International Journal of High-Rise Buildings
June 2019, Vol 8, No 2, 95-100
https://doi.org/10.21022/IJHRB.2019.8.2.95

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

The Integration of Adaptive Elements into High-Rise Structures

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Abstract

Whilst most research focuses on the reduction of operative energy use in buildings, the aspect of which (and how many) materials are used is often neglected and poorly explored. However, considering the continuous growth of the global population and the limited availability of resources, it is clear that focusing on operative energy alone is too short-sighted. The tasks lying ahead for architects and engineers cannot be accomplished with conventional methods of construction. With a share of 50-60% of global resource consumption, the building industry has a decisive impact on our environment. If business as usual continues, resources will be significantly depleted in a matter of decades. Therefore, researchers of the University of Stuttgart are investigating the concept of adaptivity as a promising method for saving resources in the built environment. The term adaptivity in the context of building structures was first introduced by Werner Sobek. It describes a method where sensors, actuators and control units are implemented in systems or facades in order to oppose physical impacts in an ideal way. The applicability of this method will be verified on an experimental high-rise building at the University campus in Stuttgart. Thus, this paper describes this innovative research project and depicts the concept of adaptivity in high-rise structures. Furthermore, it gives an overview of potential actuation concepts and the interdisciplinary challenges behind them.

Keywords: Adaptivity, Actuation, Resources, Sustainability

1. Introduction

The way buildings' load bearing structures are designed has not significantly changed over the last 50 years. Admittedly, trends like the green design movement or the tendency to more insulation has had an impact on the way buildings look, however, the overall calculation methods for structural design stayed the same. Thus, conservative methods have shaped the built environment in which 7.6 billion people are currently living (United Nations, 2017). However, the continuous increase of the global population up to 9.8 billion people in 2050 (United Nations, 2017) presents challenges that are immense, especially for the building sector. A net sum of 2.2 billion people will be added to today's population and they will need to find living space in already overcrowded urban agglomerations.

Werner Sobek states that the upcoming challenges cannot be met with traditional methods (Sobek, 2014). With a portion of 50-60% of the global resource consumption, the building industry has a significant impact. If business as usual continues, the significant depletion of resources is only a matter of decades. Some resources are already being consumed at a higher rate than they can naturally be renewed, in particular, the aggregate sand as the main ingredient for concrete - the most used substance after water (Curbach, 2013). Fig. 1 shows how current material stocks may develop, depending on various scenarios. If every global citizen were granted the standard of 2010 of the developed countries which is 335 metric tons per capita this would result in an increase of resources embedded in our built environment from 792 Gt in 2015 to 3 137 Gt in 2050 (Krausmann et al., 2017).

The Collaborative Research Centre 1244 (SFB 1244) aims at developing new methods and technologies in order to increase the resource efficiency in the building sector. It will be introduced in more detail in section 3.

2. Lightweight and Ultra-lightweight Constructions

Lightweight structures have been widely spread in various fields of science and industry for several decades. Whenever it comes to moving things (or people), building light is essential to achieve high efficiency. Therefore, the automotive and aeronautic sectors have been applying lightweight methods for a long time (Sobek, 2014). While buildings' main purpose is not the transport of people, the principle of building light to accomplish high efficiency still applies, especially when wider spans and greater heights need to be reached. Here, three different lightweight approaches can be distinguished, namely: lightweight construction materials, lightweight structures and lightweight systems (Sobek, 2016).

