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Designing a framework for actuators for adaptive structures

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Abstract

Adaptive structures have the potential to play a significant role in saving resources in the construction industry in the future. For realisation, this requires actuators that meet the requirements of different buildings with their specific load-bearing structures. In the past, the actuators were mainly developed particularly for one exemplary load-bearing structure. This paper analyses the primary classifications for buildings, followed by challenges of adaptive structures, before outlining the draft of a framework for actuators for adaptive structures to speed up and simplify development.

Keywords: product development, lightweight design, multi-/cross-/trans-disciplinary approaches, adaptive structures, actuators

1. Introduction

The construction industry is responsible for a large share of the world's resource use and greenhouse gas emissions (UNEP, 2020; Sobek and Heinlein, 2022). An approach for reducing emissions is to design civil engineering load-bearing structures adaptive.

In this approach, the load-bearing structure is supplemented by an actuator, sensors, and a controller to ensure the entire system can respond to changing load situations. Well-designed systems allow controlled reduction of deformation or stress, depending on the control objective. Theoretically, this allows lighter cross-sections of the structural elements and, thus, reduces the resource consumption for structural elements. (Sobek, 2016)

Adaptive structures have been developed within different research projects, using state-of-the-art actuators to adapt them to the new usage. Custom-made actuator concepts have only been developed for a few use cases. These concepts can handle specific requirements caused by structural elements in a more targeted manner. When developing actuators for adaptive structures, a specific framework could be beneficial for efficient development. This would allow for a direct reflection of the adaptive structure on the actuation concepts, leading to better overall solutions.

1.1. Previous research

Several examples of adaptive load-bearing structures can be found in the literature. These examples are primarily the result of research projects. The actuators used there are mostly conventional actuators from mechanical engineering or explicitly adapted. There are only a few fundamental newly developed actuators. Often, high forces are required with small strokes, which can lead to oversized actuators when adapting conventional ones.

Within the framework of the CRC 1244 and predecessor projects of the participating institutes, a few examples of adaptive structures or structure elements were developed. In the demonstrator high-rise building D1244, adaptive columns and adaptive bracings were implemented by adapting classical hydraulic cylinders (Blandini et al., 2022). The development of the actuators (cf. Figure 1) is described by Burghardt et al. (2021; 2023), while the actuation concept for the D1244 and more high-rises is described by Weidner et al. (2018) and Steffen et al. (2022) With the hydraulic actuators implemented, the deflection, e.g., caused by wind load, of the high-rise can be manipulated up to a frequency of 8 Hz with actuator forces up to 400 kN. In a predecessor project, the use of hydraulic cylinders in a tripod construction at the supports homogenized stresses in a wooden shell structure and dampened vibrations (Neuhaeuser et al., 2013). In this project named hybrid intelligent construction elements (HIKE), six HIKE have been developed (Crostack, 2018), e. g. a pneumatic textile actuator. Within the CRC 1244, Steffen et al. (2021) developed an adaptive concrete column using a new kind of actuator concept (cf. Figure 1). The concrete strength can be adjusted by using a hydraulic sleeve, and a stroke can be applied in the normal direction of the column. Kelleter and Burghardt developed an adaptive beam using new kinds of actuators (Burghardt et al., 2022; Kelleter, 2022). Here, hydraulic pressure chambers are integrated directly into a beam to manipulate the deflection (cf. Figure 1). In the follow-up, this concept is extended to the actuation of slabs (Nitzlader *et al.*, 2022b; Bosch *et al.*, 2022; Nitzlader *et al.*, 2022a). These examples highlight specific new developments of actuators for adaptive load-bearing structures.

