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DESIGN OF INTEGRATED FLUIDIC ACTUATORS FOR MULTI-AXIAL LOADED STRUCTURAL ELEMENTS

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Summary. The construction sector is responsible for high grey energy consumption and high greenhouse gas emissions. Adaptive structures can be a suitable solution to counteract this. Actuation of a beam to reduce the mass by counteracting the deflection with integrated fluidic actuators has been proven in previous studies. New challenges are brought about with the actuation of slabs due to the multi-axial load transfer. Many actuator principles are conceivable for this application. A combination of uniaxially acting actuators and complex designs that generate forces in different spatial directions in a targeted manner are possible. This paper presents various principles for the development of actuators integrated into the cross-section of a slab. These are able to manipulate the multi-axial load transfer behaviour directly. For this purpose, the actuator principles are classified according to various aspects. In a second step, numerical investigations are used to prove the effectiveness of the actuator principles.

1 INTRODUCTION

The construction sector is responsible for high grey energy consumption and high greenhouse gas emissions. For example, the use of cement is responsible for 10 % of the global anthropogenic CO_2 emissions [1]. This is aggravated by the sizing of conventional structures being based on the most critical expected loads or load combinations that rarely or even never occur. Therefore, today's conventional structures are typically oversized for most of their lifetime.

By using actuators, sensors and control units, the structure can adapt to external loads and reduce stresses and deformations. This means that adaptive structures enable less oversizing and therefore provide an opportunity to realise structures with less material. [2]

The sub-project "Integrated fluidic actuators" of the Collaborative Research Centre 1244 deals with the actuation of beams and slabs. Actuation concepts and suitable actuators are researched and developed specially for structural elements subjected to bending loads. In [3], the complete compensation of the deflection of a beam subjected to bending load could be proven numerically and experimentally. This will increase the load-bearing capacity, which can lead to material savings. In continuation, multiaxial spanning slabs, e.g. floor slabs in buildings, are now focus of the investigation.

2 STATE OF RESEARCH

2.1 Adaptive structures

Research on adaptive structures ranges from the adaption of the physical characteristics of the facades to the adaptation of structures and structural elements. An interdisciplinary research group at the University of Stuttgart has been conducting research since 2017 on both areas within the Collaborative Research Centre 1244 "Adaptive Skins and Structures for the Built Environment of Tomorrow". [4]

Actuation can be external or internal at the structural level. An example of external actuation is the “Stuttgarter Träger”, which is an adaptive beam [5] or the Smart Shell [6]. Here, the actuation forces are generated at the supports. Internal actuation has been implemented, for example, in the adaptive truss with electromagnetic linear actuators [7] or the Demonstrator Building D1244 with hydraulic linear actuators [8]. Here, the forces are generated and introduced within the structure. An example of actuation of beam elements under bending load with externally guided cable systems and hydraulic actuators is presented in [9]. An adjustable pretension can be applied to the beam. However, actuation takes place for the entire beam. One thing the examples named have in common is that the actuators used are standardised linear actuators available directly on the market. In most of the use cases, the possible stroke of the actuators is greater than required.

In order to manipulate a beam locally, actuators can be integrated directly into the cross-section of a beam. The advantage of integration is the ability to respond optimally to a wide range of load cases [10]. This approach is presented in [11]. Specifically developed fluid actuators are inserted into the concrete beam eccentrically to the neutral fibre. If a force is now generated, the eccentricity creates a moment that counteracts the externally imposed bending moment. This reduces the deflection. The functional principle has been proven both numerically and experimentally [3, 12].

