This article presents a concrete beam of typical building dimensions that compensates deflections by means of integrated fluidic actuators. These actuators offer the possibility of reacting optimally to general loading. The investigation is carried out on an approximately 4-m-long beam with integrated hydraulic actuators. To ensure the overall functionality, accurate dimensioning of the beam as well as the hydraulic system is mandatory. Analytical design of the beam and actuation system are carried out for predimensioning. Experimental testing validates the function and demonstrates that the adaptive beam works as predicted. A fully compensation in deflection is possible. Therefore, a significant increase in load-bearing capacity is possible with the same material input compared to conventional beams.

KEYWORDS
adaptive structures, beams, fluidic actuators, integrated actuators, lightweight construction

1 | INTRODUCTION

The creation of a built environment involves enormous consumption of energy and material resources. For example, the building industry is responsible for approximately 38% of global greenhouse gas emissions.[1] The most widely used building material worldwide is reinforced concrete.[2] This extensive use has a detrimental effect on the environment. Cement, one of the main components of concrete, is responsible for up to 10% of global anthropogenic CO_2 emissions[3] and 6% of anthropogenic greenhouse gases.[4] However, not only emissions but also material availability is a problem to be considered. Sand, another main component of concrete, is already scarce today.[5]

In addition, today's conventional methods to build load-bearing structures are not resource efficient. For example, the design of structural elements under bending is typically stiffness-governed (instead of strength-governed) and the reduction of deformations is critical to avoid damage to nonstructural elements.[6] Especially when it comes to beams

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Timon Burghardt and Christian Kelleter contributed equally to this study and should be considered co-first authors.

and slabs that are mainly subjected to bending, material utilization is not efficient because the area in the proximity of the neutral fiber, which separates the tension and compression zones, is almost unloaded.[7] Furthermore, the design loads rarely (often never) occur during the life of the structure. For example, design loads for wind and snow occur with a statistical probability of once in 50 years.[8] This means that the majority of the material is rarely in a nearly fully stressed state. Conventional structures are therefore oversized for most of the occurring load cases.

Adaptivity represent a resource-saving and lower-emission approach. Adaptive structures are able to react to external loads in such a way that deformations, stress peaks, and vibrations are reduced. For this purpose, sensors detect the current state of a structure and a control system calculates the deviation from the desired state. By applying appropriate actuation forces, the structure is influenced in such a way that it assumes the desired state.

Previous investigations on adaptive concrete beams that reacts to bending loads by means of integrated actuators have only been carried out on small-scale prototypes in laboratory tests.[9] The hydraulic actuators, which are also referred to as "fluidic" actuators in this work cause a moment that opposes to that applied by the external single or line load. This work demonstrates that this concept can be transferred to real-scale concrete beams. For this purpose, an approximately 4-m long-beam equipped with hydraulic actuators are investigated. Sizing of the beam and the analytical calculation of the required hydraulic pressure is presented. Experimental validation is carried out on a prototype of the adaptive beam through a four-point bending test.

2 | STATE OF RESEARCH

Research on adaptive structures started in the early 1970s[10] with the aim of manipulate stresses, deformations, and vibrations. According to Housner et al.[11] the adaptive bending beam presented in this article can be classified as a system that enables active influencing of the load-bearing behavior. Using an energy input, actuators introduce forces into the structure in such a way that the load transfer and/or the vibration behavior is manipulated. Within the Collaborative Research Centre 1244 (CRC 1244) "Adaptive Skins and Structures for the Built Environment of Tomorrow", an interdisciplinary group of researchers at the University of Stuttgart has been working on developing structures and facades that actively change their behavior and/or properties in a controlled and autonomous manner.[12]

Actuation can be external, for example, when it is applied at the supports or generated and transferred directly in the structure (internal actuation). For single structural elements, such as beams, a hydraulic actuator integrated in the body of the beam is an example of internal actuation.[9] For whole structure systems, such as truss structures, an individual bar that is equipped with an actuator is an example of internal actuation.[13] In previous work, hydraulic cylinders have been employed to control the response of a high-rise building structure,[12] and electromechanical actuators have been used to control the response of an adaptive cantilever truss prototype.[14] Examples of external actuation include a model of a truss in which one support is actively rotated to compensate for deformations[15] and the Smart Shell, a wooden shell of which three of the four supports can be moved through hydraulic actuators.[16]

Investigation of beam structures that react to bending loads by means of adjustable prestressing is given in Schnellenbach-Held et al.[17] Hydraulic actuators are employed to tension an external cable system to reduce displacements under vertical loads. In Bleicher[18] a stress ribbon bridge is presented in which pneumatic actuators are installed in the handrail and the actuation force is thus introduced into the structure via the surface. The actuators reduce vibrational motion.