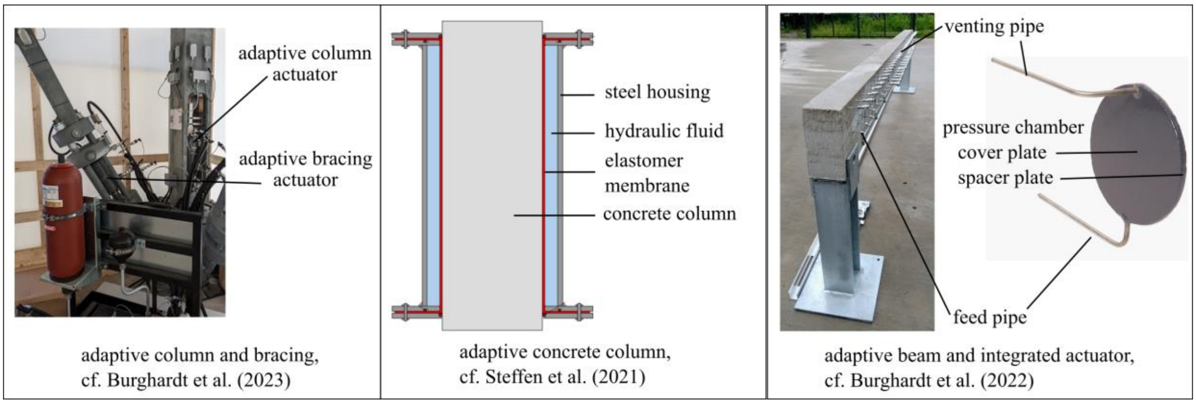

Figure 1. Examples of actuator and actuation concepts for adaptive structures, cf. (Burghardt et al., 2023; Steffen et al., 2021; Burghardt et al., 2022)

As part of the research on adaptive trusses at EPFL Lausanne, a cantilever and a simply supported adaptive truss were developed using commercially available electromechanical actuators. The actuators are integrated directly into the truss. Here, the deflection is manipulated. (Senatore et al., 2018; Reksowardojo et al., 2019)

An adaptive beam with external actuators was created at the University of Duisburg-Essen (Schnellenbach-Held et al., 2014). Here, an investigation took place to find a suitable operating principle for the actuator. In the end, the choice also fell on classic hydraulic cylinders.

Other examples of semi-actively damped buildings have a different objective and usually have no actuator for influencing, so they will not be discussed further.

Some of the studies describe the methodology used to develop the actuators. In (Honold et al., 2019), the development process focusing on the interdisciplinary interaction in the CRC1244 for the D1244 is described, leaving the process on a high level. In (Bosch et al., 2023), a specific procedure for developing integrated fluidic actuators in slabs is presented. Due to its detail level, this is not directly transferable to other load-bearing structures. A specific framework for developing actuators for adaptive load-bearing structures does not exist. The closest to this is Crostack (2018), where the V-model is used as a basis. Nevertheless, the focus here is on HIKE and not on actuators for load-bearing structures, leading to a different framework expression.

1.2. Research approach and structure of the article

In the past, the adaptions of state-of-the-art actuators and new actuators were developed for individual purposes. To simplify the approach and speed up the development, a framework is created to collect design principles and make them available, depending on the characteristics of the structure. For this

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purpose, the standard classification of building structures is analysed in the beginning. Then, as a process model, the V-model from mechanical engineering is explained in more detail. Based on research results from the collaborative research centre 'Adaptive skins and structures for the built environment of tomorrow' CRC1244 (Sobek *et al.*, 2021), challenges and motivators for adaptive structures are presented. Finally, based on the V-model, a first framework is built, which clusters different areas of actuator development. The framework will be understood as a starting point for further consideration and enrichment. It should be possible to develop actuators more specifically for structural elements and thus simplify implementation in practice when using the framework. The accompanying research question is:

What does a framework for developing actuators for adaptive structures look like?

Comparable to (Crostack, 2018), the VDI 2206 with the V-model can serve as a basis, whereby it should be noted that the combination of structural elements, actuator, sensors, and control units results in some kind of mechatronic element.

2. Preparing the input for the framework

2.1. Classification of structures

Usually, an essential target of a civil structural design is its physical implementation (Block *et al.*, 2019). This results in certain requirements, such as specific design, function, construction and building physics, that every building must meet. (Block *et al.*, 2019) (compare Figure 2).