2.2 Actuators

Actuators generate forces or strokes by using energy. Different operating principles exist using electromagnetic, pneumatic, hydraulic and piezoelectric effects, for example. An overview with different actuator types and their respective advantages and disadvantages is presented in [11]. A classification of actuators with their respective stroke lengths and actuating forces is given in [13]. This allows an initial selection of suitable types. In [11] it is stated that hydraulic actuator principles seem to be the most suitable for this field of application when taking requirements for integrated actuators into account. An actuator consists of the three main components, as shown in Figure 1, based on [13, 14]. The energy supplier provides a controlled non-mechanical energy, which is converted into a mechanical energy by the energy converter [14]. The energy conductor transfers it to the surrounding system [14]. In particular, the targeted introduction of forces into the concrete is decisive for the feasibility of different actuation concepts. Therefore, the energy conductor is primarily considered for the following investigation.

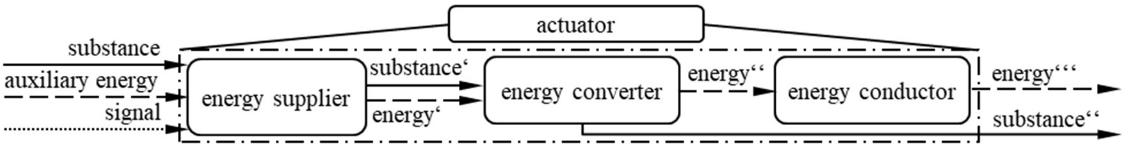


Figure 1: Functional components of an actuator, based on [13, 14]

3 SLAB ACTUATION

Actuation is particularly efficient if the generated internal forces or displacements inside the structure are exactly opposite to those from external loads. Slabs are loaded primarily out of plane, meaning that loads are mainly carried by means of bending. In principle, various approaches for actuation are conceivable to generate bending in a slab, which corresponds approximately to the opposite of the bending from external loads. The main differences are whether the actuating forces are introduced as moment, parallel or normal to the forces from external loads. Thereby the actuator can be located outside or inside the structure.

The new approach is to integrate fluidic actuators into the cross-section of the slab. By means of the eccentric position to the neutral plane, different actuation forces can be generated than with purely internal actuation as used, for example, in [7, 8]. With this concept, the applied forces are short-circuited locally and therefore quickly dissipate; see Table 1. This makes it possible to react precisely to a large number of load cases and thus variable moment curves. Actuating forces can be introduced very precisely where they are needed.

With two-way slabs, a multi-axial load transfer can be assumed. Therefore, moments in x, y and xy direction have to be considered. Consequently, an actuator should also be able to manipulate moments in several spatial directions. Usually, non-prestressed two-way slabs span a distance of 4 – 8 m [15]. Depending on the use case, live loads of around 5 kN/m² are to be assumed [16], meaning that moments from external loads of 12 kNm/m along both spatial directions must be considered in this rough estimate. These moments must be strategically superimposed by the active moments. Depending on the design of the actuation concept, actuators may also have to be able to generate somewhat higher moments, e.g. to ensure the superposition in areas where no actuators have been placed. The actual forces to be considered when designing the actuators must be determined in the course of designing the actuation concept for the specific case. Figure 2 shows an example of an actuation principle for a slab. The forces are introduced above the neutral plane so an actuation moment is generated.

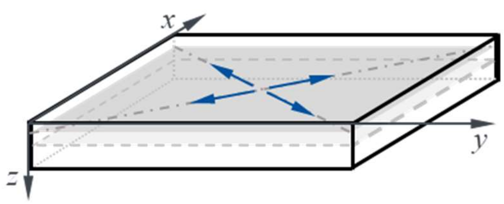


Figure 2: Example of an actuation principle for a slab; blue shows the induced forces

Here, a new field of research is opened both in terms of the structure to be actuated and the actuator to be developed. In particular, multiaxiality needs new approaches, as it is not yet clear how this can be actuated in a targeted way. The challenge is that the actuation concept and the actuator concept influence each other. Therefore, a way must be found to address both topics as separately as possible. In doing so, the mutual influences can also be determined and evaluated.