Traditionally built structures are designed to resist the

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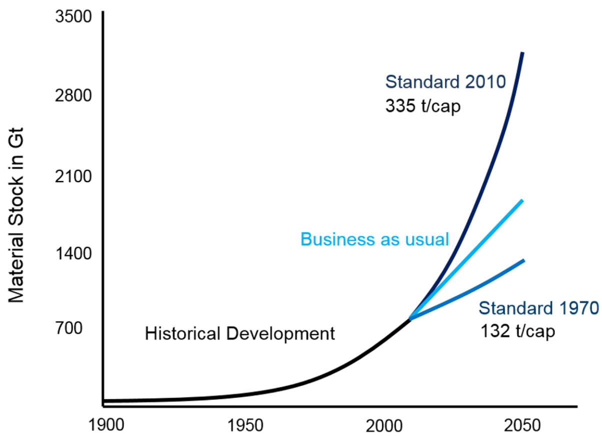


Figure 1. Stock development and scenario from 1900-2050; Source: ILEK based on (Krausmann et al., 2017).

worst load case that may hypothetically occur during a structure's lifetime, e.g., an earthquake. Therefore, these structures are usually over-designed for the majority of their lifespan. This means that a significant share of the material embedded in structures such as buildings or bridges is not needed unless that worst load case occurs. However, simply decreasing the amount of built-in material, renders the structure more vulnerable to external impacts - unless specific measures are taken (Neuhaeuser et al., 2013). Introducing adaptivity into the built environment, by enabling structures to react actively to different load-case scenarios, e.g. extreme wind or earthquake conditions, is such a specific measure.

In particular, adaptive structures manipulate the load transfer by reducing deformations, stresses and vibrations. Consequently, peak stresses can be avoided and material hitherto used to compensate these peak stresses becomes dispensable. Thanks to adaptivity, the mass of lightweight structures can thus be reduced even further – these structures become ultra-lightweight structures. To reach this solution, sensors (e.g., strain gauges) are placed on or in the structural parts that recognize every change of condition in the structure that might occur as a result of external influences. The recorded information gets processed by control units, which – if needed – initiate a movement of the actuators that lead to a secondary stress field, ideally equalizing the overall stresses in the system (Sobek, 2014).

This concept has been worked on at the Institute for Lightweight Structures and Conceptual Design in interdisciplinary cooperation for 15 years and was successfully validated through the Stuttgart SmartShell. A wooden shell spanning 10 m × 10 m with a thickness of only 4 cm. Thanks to hydraulic support cylinders, three of the structure's four bearings can be moved in three dimensions (Fig. 2), allowing the shell to actively compensate static and dynamic loads in milli-seconds. The mass of the SmartShell could thus be reduced by more than 70% when compared with a conventional shell structure (Sobek, 2014).

Adaptivity leads to a reduction of material and thereby also of embodied energy. On the other hand, it results in an increase of operating energy due to the supply for the actuators. Fig. 3 compares the energy consumption behaviors of active and passive designs. The more active a system is the less embodied energy it needs, while its use of operating energy increases. For passive systems the equation is the other way round. The objective therefore is to find the optimum mean point between active and passive measures.

The next step is to apply this concept to high-rise structures. Here, the Collaborative Research Centre 1244 supplements previous results.

3. Collaborative Research Centre 1244

Since 2017, the Collaborative Research Centre 1244

Figure 2. Stuttgart SmartShell movement of bearings; Source: ILEK, Gabriele Metzger.

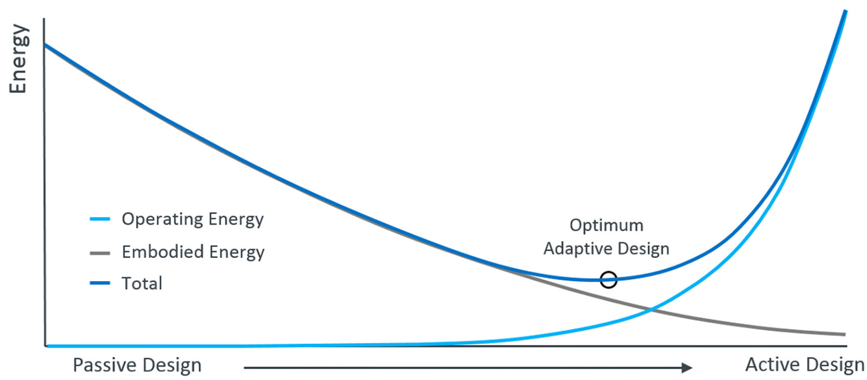


Figure 3. Energy consumption behavior for active and passive design; Based on: Senatore et al., 2018.