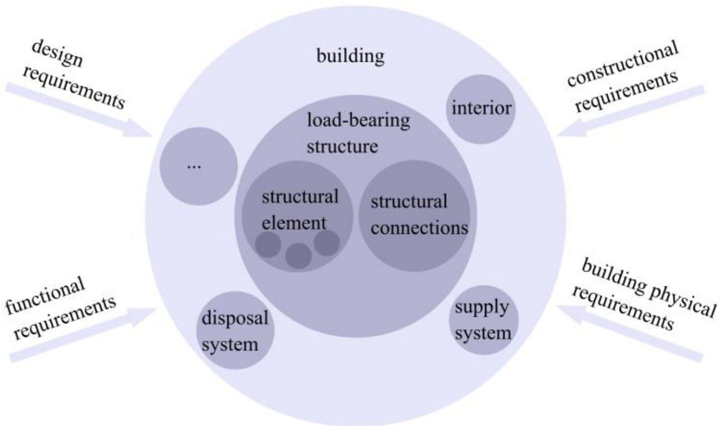

Figure 2. Schematic visualisation of a building with a focus on the load-bearing structure, based on (Büttner and Hampe, 1985)

An essential requirement is the stability of the load-bearing structure (Block *et al.*, 2019). According to (Büttner and Hampe, 1985), environmental influences and the intended use are the main criteria for fulfilling the requirements when developing civil engineering load-bearing structures. The entire structural load-bearing system can be subdivided into individual structural elements and their structural connections. A structural element is determined by its geometry, i. e. main and cross-sectional geometry, and its material, compare Figure 3.

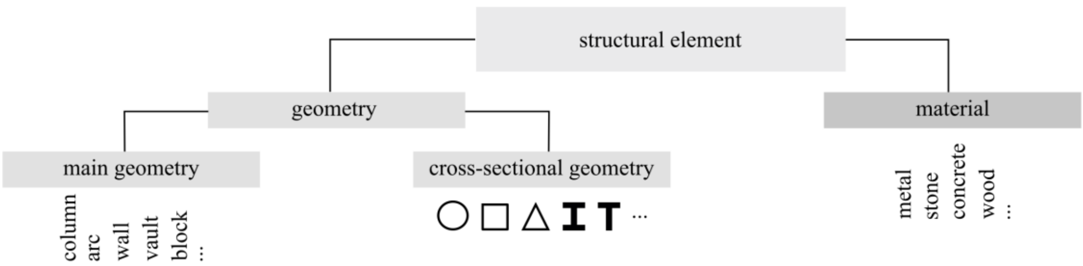

Figure 3. Defining specifications of structural elements, compare (Büttner and Hampe, 1985)

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The load cases on the structural element result from the use and function of the structure in combination with the existing connections. Common load types depending on the existing geometry are shown in Figure 4. The primary load transfer, normal force, and/or bending are also indicated. Structural elements have a typical span when used for buildings. A qualitative representation is given in Figure 4. The structural element can be dimensioned with the forces depending on the material. Typical building materials for different types of structures are steel, concrete, wood, glass, or brickwork, spanning a broad field of different material parameters. Besides the load transfer, the type of building defines different requirements regarding, e.g., safety and lifespan for the load-bearing structure and the interior, e.g., technical facilities, elevator, and piping (Kister, 2022).