The outer shape of the actuator is defined as the interface between the actuation and actuator concept. Outside, and so part of the actuation concept, is the place of force utilisation in the structural element. Inside is the place of force generation by the actuator. The force transfer within the actuator is thus part of the actuator concept. A broad variation can be generated at this point. This is shown in the following by means of example concepts and a way is described to generate and evaluate a suitable multi-axial actuator concept in a preliminary study in order to obtain concrete specifications for further development.

4 ACTUATORS FOR MUTLI-AXIAL LOADED STRUCTURES

The optimal design of an integrated fluidic actuator for multi-axial loaded structures can only be found in combination with an optimal actuation concept. If the only known fact is that forces have to be introduced at specific locations, a wide field of possible actuator concepts is opened up. These concepts must meet different requirements. The multi-axial load transfer of the slab and the intended actuation concept result in the need for actuation of at least two spatial directions. In addition, the actuators must have a service lifetime corresponding to that of buildings or, alternatively, maintenance must be possible. This is an argument for robust and simple actuators with few sealing points and few moving parts which experience abrasion. Furthermore, structural integration must be as easy to implement as possible so that it can be carried out directly on a construction site. Restrictions imposed by the structural element also result from the material parameters, such as the compressive strength.

One challenge resulting from this is to find the optimal base geometry for the energy conductor. Therefore, a method for finding the optimal concept is developed. One approach is to change specific parameters of the actuator energy conductor concepts in an organised way and create overview tables including key facts and characteristic values. The concept for the energy conductor depends on the chosen energy converter. To further classify the actuator concepts, three concept classes can be set up. This is described in the following.

4.1 Classification of concepts

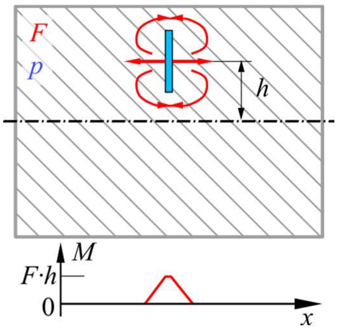
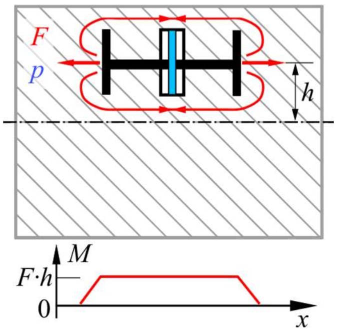
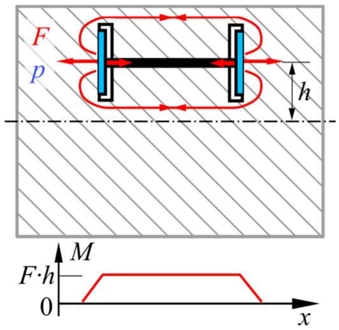
As stated before, the integration of actuators in the cross-section of a structural element leads to quickly dissipating forces around the force-applying surfaces. To increase the effective range, the distance between the force-applying surfaces of force and counterforce can be increased. In order to implement this, a force-conducting structure between the surfaces is necessary. The location of force generation (energy converter) can be considered centrally located in the actuator structure or distributed over the whole structure. Through these considerations, three concept classes (CC) of integrated actuators for multi axial load cases can be defined as seen in Table 1. The authors will speak of:

- central, locally acting actuator concepts (CC1), if the force-applying surfaces are directly next to each other and coincide with the energy converter,

- central, semi-locally acting actuator concepts (CC2), if energy is converted centrally and the force is directed to different points, e.g. the boundaries, of the actuator structure,
- decentral, semi-locally acting actuator concepts (CC3), if the energy conversion is decentral and the actuator structure is supported internally.

The classification is given in Table 1 with schematic examples. Below the schematic, a moment distribution along the structural element is shown. The moment M is calculated by multiplying the force F by the pressure p with the lever arm h, which describes the distance to the neutral fibre in case of a beam or neutral plane in case of a slab.