Adaptive Skins and Structures for the Built Environment of Tomorrow (SFB 1244) has been investigating the implementation of adaptive elements into a building's structure. SFB 1244 brings together 14 institutes of the University of Stuttgart and three non-university institutions from the fields of lightweight structures, component development, system dynamics, planning theory, visual analysis, design and many more.

As demonstrated above, the integration of sensors, control units and actuators into a building requires an intense interdisciplinary collaboration. The number of research topics incorporated in SFB 1244 is very large. Therefore, this paper mainly concentrates on the research fields applied to an experimental high-rise building's structure, which was first introduced in (Weidner et al., 2018) and is currently being realized on the campus of the University of Stuttgart. Fig. 4 shows a picture of the mock-up of the 36.5 m tall structure. Here, all of the research results of SFB 1244 will be tested under real conditions.

The building has a slenderness ratio of 1:7. The floor plan measures approx. 5 m × 5 m. The load bearing structure made of steel (S235 and S355) is subdivided into four units which are structurally identical. Each unit encompasses three stories, resulting in a total of twelve floors. Each story can be individually equipped and accessed via an adjacent supply and circulation tower, where all vertical transportation elements such as stairs, elevator, pipes and shafts are located.

The loadbearing structure consists of four columns in every corner of the square footprint. These columns are braced on each side by two diagonal tension only elements. Crossbeams on each level link the four columns and offer a support area for the wooden floor slabs and the façade elements. The columns consist of square hollow sections that measure 300 mm × 300 mm with a thickness of 10 mm. The crossbeams are composed of two rectangular hollow sections measuring 200 mm × 120 mm with a wall thickness of 10 mm. The diagonals are made out of steel sheets measuring 150 mm × 15 mm.

The dimensions of the load bearing structure are a consequence of the building's experimental nature. During its lifetime it will be confronted with a multitude of varying excitation and control scenarios, making fatigue the dominant design factor. Overall, the highly modular system in combination with its bolted connections, results in a 100% exchangeable and replaceable load bearing structure. This allows for an easy modification and replacement. Thus, different materials or various bracing systems can be installed and tested during the ongoing research project.

The same principle of exchangeability also applies to the façade components. Research of SFB 1244 also considers the potential of adaptive façade elements. These elements can adapt their characteristics according to changes in the external or internal environment. The experi-

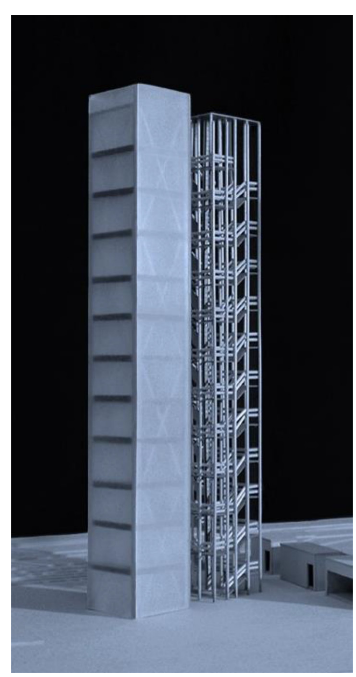


Figure 4. Experimental High-Rise Building, Picture of Mock-up.

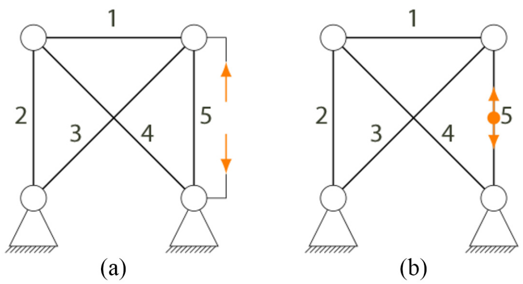


Figure 5. Different actuation concepts (a) parallel (b) serial; Source: ISYS.