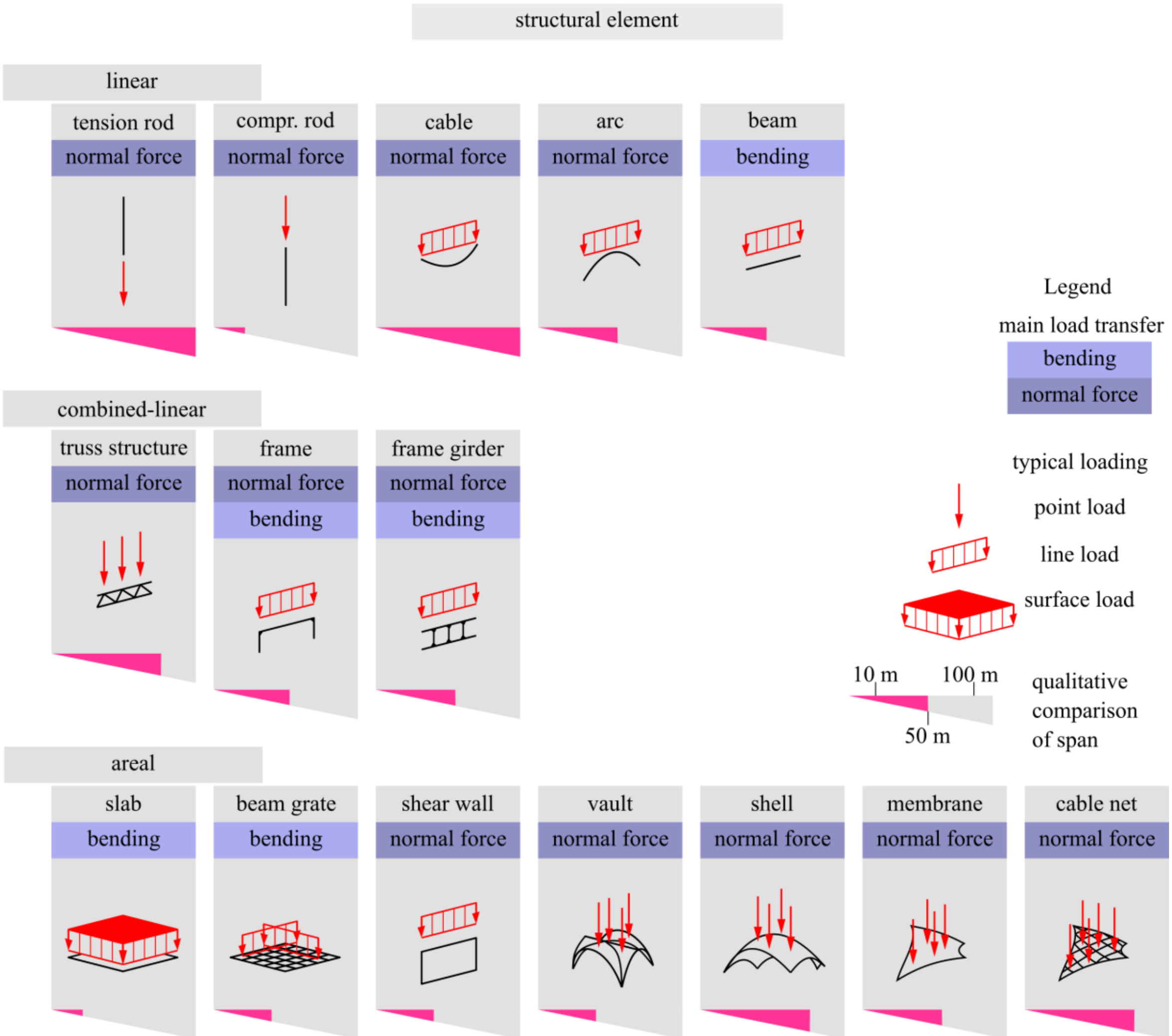

Figure 4. Common types of structural elements with typical loading and typical load transfer, compare (Block et al., 2019)

These requirements, in combination with the dominant loading for dimensioning, form a set of requirements for additional components in each individual structural element, e. g. regarding potential construction space based on the cross-sectional geometry.

Combined with actuators, sensors, and a control system, structural elements can react to external loads to minimise deformation or optimise stress distribution (Sobek, 2016). Following this, the utilisation of the material can be increased, and/or critical frequencies can be damped actively. Therefore, the cross-sections of structures can be thinner, reducing the necessary building material. An efficient actuation is given when the structural element's primary load transfer (conventional loading) is counteracted with the same type of load from actuation (Steffen, 2023).

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2.2. Motivators for adaptive structures

The main driver for the development of adaptive structures is the reduction of the ecological footprint of the structures. The energy consumption is shifted from the construction phase to the utilisation phase by saving construction material and thus reducing the grey energy and grey emissions. In the utilisation phase, load-bearing capacity is optimised by actively adapting the structure. Ideally, non-fossil-based energy is used for actuation. To achieve a benefit, the sum of emissions over the life cycle of the adaptive structure should be lower than the emissions of a conventional structure. This requires a comprehensive life-cycle analysis. Borschewksi et al. (2022) lay out the principle benefits.