If the actuators are external and placed at the supports, local manipulation or forces and displacement are generally not possible. Instead, internal actuation of structural elements allows the local manipulation of specific sections within the structure. For this purpose, parts of the actuator system or the entire actuator system are integrated into the structure. A concept for the manipulation of beams subjected to bending by means of integrated fluidic actuators has been presented in Weidner et al.[19] For this purpose, actuators are employed to introduce a force eccentric to the neutral fiber into the beam. The resulting moment counteracts the bending moment caused by the external load and thus reduces the deflection of the beam. The actuation concept is illustrated in Figure 1.

Thus, this concept transforms the original stiffness problem into a strength problem. As the actuators introduce compressive forces into the beam, a significantly higher portion of the material in the upper section of the beam is subjected to compressive stress in the adaptive state. Ideally, a homogeneous stress band is distributed along the beam and between the actuators. Since the load is transferred via the actuators and these expand during actuation, the compressive stresses in the actuator planes are significantly lower. In the adaptive state, even low tensile stresses can occur. Overall, the pressure zone in the upper section of the beam is more distinct in the adaptive state than in the passive state. In

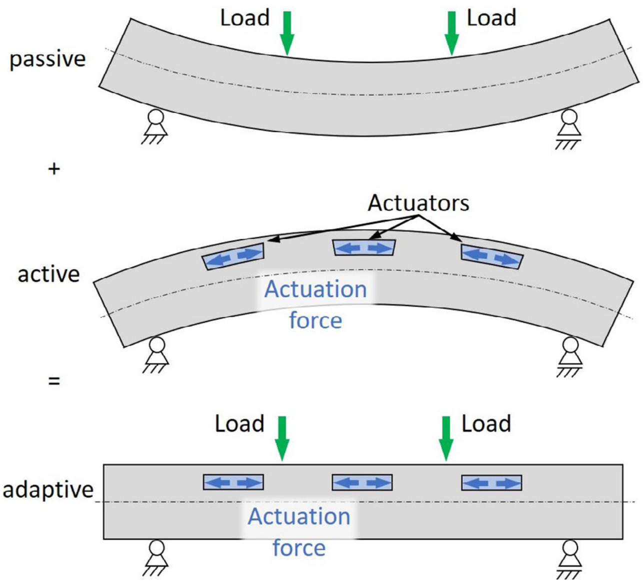

FIGURE 1 Schematic illustration of the actuation concept: Superposition of the passive (top) and active state (middle) to the adaptive state (bottom). *Source*: IKTD

the passive state, the area below the neutral fiber is subjected to tensile stress. In the adaptive state, the tensile stress decreases significantly.[20]

Therefore, a better utilization of the material and a reduction in material consumption can be achieved.[9] An analytical approach for calculating the required hydraulic pressures in the actuators as well as for describing the resulting bending moment curve is presented in Kelleter et al.[21] In Kelleter et al.[9] the actuation concept is evaluated using a reinforced concrete beam with a span of approximately 1 m. A good correlation of the results from a finite element (FE) analysis and experimental laboratory tests on a prototype has been shown. Investigations on beams subjected to bending loads have only been carried out so far on small-scale models in laboratory tests. In this study, the actuation concept is transferred to a beam with realistic dimensions. The actuators adapted for this application are also presented.