Table 1: Classification of actuator concepts, black parts energy conductor, blue parts energy converter

central		decentral
local	semi-local	
CC 1	CC 2	CC 3
		

The concept classes each have advantages and disadvantages. The concept class CC1 is of limited effective range. This would lead to a high number of actuators, which does not seem practical for realisation. The concept class CC2 does not seem promising in terms of construction space. In particular, the concept class CC3 (decentral, semi-local) is considered promising, which is why the procedure is mainly presented below for examples of this concept. These concepts offer the possibility of converting energy over a large area, a planar force application and a reduced need for leverage structures, which would increase the component dimensions and the number of parts required. The actuator itself must only have defined contact points to the structural element, which means that an enclosure or a separation medium must be provided around an energy conductor structure apart from the force application points. It is necessary to take this into account for the design of a CC2 and CC3 concept. Therefore, the simplest possible energy conductor structure is preferred.

4.2 Systematic generation of concepts

A multi-axial load case in a structure can be achieved in different ways. One possibility is to combine two actuators acting independently of each other in different directions. Interactions only occur through the connected surrounding of the actuated structural element. If only one actuator is to be used, the energy conductor can be designed to achieve multi-axis capability. Concepts based on this usually belong to the previously mentioned CC2. Alternatively, the number of energy converters can be increased to transmit the force in a concentrated or separated manner. The energy converters are connected to each other via the energy conductor.

Otherwise, this solution would be identical to the simple combination of individual actuators. Through the design of the energy conductor, the dependence between the actuation of the different spatial directions can be selected to be stronger or weaker. To ensure a lightweight design, it appears to be appropriate to subject energy conducting structures to dual use and thus to actuate two spatial directions with as little material and energy input as possible. In this way, supporting effects between the spatial directions can also be used effectively, which would otherwise have to be avoided for the targeted introduction of forces. By varying rigid and hinged parts, such as joints, the coupling of different spatial directions can be specifically achieved or avoided, thus adapting to different load situations when needed. If the length or angle of connecting elements is varied, the force distribution in the structure can also be influenced. Concepts based on this assumption can be either CC2 or CC3, depending on the placement of the energy converter.

In order to generate different concepts for the energy conductor in a structured manner, a basic concept for the energy converter has to be chosen first. The energy conductor depends strongly on this determination. Here, the choice is made for the concept with the smallest travel but also the highest expected robustness and freedom in defining the pressurised surfaces: a simple membrane concept which converts fluidic energy to mechanical energy by means of deformation. The second constraint to be defined is the class of target concepts. Based on the discussion in chapter 4.1, CC3 is chosen.

An illustrative geometry of an actuator concept is given in Figure 3. Even varying the small number of basic features shown here results in a large number of different concepts for the following investigation. More features as transverse contraction of materials or a higher number of tension or pressure rods could be added. Some combinations are contradictory, e.g. the use of a middle structure in combination with levers, and therefore not considered. For the lever concepts, the angle α is a relevant parameter for the arrangement. The concepts generated in this way are to be considered as single-axial concepts, two-axial concepts or as somewhat in between based on the combination of the arrangement. The maximum number of spatial directions is limited to two directions, which are orthogonal to each other to reduce complexity as a first step. A biaxial concept is also required for the most part in terms of the actuation concept. For different spatial directions this procedure can be set up as well.

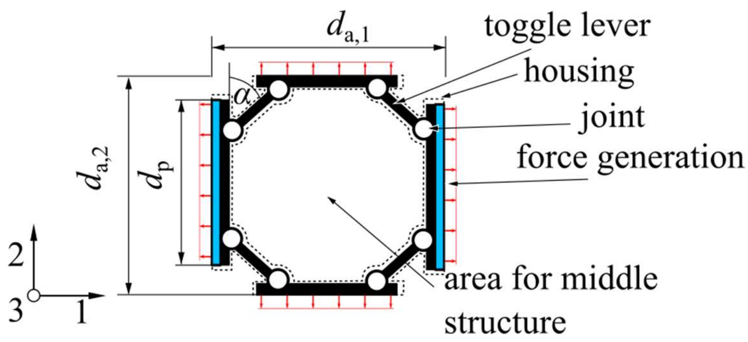


Figure 3: Exemplary geometry with toggle lever; red arrows show the outgoing forces, the energy converter is coloured blue, a white dot represents a hinged joint, the black parts are connecting rods.