Not every existing structure is equally suitable for adaptation. It makes sense to design a structure that is as adaptable as possible to generate the smallest possible carbon footprint. Influence matrices can be used as a measurement for adaptability (Steffen, 2023). Whether appropriate actuators can be developed is not examined there.

In their investigations of adaptive structures, Senatore et al. (2018) attempt to consider the energy requirements of the actuators during optimization of the structure. This is intended to achieve a holistic optimum of the adaptive structure.

Both adaptive façades and adaptive structures are the main focus of the CRC 1244. For adaptive façades, Borschewski et al. (2023) collect different motivators. Besides further design opportunities and additional functions to the façade, like communication, especially the increase of comfort inside and outside the building while reducing the need for energy, reducing the emissions and the costs in the use phase are the primary motivators (Blandini *et al.*, 2023). In contrast to adaptive load-bearing structures, the savings potential of adaptive façades is not primarily restricted to the construction phase but to the utilisation phase.

2.3. Development method V-Modell - VDI 2206

The V-model described in VDI 2206 (2021) is a process model for the development of mechatronic systems. For such a system, according to Figure 5, the system requirements are defined first before a system architecture is developed based on this. This leads to specific component requirements for the component design in the individual disciplines involved. Solutions for software, electronics, and mechanical components are developed. These are integrated into a system. The special feature is continuous property verification during the system integration and validation at the end of the integration. This involves checking whether the solution ('right branch of the V') matches the requirements ('left branch of the V'). If the target is not met, an iterative process continues to run through the V-Modell in one or more loops to increase the maturity level of the product.

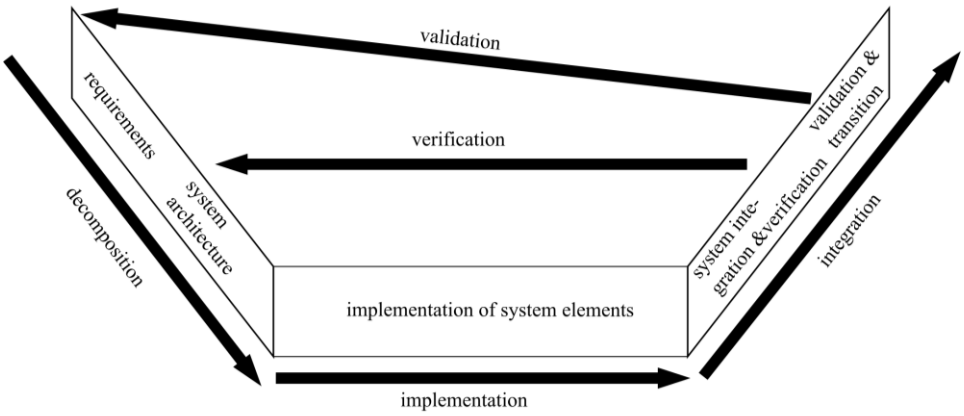

Figure 5. Schematic visualisation of the V-Model, based on VDI 2206 (2021)

2.4. Challenges for a support for the development of actuators for adaptive structures

During the development of the actuator technology for adaptive slabs as well as for further projects within the CRC 1244, various challenges arose:

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- strong dependence of the actuator requirements (e.g. forces, strokes) on the structural material,
- strong dependence on the installation situation as well as building type and load situation,
- primarily qualitative statements as a starting point for development,
- conflict of goals, limited energy density vs. energy saving potential,
- estimation of service life difficult due to the interaction of supporting structure - actuator,
- different understanding of terms between disciplines.