3 | DESIGN AND DIMENSIONING

3.1 | Object of investigation

A four-point bending test on the adaptive beam with a total load of one ton (approximately 9.81 kN) is defined as the load case to be investigated. The actuation concept is based on.[9] The dimensions of the reinforced concrete beam are 4.40 m in length (L), 0.15 m in width (W), and 0.30 m in height (H; Figure 2). The length of 4.40 m corresponds to the length of a crossbeam in the experimental high-rise demonstrator of the CRC 1244.[19] Thus, these dimensions correspond to a realistic scale, but the beam is still easily manageable for experimental testing. The weight of the adaptive beam is approximately 490 kg. The maximum external load is twice as high as its own weight. Typical floor slabs in residential or office/administrative buildings usually have a self-weight of more than twice the live load.

Figure 3 shows the opened formwork with inserted reinforcements and actuators. According to Kelleter et al.[9] a distance between the actuators of 100-mm results in order to achieve a homogeneous stress distribution along the beam and to counteract the external bending moment. With a length of 4.40 m, this leads to a total of 43 actuators, which are installed in the compressive zone of the beam. This set of actuators ensures that any area of the beam can be manipulated. Moreover, the chosen arrangement makes it possible to react optimally to each external load case that generates linear bending moment curves by means of an individual control of each actuators. Therefore, in addition to the four-point bending test presented here, investigations of other load cases are also possible with this adaptive beam.

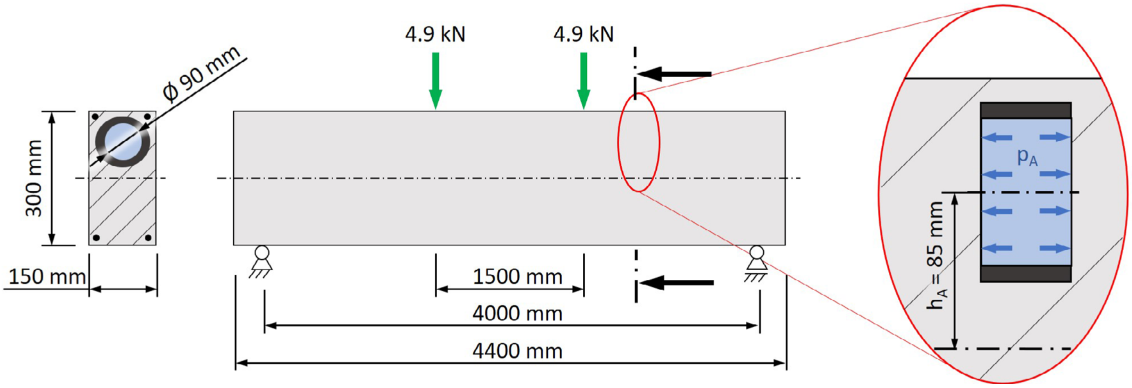

FIGURE 2 Dimensions of the adaptive beam with integrated actuators. *Source*: IKTD/ILEK

FIGURE 3 Open formwork with inserted reinforcement and actuator. *Source*: ILEK

A concrete with an experimentally determined Young's modulus of 25,600 N/mm² is used. B500 S ripped reinforcing steel bars (minimum yield strength of 500 N/mm²) are selected for the longitudinal reinforcements with a diameter of 10 mm that is necessary to take the tensile stress in the passive state. The minimum shear force reinforcement also results from this state. A bar diameter of 6 mm is therefore used. The reinforcement layout has been adapted to fit with the actuator positions. The shear force stirrups have been positioned within the permissible longitudinal spacing in such a way that there is no contact with the actuators and the hooks are located within the compression zone even in the adaptive state. The stirrups hooks are placed to avoid interference with the actuators. Since shear force stirrups are only bent and not welded at the overlapping joints, bending of the stirrup hooks due to tensile stresses is prevented. The hooks are positioned to ensure that the homogeneous stress distribution between the actuators is not disturbed. Therefore, the stirrups always run at the same distance from the outer surfaces of the beam. Compared to other hook types, the space between the actuators is not disturbed by, for example, the ends of the reinforcement bars bent in one side.

3.2 | Fluidic actuator design

The main task of the actuators is to generate the required forces or deformations and to introduce them into the beam. For application, hydraulic actuators seem to be the most suitable.[22] According to Isermann[23] three functional units must be considered in the development of the required actuators. First, the auxiliary energy must be made available to the actuator by the energy supplier. The main task of generating the force (or deformation) is performed by the energy converter. Then, the energy conductor transmits the generated force to the adjacent structure.