The concepts are systematically created by varying the features shown in Figure 4, leading to a large number of different concepts.

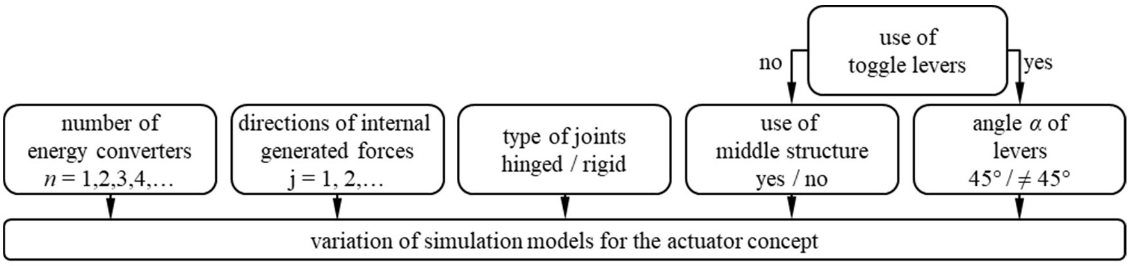


Figure 4: Variation of features for the energy conductor

Based on this, the following quantities are created to describe the concepts. The ratio of the number of directions of the generated forces in the energy converter j to the number of resulting force directions of the actuator is defined by the multi-axiality factor C_m. This factor makes it possible to determine whether the concept can be used directly in several directions and allows an initial statement as to whether the axes can be controlled independently of each other.

$$C_\mathrm{m} = \frac{\text{Number of internal generated force directions } j}{\text{Number of directions of force transmission to the structure element}} \tag{1}$$

The force transmission index R_i describes for each direction $i = 1,2,3$ the ratio of the number of internally pressurised surfaces $R_{i,\mathrm{in}}$ to the number of force-dissipating surfaces $R_{i,\mathrm{out}}$. This factor allows a rough estimate of the basic shape of the concept and the force flow without knowing the chosen geometry. Based on the parameters R_i, the internal force factor R_s is calculated based on the difference of the sums of the force directions $R_{i,\mathrm{in}}$ and $R_{i,\mathrm{out}}$. It enables a statement to be made about how efficiently the forces introduced are also transferred to the structural element and do not just cause a short circuit within the actuator. This factor will be investigated further in a numerical study.

$$R_\mathrm{s} = \sum R_{i,\mathrm{in}} - \sum R_{i,\mathrm{out}} \tag{2}$$

With the number of flexible parts n_F, a qualitative assessment can be made about the risk of failure considering abrasion according to the requirements named above.

The internal load factor L_i indicates the expected relevant internal load conduction. Tractive or compressive force is preferred. Both these load cases lead to an easy-to-calculate deformation of the structure and a simple load transfer within the structure. Bending moments lead to uncertainties in load transfer behaviour.

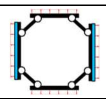
The surface ratio factor A_S describes the relation between the converter surface A_in to the external surface of the actuator A_outer.

$$A_\mathrm{S} = \frac{\text{Energy converter surface}}{\text{Outer surface of the actuator}} = \frac{\sum A_\mathrm{in}}{\sum A_\mathrm{outer}} = \frac{n \cdot d_\mathrm{p}}{2 \cdot d_{\mathrm{a},1} + 2 \cdot d_{\mathrm{a},2}} \tag{3}$$

The geometrical parameters $d_{\mathrm{a},1}$, $d_{\mathrm{a},2}$ and d_p are shown in Figure 3. Choosing a concept with a smaller surface ratio factor A_S leads to a higher energy density needed for the energy converter or to an additional lever concept in the structure if the output forces per spatial direction are considered constant. If the entire surface of the actuator is used, qualitatively lower forces are necessary to be generated by the energy converter.