In this setting, quantitative statements are challenging to obtain. Ultimately, this means that an optimal solution cannot necessarily be found. In the following, a proposal for a framework as a support for developing actuators for future developments will be suggested. The following criteria are considered:

1. The method sorts in different design criteria and helps to understand the impact on the actuator.
2. The method provides an entry point for a detailed consideration of an actuator or a targeted development.
3. The method tries to be valid across the board, yet a suitable preselection is made through specific definitions.
4. The method is flexible enough to react to possible new findings.
5. New actuator principles and limits can be integrated without problems. Thus, modularisation or other topics can be integrated without problems.

3. Sketch of a framework for actuators for adaptive structures

If an actuator is considered in the context of the various layers of the structure, see Figure 6, requirements and design principles arise for the actuator depending on the layer.

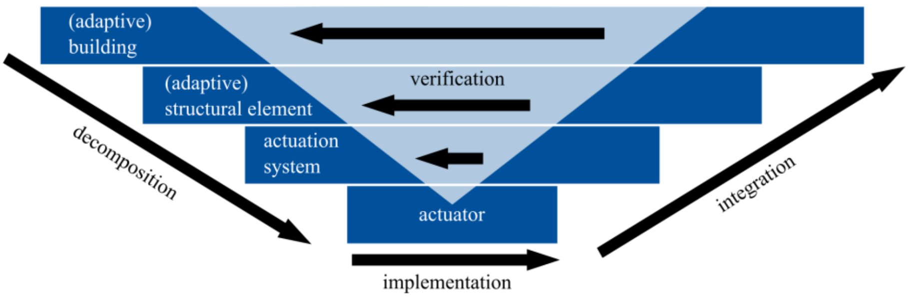

Figure 6. Abstract layers for the framework

In this context, different layers of system integration of the actuator are spanned. At the lowest level, the combination of subsystems of an actuator, according to (Czichos, 2019; Isermann, 2008), results in a complete actuator. This interacts with more actuators of the entire structure building up an actuation system. On the other hand, the actuator can be integrated into the logic of the elements of the structure. This is exemplarily shown in Figure 7. Thus, the specification of the structural element is extended by an adaptive component, in this case, an actuator, resulting in an adaptive structural element.

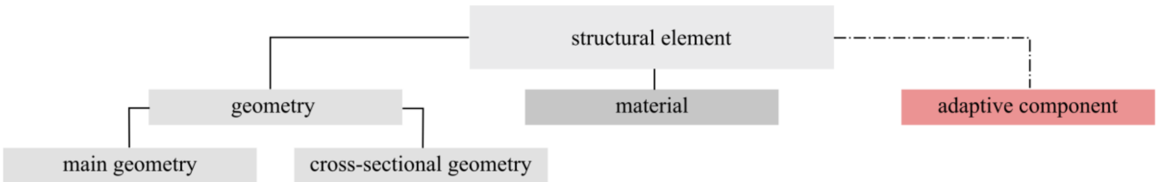

Figure 7. Extended specification for a structural element with adaptive component

The combination results in an adaptive load-bearing structure or an adaptive building. Interactions with the previously mentioned adaptive façade occur in the last layer (the adaptive building). However, this will not be considered in the following. If these levels are ordered according to granularity, the structure shown in Figure 6 results. Here, the V-model can be referenced indirectly by inferring the requirements of the subsystems from an overall system and verificating the properties of each layer of the system according to the requirements. The focus is set on the actuator at the lowest level and, therefore, on the

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decomposition. In the next step, specifications are assigned to the individual levels that significantly influence the requirements for the actuator system and the individual actuator. This is mainly based on the observations from the development projects in CRC 1244. In addition, design principles that emerge from these requirements or specifications are to be defined. The exact characteristics are not part of this paper and will be investigated in a later step. The specifications represent a first draft and do not claim to be complete at this stage. However, according to the criteria for the framework, this is not desired to allow flexibility and adaptability to new findings. However, known solutions for adaptive structural elements should be able to be sorted into revised variants of the framework. For the examples of adaptive structures mentioned in the previous chapter, this is possible for the presented framework. In Figure 8, the draft of the framework is shown. The framework is divided into five columns:

1. considered layer,
2. specifications of the layer,
3. characteristics of the specification,
4. emerging requirements for the actuator (system),
5. derived design principles.