Hydraulic valves are used as energy suppliers. These are mounted on an external hydraulic power unit and are thus located outside the beam. This arrangement makes it possible to test the response to different load cases with little technical effort. For this purpose, several actuators are grouped into pressure stages (cf. chapter 3.3), and these groups can be varied depending on the respective load scenario.

The actuator design combines the energy converter and energy conductors. These are integrated into the beam as a lens-shaped pressure chamber (Figure 4). The pressure chambers are made of welded steel sheets (structural steel S235) and connected to the valves by hydraulic pipes. The actuator force is generated via the hydraulic pressure on the walls of the pressure chambers (energy converter) and as the pressure chamber expands. The force is transmitted to the beam structure via the steel cover plates (energy conductor). Therefore, the casing serves both as sealing and force transmission. Due to the orientation and the stiffness of the pressure chamber, the generated force acts only in the longitudinal direction of the beam. In order to minimize energy losses due to self-deformation of the pressure chambers, the cover plates of the actuators are as thin as possible. In radial direction, the wall thickness is increased to prevent unwanted deformation. A bending moment is thus generated via the eccentric position of the actuators in the pressure zone of the beam and is adjusted by controlling the hydraulic pressures.

When designing hydraulic systems, it must be ensured that there is as little air as possible inside the system. Due to the compressibility of air, local pressure fluctuations, and component damage, for example, seals, may occur, requiring air separation.[24] For this reason, another pipe is located at the upper end of the pressure chamber for venting when the chamber is filled with oil. After venting, this pipe is closed with a sealing plug.

The pipes exit the body of the beam in the area of minimum tensile stresses in order to avoid the weakening of these critical zones. Non-critical zones are, on the one hand, the neutral fiber, where feed pipes run, and the section between two actuator chambers, where the vent pipes are positioned.

3.3 | Analytical calculation of the hydraulic pressures

The analytical calculation of the pressures is performed according to Kelleter et al.[9] For the four-point bending test, the counter-moment generated by the actuators can be approximated with sufficient accuracy using a total of six different pressure stages. This reduces the technical effort (number of valves, pipes, sensors, control units, etc.). Therefore, several actuators are connected together to form one pressure stage. As a result, one pressure stage is located in the center of

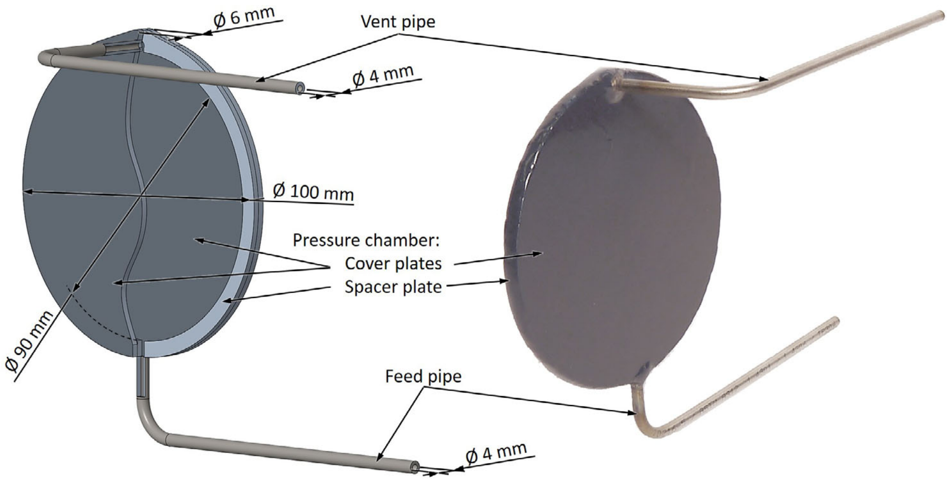

FIGURE 4 Design of the integrated fluidic actuator: Visualization (left) and realization (right). *Source*: IKTD/ILEK