As an example, the description of the concepts with these features is given by the concept shown in Figure 3. Table 2 shows the result.

Table 2: Result table with one exemplary concept

		C_M	R	R_s	n_f	L_i	A_S
1		1/2	R_1 4/2 R_2 0/2 R_3 0/0	0	4	compression	1/2

The number of energy converters n is 2. The internal forces are generated only in direction 1. Forces are transmitted into the structure in direction 1 and 2 ($C_m = 1/2$). The toggle levers are hinged at an angle α of 45°. This leads to the following characterisation: Two surfaces per energy converter are pressurised resulting in four pressurised surfaces in direction 1 and force is generated but just derived on two surfaces in this direction ($R_1 = 4/2$). In direction 2, no surface is pressurised internally but two surfaces introduce forces to the structural element ($R_2 = 0/2$). In direction 3, no force is applied or derived.

Only the toggle levers are flexible. That means, the flexible parts factor n_f is four. The surface ratio A_S factor is approximately 1/2.

5 NUMERICAL INVESTIGATION

The geometric investigation is complemented by a finite element method (FEM)-based numerical study. Here, the expected behaviour as well as the effectiveness of the concepts with each other will be presented.

5.1 Geometric model and mesh

Since this is a preliminary study for the exact design of the actuators, simplified actuator models are used here. The influence of the actuation on the concrete structure is neglected, as only actuator concepts are investigated. The concrete surrounding of the actuator is modelled as a contact surface only to a limited extent in order to be able to define a contact, but at the same time to eliminate the deformation influence in the height direction of the concrete. The influence on the concrete structure due to the actuation is not part of this parameter study. This puts the focus on the forces that can be derived out of the actuator into the structural element. The concrete in between the structure is neglected.

Furthermore, since some effects, such as deformations, are strongly dependent on material parameters and diameters, a uniform choice is made for the models here as well. The quantities x are normalised by the outer dimension of the actuator d_a, compare equation (4).

$$x^* = \frac{x}{d_\mathrm{a}} \tag{4}$$

All models used in the following investigation are modelled with the given outer edge length of 400 mm. The other geometric values are chosen according to the normalised values given in Table 3. In Figure 5 an exemplary geometric model with boundary conditions is shown.

Table 3: Parameters of the geometric models

	Symbol	Value	Unit
Actuator outer edge length	d_a	400	mm
Normalised actuator outer edge length	d_a^*	1	-
Normalised pressure chamber back wall thickness	a^*	0.05	-
Normalised pressure chamber cover thickness	s^*	0.0025	-
Normalised pressure chamber height	h_p^*	0.1	-
Normalised pressure chamber width	d_p^*	0.85	-
Normalised pressure chamber depth	a_p^*	0.0125	-
Normalised dimension of force conduction structures	b^*	0.05	-