If a characteristic is selected at the upper layer, the selection should be restricted to the lower layers to sort out solutions that do not make sense. Ultimately, it is possible to check at an early stage whether a variant can be implemented with known technologies. Nevertheless, in the integration process of the V-model, the properties of the actuator and the adaptive structural element need to be verified.

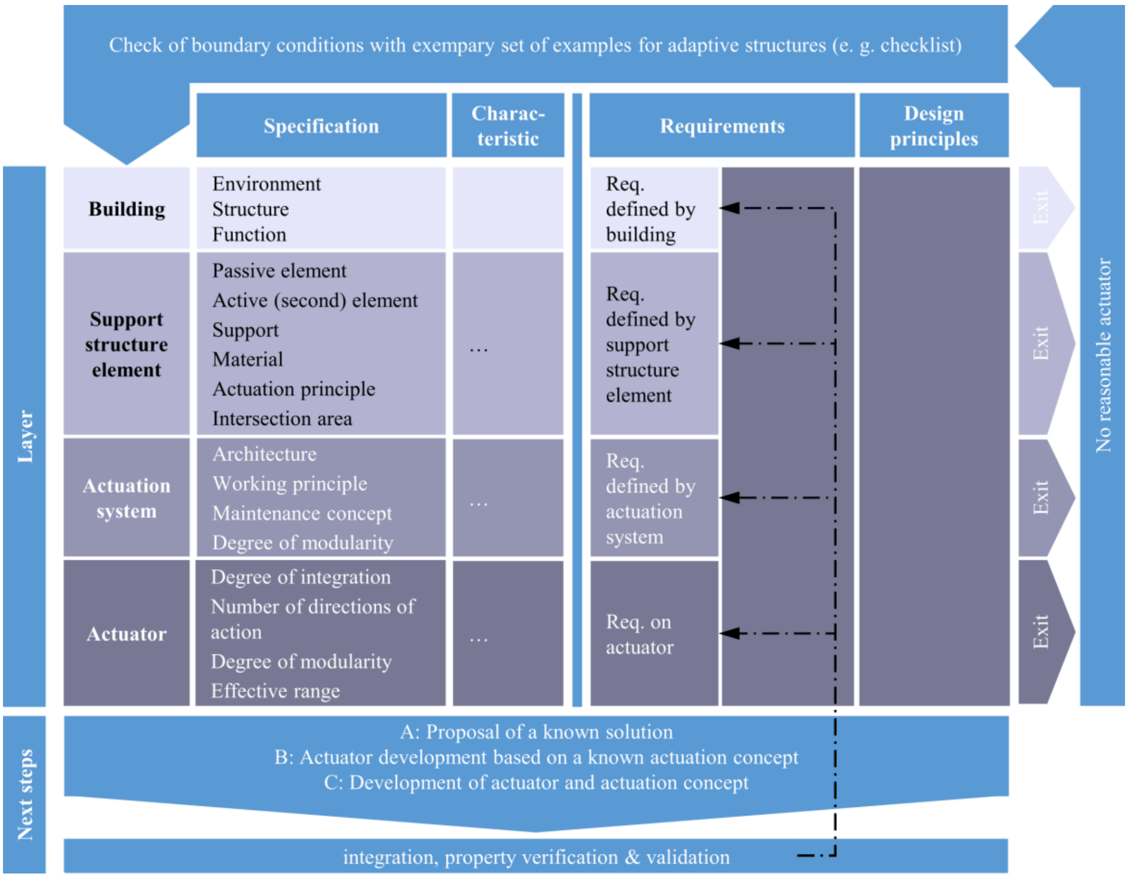

Figure 8. Draft of the framework for the development of actuators for adaptive structural elements; the complete characteristics need to be defined in a later stage

In the first level, the environmental, structural, and functional parameters are selected based on the basic structure of buildings. If, for example, actuation is intended for an industrial building, on the one hand, other loads are necessary for the structural elements and thus also other forces for the actuators. On the other hand, the typical periphery of this type of building gives a preference for possible physical principles of action and the consideration of whether the actuators should be better supplied via a central

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or decentralised unit. The second level describes the adaptive load-bearing structural element. Based on the design of load-bearing structures, a passive element is combined with an active element, resulting in an active element. Together with the support conditions and the cross-section, loads can be estimated, ultimately defining the actuator system's necessary energy density and actuating strokes. A preselection for the actuators is created by defining the basic actuation principle.