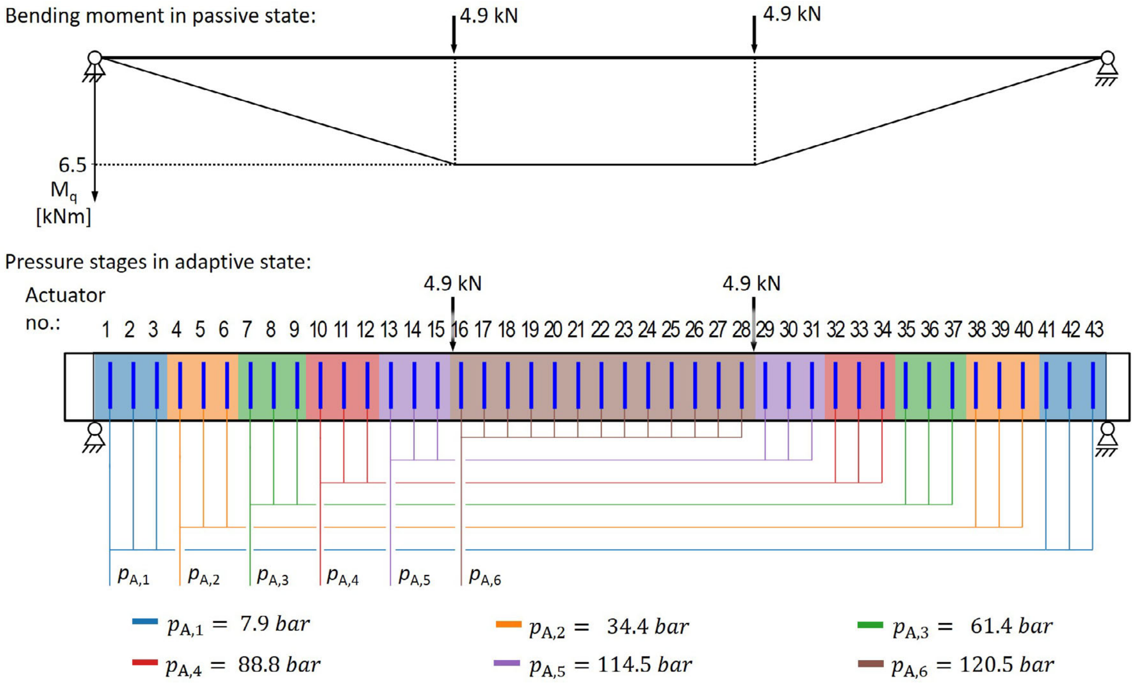

FIGURE 5 Bending moment in passive state (top) and pressure stages in the adaptive state (bottom). *Source*: IKTD/ILEK

the beam with 13 actuators and five pressure stages toward the supports on each side, each consisting of three actuators. The hydraulic pressure $p_{A,i}$ inside an actuator i is determined analytically taking into account the bending moment $M_{q,i}$ at the position of actuator i, the pressure surface $A_{A,i}$, and the distance between the center of the actuator and the axis of gravity of the beam $h_{A,i}$ as follows:

$$p_{A,i} = \frac{M_{q,i}}{A_{A,i} \cdot h_{A,i}}, \tag{1}$$

The diameter of the pressure surface inside the chamber is 90 mm (cf. Figure 4), resulting in a pressure surface A_A of 6361.7 mm^2. The concrete covering above the actuators is approximately 15 mm. Consequently, the eccentricity (from the center of the pressure chamber to the neutral fiber h_A) is 85 mm. The effective distance between the supports is 4.16 m and between the load application points is 1.5 m. With a load of one ton (9.81 kN) applied equally over both load application points, the maximum bending moment is 6.5 kNm (Figure 5, top). The resulting pressure for a load of 9.81 kN reaches a maximum pressure of 120.5 bar. The distribution of the pressure stages over the beam is shown in Figure 5 (bottom).

4 | EXPERIMENTAL EVALUATION

4.1 | Test setup

The test setup is shown in Figure 6. The adaptive beam is supported at the two ends. Both supports allow a sliding movement of the beam in the longitudinal direction. The load is applied using a variable number of steel bars up to a maximum of one ton which are attached to suspension points by springs. This allows the load to be applied gradually as the steel bars are lowered. Lowering and lifting is performed with a manual pallet jack. The spring travel is continuously measured with a laser distance sensor. The load acting on the beam can be determined by comparing it with the previously determined spring characteristic.