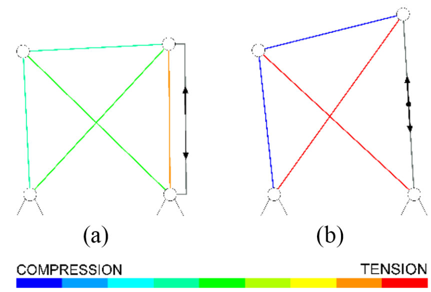


Figure 6. Effects of actuation on the passive elements (a) parallel (b) serial.

mental building will also be used to test such adaptive façade elements; therefore, its outer appearance will constantly change over time as well.

4. Adaptivity in High-rise Structures

There are two main approaches for actuating trusses and frameworks, depending on the position of the active element, the actuators, in respect to the passive structure: parallel actuation (Fig. 5(a)) and serial actuation (b). In the case of parallel actuation (a), the active element is placed parallel to the passive structure; therefore, it can be decoupled from the direct load transfer. Hence, the separated actuation unit can be designed for the actuation forces only.

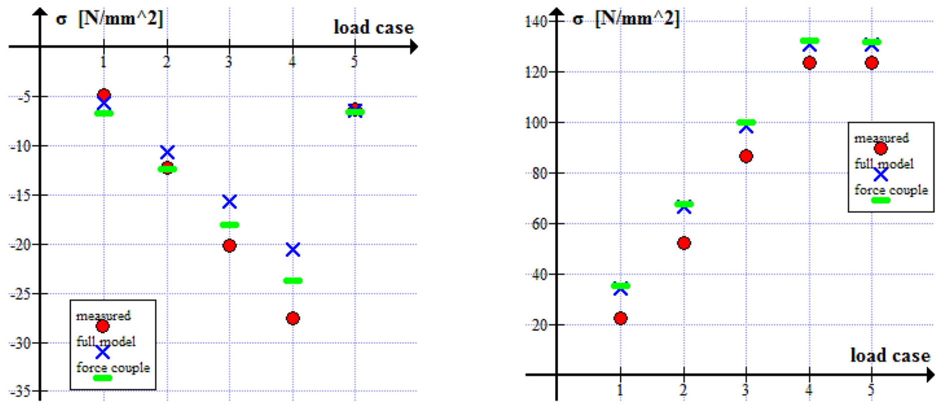
Incorporating the actuator into the load bearing system leads to serial actuation (b), which requires fewer components. However, in this case the active element also has to withstand the forces induced into the system by external loadings since it is now part of the load path. This leads to higher safety requirements for the active elements (Weidner et al., 2018). The analysis of safety aspects for adaptive structures is considered in a separate research project as part of SFB 1244 (Ostertag et al., 2018).

As shown in Fig. 6, another crucial difference lies in the impact that each actuation principle has on the load bearing structure. In this statically indeterminate example, both systems possess the same properties and are loaded with the same actuation force, actuating the same element (no. 5 in Fig. 5). The only difference is the type of actua tion.

The effect of parallel actuation (a) is primarily local, as the force is short-circuited by the passive element (no. 5). Serial actuation (b) allows for the manipulation of internal forces in the surrounding elements (no. 1-4) and thus can generate larger deformations.

The general strategy for adaptive structures therefore is to use serial actuation for controlling the overall deformation of a system - and parallel actuation for manipulating the stress state in a particular element. In the case of high-rises, the tension and compression forces in the perimeter columns due to wind loads could thus be compensated by parallel actuation of the columns; the overall deflection could be reduced by e.g., diagonal bracings actuated in series. This corresponds to the implementation of the active elements that are tested in SFB 1244's experimental building.

Figure 7. Adaptive frame, a full-scale prototype; Left: Visualization with adaptive elements (blue) Source: IKTD/ILEK; Right: Photography of frame at ILEK platform Source: ILEK.



(a) Active column

(b) Passive diagonal

Figure 8. Test results of the prototype frame for active column and passive diagonal, comparison measurements and simulations.