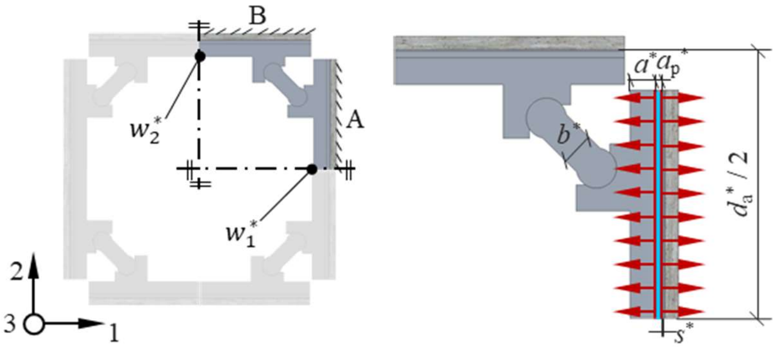


Figure 5: Exemplary geometric model; red arrows define the force introduced

As a material, steel is chosen with following parameters: Young's modulus of 206,000 MPa, Poisson's ratio of 0.3 and density of 7,850 kg/m^3. The material behaviour is assumed to be linear-elastic. The deformation of the structure is necessary for the comparison of the concepts. A uniform force per force introduction surface is assumed as input parameter. The force applied is based on the values given in chapter 3, which leads to a force of 170 N/mm when considering a lever of about 70 mm. In modelling this is applied as pressure. A fine mesh with a minimum mesh size of 1 mm consisting mostly of Hex20 and some Tet10 elements is used for meshing. In total, the number of elements reaches around 70,000. This is sufficient for the chosen investigations and geometry allowing fast and simple meshing of a wide variety of geometries.

5.2 Evaluation variables

For evaluation, the resulting pressure at the force application surfaces is averaged and multiplied by the force application surface. This allows the force transferred into the structural element to be determined. To evaluate the dependence of the spatial directions, a quotient is formed between the forces transferred per spatial direction in the normal direction. The force normal to the contact area A or B is $F_{\mathrm{A\,n}}$ or $F_{\mathrm{B\,n}}$, respectively.

$$q = \frac{F_{\mathrm{A\,n}}}{F_{\mathrm{B\,n}}} \begin{cases} < 1\text{: spatial direction 2 actuated more strongly than 1, low multiaxiality} \\ = 1\text{: spatial direction 2 actuated as strongly as 1, high multiaxiality} \\ > 1\text{: spatial direction 1 actuated more strongly than 2, low multiaxiality} \end{cases} \quad (5)$$

A normalised displacement is defined as a further criterion. This is evaluated per spatial direction (w_1, w_2) as well as globally (w_t). For the CC3 concepts w^* is calculated as follows:

$$w^* = w \cdot \frac{E \cdot I}{\sum F_{\mathrm{in}} \cdot \left(\frac{d_{\mathrm{a}}}{2}\right)^3} \tag{6}$$

Young's Modulus is designated E, I is the moment of inertia, F_{in} is the sum of generated forces, d_{a} is the outer diameter of the actuator. The equation is based on the deformation of a beam. This assumption is related to the choice of energy converter. Once again, it becomes clear that the energy converter and the energy conductor cannot be considered completely separate from each other. Normalisation is mainly necessary if statements about deformation are required for a scaled design of the energy conductor. Most of the time, it is sufficient to consider one of the three displacement values, as the actuator parts are kinematically coupled. The first two locations are the centres of the outer structure in the normal direction, compare figure 5. The global maximum displacement is determined as a third value. The values enable a statement to be made about the expected weight of the actuator with a known maximum stroke of the energy converter in relation to the other concepts. If the actuator is scaled up or down, the maximum possible stroke defined by the energy converter does not change significantly. The maximum stroke is nearly the same as the permissible maximum absolute displacement value. Considering the outer actuator dimensions, the permissible relative displacement can be calculated. The absolute displacement could be reduced by using more material.

5.3 Results

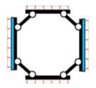
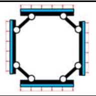
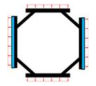
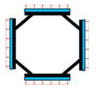
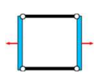
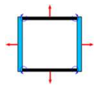
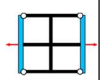
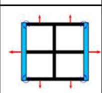
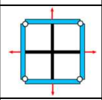
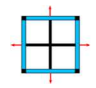
The results of the geometric analysis as well as the numerical investigation are presented in Table 4. The effectiveness of the multi-axiality of the concepts can be determined in particular by the characteristic value q. For concepts in which forces are only applied in one spatial direction in the actuator, this indicates the extent to which the second spatial direction is activated, considering equation (5). In that case a value close to 1.0 is promising.