The deflection of the beam is measured by means of a second laser distance sensor. Furthermore, strain gauges are attached to the top and bottom of the beam. In addition, each of the six pressure stages (cf. Section 3.3) is equipped with a sensor for measuring the hydraulic pressures. The values measured by the laser distance sensor and the pressure sensors are used to control the beam.

The pressure of the actuators inside the beam is supplied by a hydraulic power unit. Proportional valves are used to adjust the pressures in the different pressure stages. The power unit and the valves are controlled via a programmable logic controller (PLC). Matlab/Simulink is used for programming and controlling the PLC.

A simple cascade control is used for the experiments. In a first step, the required pressure in the actuators is determined according to the measured and the specified target deflection, which is set to zero in this test. Based on the comparison with the measured hydraulic pressures, a further inner cascade controls the opening of the proportional valves accordingly.

4.2 | Experimental procedure

Several tests were carried out with different loads by varying the number of steel bars. Furthermore, tests without actuation were performed in order to determine a reference deflection under self-

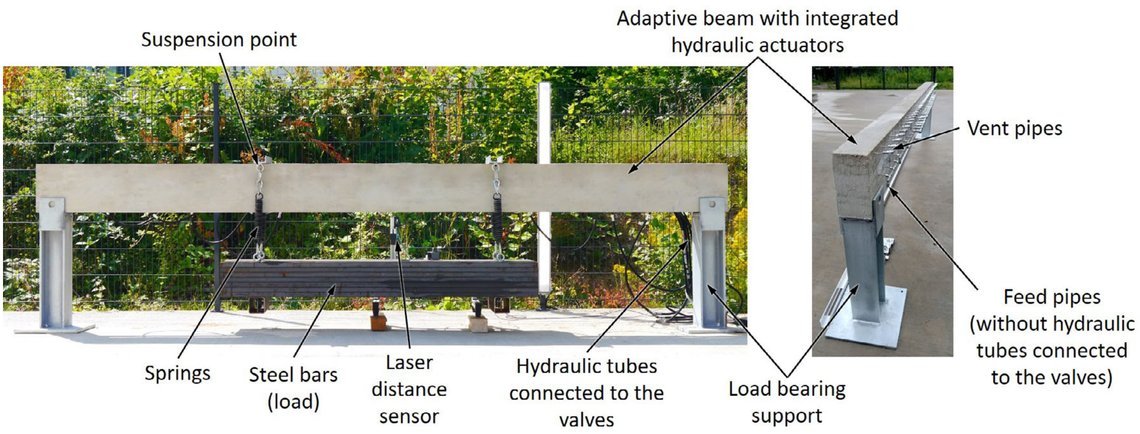

FIGURE 6 Test setup. *Source*: IKTD/ILEK

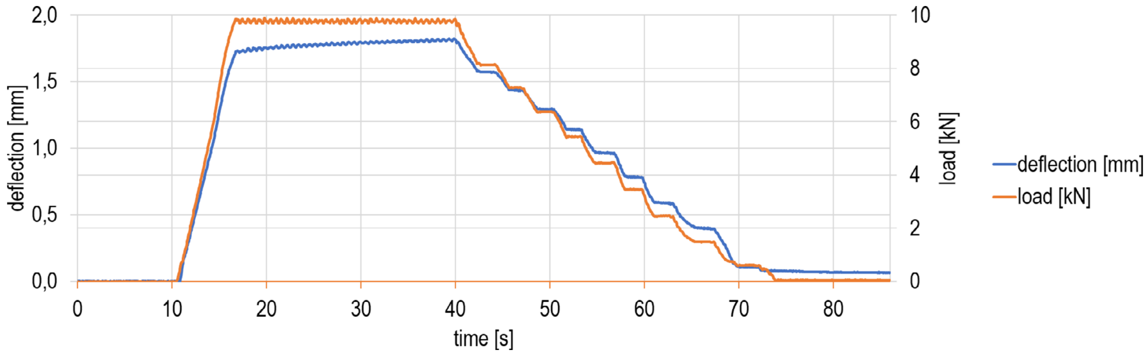

FIGURE 7 Results of a four-point bending test with a passive beam. *Source*: IKTD

weight. The aim of the tests with actuation was to prevent deflection of the beam. Once the control is started, no further intervention of an external operator in the control is necessary. If the steel bars are lowered and thus the load increased, the laser distance sensor detects minimal deviations from the zero position and the proportional valves are automatically controlled appropriately in order to reach the zero position again.