Further design principles can be derived by considering the material. In the third level, the actuation system is further specified. Here, the architecture specifications, the actuator operating principles, maintenance concepts, and degrees of modularity are pending. Ideally, a preselection by conditions has already been made with the selection in the upper layers so that only appropriate concepts are available for further selection, and thus, requirements and design rules are passed on to the detailed actuator.

The fourth and last layer describes the actuator. Here, the area between the combinatorics of solution principles and the specifications requested is blurred. The degree of integration of the actuator components within the structural elements, the number of possible directions of action, and the modularity of the actuator itself must be considered. A specification of the desired effective range and, thus, indirectly, a limitation of the number of actuators can also be found here.

Based on these specifications and the resulting requirements as well as design principles, it is possible:

a) to select a solution from known solutions that are clustered accordingly,
b) to develop a new actuator concept based on a known actuation concept or
c) to develop an entirely new actuator and actuation concept.

In case c), it is essential to note that this can only be done in combination with developing a suitable actuation concept. This requires close coordination between the disciplines involved. The run-through of the framework already gives a predefinition. It is crucial to critically approach the individual points selected and question whether another solution would be more suitable. An example of a procedure of a new development for an adaptive slab is given in (Bosch *et al.*, 2023). This could also be generalised to other structural elements. At least, further relevant points for the development can be seen there.

Especially if case b or c results from the run-through, the developed new actuator and actuation concept must be verified step by step according to the V-model.

Figure 9 shows the exemplary characterisations of the layers for the adaptive column of Burghardt et al. (2021; 2023). Requirements arise from each of the characteristics and out of the combination of these. For example, the location combined with the kind of structure leads to a typical load scenario, which allows calculating forces and strokes for an adaptive tension-compression rod. The requirements are determined by Burghardt et al. (2021). The knowledge of the material furthermore allows inside in typical damage mechanism. Here, there is, for example, a difference between concrete's brittle behaviour and steel's ductile behaviour. Also, the tolerable maximum stress and kind of stress differ. This directly impacts the design of the connection points between active and passive components. Further details are subject to subsequent work.

Building	***Specification***	Environment	Structure	Function			
	Characteristic	*Campus Vaihingen, Germany*	*Truss structure*	*Demonstrate*			
Support structure element	***Specification***	Passive (1.) element	Active (2.) element	Support	Material	Actuation principle	Intersection area
	Characteristic	*tension / compr. rod*	*tension / compr. rod*	*point support*	*steel*	*parallel*	*anisotrop*
Actuation system	***Specification***	Architecture	Working principle	Maintenance concept	Degree of modularity		
	Characteristic	*central*	*hydraulic*	*defined interval*	*small*		
Actuator	***Specification***	Degree of integration	Number of directions of action	Degree of modularity	Effective range		
	Characteristic	*energy converter and transmission*	*one (both ways)*	*small*	*global for one element*		

Figure 9. Exemplary characteristic of the adaptive column by Burghardt et al. (2021; 2023)

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4. Conclusion

Adaptive structures can contribute to the reduction of emissions and resources in the construction industry. Therefore, the best combination of actuator and actuation concept is essential to optimise emission reduction. Additionally, different requirements, e.g. safety and accessibility, must be fulfilled by the actuators to enable the usage in actual buildings. When developing actuators, all these different aspects are considered. To reduce the development effort needed, this contribution presents a first draft of a framework for developing actuators for adaptive structures using ideas of the V-Model and known characterisation of building structures. The framework needs to be filled with specifications and validated with known adaptive structural elements in the following steps. In this process, the shown characteristics might change slightly.

It is planned to build up a database with logical connections between different characteristics and arising design principles as well as requirements on the actuator and the actuation system. The known examples from the literature and the cooperative research centre CRC 1244 should be used for this.

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