In particular, concepts 1, 3 and 6 show a high multi-axiality q with only one force direction applied, while concepts 5, 7 and 8 show only a low multi-axiality effect. Thus, they are not very effective for a multi-axial actuation task. For concepts 2, 4, 9 and 10, the characteristic value q has no major relevance. Since forces are directly converted in two spatial directions, the characteristic value can only result in a value of 1.

More interesting for these concepts is the characteristic value of displacement w^*. In concept 10, the values are lower than in concepts 9, 4 and 2. This means that a lower displacement of the structure can be achieved here with less material input in the construction of the final actuator design. Therefore, a lighter actuator can be expected. For this case, the effectiveness is to be rated higher. In a direct comparison of concepts 1 and 2, lower displacement can be seen in the case of force generation in two spatial directions. The forces support each other within the structure, which reduces the overall displacement.

If the aim is to achieve a low displacement, concept 2 is to be preferred over concept 1, since its effectiveness is thus greater. The choice also depends on the outer dimension of the actuated area of one actuator. If it is smaller, larger relative displacement can be accepted, because the stroke of the energy converter does not change much. The absolute displacement should not change. The right concept can only be chosen in combination with the actuation concept.

Table 4: Results of the geometric and numerical investigation for exemplary concepts

		Geometric pre-investigation						Numerical investigation	
		C_M	R	R_s	n_f	L_i	A_S	q	w^* in 10^{-4}
1		1/2	R_1 4/2 R_2 0/2 R_3 0/0	0	4	pressure	1/2	1	w_1^* 1.04 w_2^* 0.007 w_t^* 6.35
2		2/2	R_1 4/2 R_2 4/2 R_3 0/0	4	4	pressure	1/1	1	w_1^* 0.188 w_2^* 0.188 w_t^* 2.74
3		1/2	R_1 4/2 R_2 0/<2 R_3 0/0	< 1	0	bending	1/2	1.4	w_1^* 2.06 w_2^* 0.018 w_t^* 2.06
4		2/2	R_1 4/2 R_2 4/2 R_3 0/0	4	0	pressure bending	1/1	1	w_1^* 0.496 w_2^* 0.498 w_t^* 1.38
5		1/1	R_1 4/2 R_2 0/0 R_3 0/0	2	2	pressure	1/2	5	w_1^* 27.77 w_2^* 0.856 w_t^* 27.77
6		1/2	R_1 4/2 R_2 0/< 2 R_3 0/0	< 1	0	bending	1/2	1.3	w_1^* 10.58 w_2^* 0.037 w_t^* 10.58
7		1/1	R_1 4/2 R_2 0/0 R_3 0/0	2	2	pressure	1/2	10	w_1^* 0.635 w_2^* 0.0014 w_t^* 2.42
8		1/2	R_1 4/2 R_2 0/< 1 R_3 0/0	< 2	0	pressure bending	1/2	7.6	w_1^* 0.606 w_2^* 0.0006 w_t^* 2.12
9		2/2	R_1 4/2 R_2 4/2 R_3 0/0	4	2	pressure	1/1	1	w_1^* 0.309 w_2^* 0.309 w_t^* 1.18
10		2/2	R_1 4/2 R_2 4/2 R_3 0/0	4	0	pressure bending	1/1	1	w_1^* 0.291 w_2^* 0.291 w_t^* 0.971

7 CONCLUSION

The procedure presented is a possible approach to find actuator concepts for an integrated actuator consisting of energy conductor and energy converter without the precise knowledge of the actuation concept in a wide field of possible solutions. First, an energy converter concept is defined. Afterwards, different concepts for the energy conductor are derived and compared by geometrical and numerical investigations. By defining more specific requirements of the actuation concept, it should be simpler to choose the optimal actuator concepts. The procedure needs to be optimised further for generating the best possible combination of actuation and actuator concept for slabs.

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