4.3 | Test results

At first, the beam is tested in the passive state, without pressurizing the actuators. The test results are given in Figure 7. In the passive state, the beam deflects by about 1.8 mm under a load of 9.81 kN. In the section with almost constant load between seconds 15 and 40, the deflection continues to increase due to the settling effects of the beam at the supports and load application points. This change in deflection under load is also evident at the end of the test after unloading. The step-like unloading results from the pumping movements when the steel bars are lifted with the pallet jack.

Figure 8 shows the measurement results of a test under the same load of 9.81 kN with active deflection control. From second 5, the steel slabs are lowered and the load on the beam increases. The maximum load is kept until second 8. The beam is unloaded again from second 50 onward.

The hydraulic pressures increase and decrease with the increasing and decreasing external load, respectively. Furthermore, oscillations in the beam deflection and the pressures in the three higher pressure stages can be seen in the stage with constant load. This effect is caused by the employed proportional valves reacting too slowly to the control input, which leads to a vibration of the valves. The resulting oscillations in the hydraulic pressures also cause the beam to oscillate. In the adaptive state, the deflections are contained within 0.2 mm under the maximum load. By optimizing the control, the range of deflection in the adaptive state could be reduced further.

Figure 9 compares the measured hydraulic pressures with the analytically calculated pressures. The range of measured pressure oscillations is also plotted. The measured and calculated pressures match well. A good prediction of the required pressures is therefore possible with the analytical calculation.

A comparison of the test results of the passive and adaptive beam is shown in Figure 10. Here, deflection is plotted vs load. In the passive state, a hysteresis-shaped curve is shown due to the settling effects at the supports and load application points. The potential of the concept of adaptive structures is shown here at maximum load.