5. Adaptive Frame

In order to evaluate and validate the simulations, a prototype frame was installed at the end of 2018. It is a full-scale part of a module from the experimental high-rise building and it measures 9 m in height and 5 m in width. It consists of one parallel actuation unit with two actuators located in one steel column (further being referred to as "active column"), as well as one actuator incorporated in series in one diagonal bracing element ("active diagonal"). The prototype was also used to check the functionality of the assembly and the connections between passive and active structures. As already mentioned, building adaptive structures is a highly interdisciplinary approach. The joints between civil and mechanical engineering are very complicated to design as every discipline has different requirements in terms of tolerances and normative specifications. Thus, new design and planning techniques need to be developed, which is another research topic implemented in SFB 1244.

Fig. 8 shows the results of first tests of the prototype. Each graph depicts the measured and simulated values from two strain gauges, one in the active column (8a), and one in the passive diagonal (8b). For a better understanding, the measured strains are converted into stresses, assuming a uniform E-modulus of 210,000 N/mm^2. Table 1 shows the different load cases and actuation forces, which were examined in a test run.

The active diagonal is tensioned gradually in steps of 50 kN from 50 to 200 kN (load case 1-4). In the fifth load case, the induced stress state in the active column is counteracted by the parallel actuation unit of the active column. To validate the measurements, two different FE-models were created.

Table 1. Implied actuation forces for the load cases 1-5

Load case		1	2	3	4	5
Actuation force [kN]	diagonal	50	100	150	200	200
	column	0	0	0	0	-200

Firstly, in the case of the "full model" the actuation units are modeled as link-elements, using the section and material properties of the defining structural member of the actuation unit and the actuation forces are modeled as temperature loads. Secondly, in the "force couple"-model the actuation units are deleted from the model and replaced by a force couple acting on the respective nodes.

Overall, the measured values match those of the simulation. The constant minimal offset observable in Fig. 8(b) between measurement and simulation implies a fixed error due to imperfections or scattering material properties. Fig. 8(a) shows the effect of the stresses decreasing from load case 4 to 5. The change of stresses in the passive diagonal is negligible due to the restricted influence of the parallel actuation, as discussed in chapter 4. Additional tests are performed to identify the causes of errors and to improve the quality of the simulations. In general, these tests correspond to the predictions of the simulations, thus, confirming the concepts of serial and parallel actuation.

6. Conclusion and Outlook

Introducing new building technologies clearly becomes more and more important due to an increase in global population and a potential shortage of natural resources. As a further evolution of conventional lightweight construction is limited, researchers of the University of Stuttgart now investigate the integration of active components such as sensors, actuators and control units into a load-bearing structure. Consequently, a structure's load transfer behavior can be actively influenced, allowing for the building of ultra-lightweight constructions.

Initial tests on a full-scale prototype frame show that previous calculations correspond to the actual test results and therefore prove the validity of this innovative concept. A subsequent intermediate goal will be reached with the completion of the world's largest adaptive structure, a 36.5 m tall adaptive high-rise building. The testing of the actuation and monitoring concepts on this structure will provide a significant indication of the applicability of these concepts to bigger structures, e.g., high-rise buildings with different bracing systems.

In the following years, the ongoing Collaborative Research Centre 1244 will provide important knowledge and practical experience about building with adaptive skins and structures that can significantly influence and change prospective building methods. The further research objectives aim at investigating not only the influencability of a structure's load path but also the implementation of adaptive facades and the associated relation between inhabitant or user and building.

Acknowledgments

The authors gratefully acknowledge the generous funding of this work by the German Research Foundation (DFG - Deutsche Forschungsgemeinschaft) as part of the Collaborative Research Centre 1244 (SFB) "Adaptive Skins and Structures for the Built Environment of Tomorrow" 279064222/project Z01, A06, C02 and A01. Moreover, we would like to thank our sponsor Liebherr-International Deutschland GmbH for their support.

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