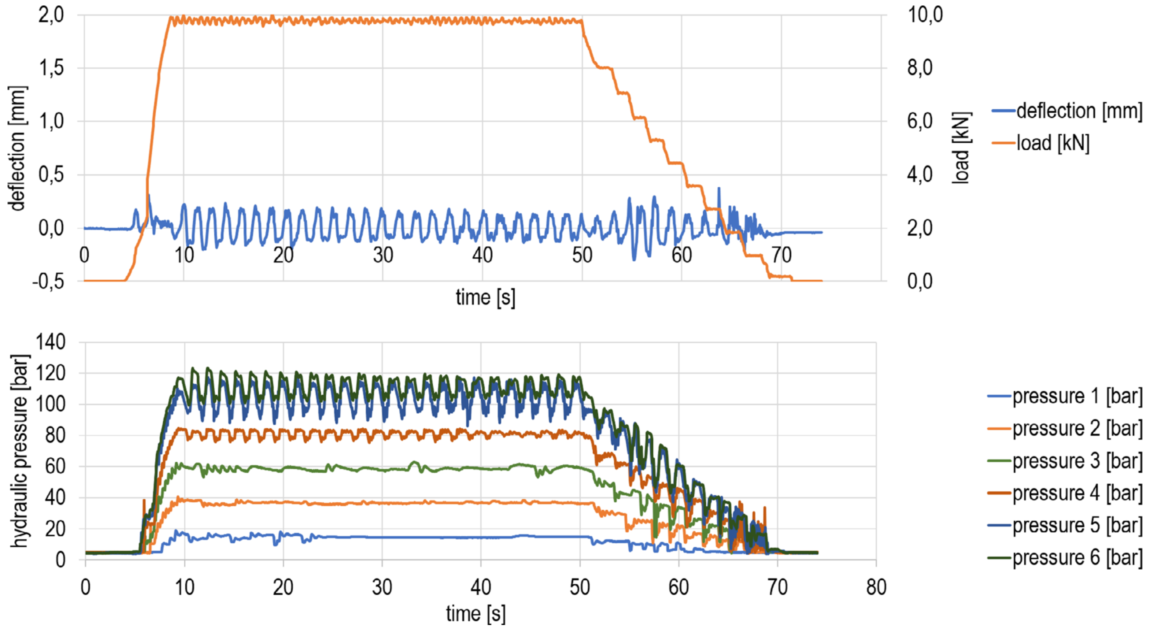

FIGURE 8 Results of a four-point bending test with an adaptive beam. *Source*: IKTD

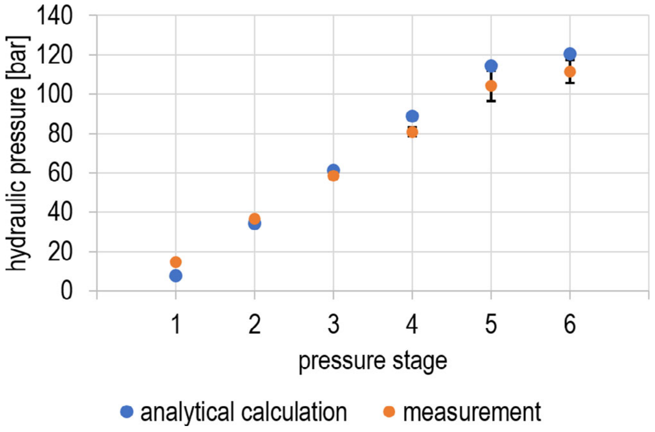

FIGURE 9 Comparison between calculated and measured pressures. *Source*: IKTD

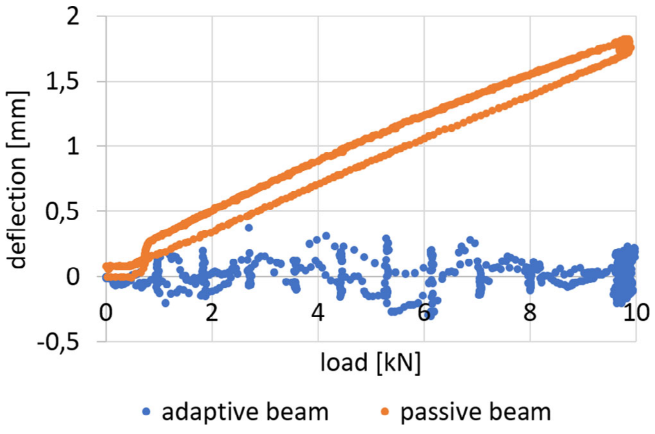

FIGURE 10 Comparison of passive and adaptive beam. *Source*: IKTD

Compared to the passive beam, the deformation was reduced by approximately 90%.

5 | CONCLUSION

A promising approach toward resource-efficient construction is the use of adaptive structures and structural elements. For this purpose, forces are introduced into the structure or the structural element in order to manipulate the load transfer and thus improve the utilization of the material.

In this study, the object of investigation is an approximately 4-m-long adaptive bending beam made of reinforced concrete. Integrated fluidic actuators generate a moment that opposes the bending moment caused by external loads. Through the superposition of the actuation and the bending moment, the deflection of the beam is reduced.

Using an analytical approach, the required hydraulic pressures of the actuators were determined for the defined test scenario. The experimental verification was performed with a four-point bending test. For this purpose, the beam was loaded with the weight of 1 ton, in other words, with a load double its self-weight. The results showed that the deformation can be almost completely compensated. A reduction in deflection of approximately 90% is possible in comparison to the passive beam. Therefore, adaptive beams enable a significant increase in load-bearing capacity with the same material usage in comparison with conventional beams.

The installation of the hydraulic pipes is quite complex and takes up significant space. Future work could look into integrating other components, for example, the valves, into the beam as well as the use of other actuator types that do not require supply pipes. Moving loads and time-varying loads in general should also be tested. This will prove experimentally the possibility of responding to any load case. Ongoing work is investigated the extension to the actuation concept described in this article to two-dimensional structural elements, for example, slabs.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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