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A CASE STUDY ON TAILORING STIFFNESS FOR THE DESIGN OF ADAPTIVE RIB-STIFFENED SLABS

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Abstract. Floor and ceiling slabs are commonly used in construction and therefore provide a great potential to save material. In this paper, an adaptive ribbed ceiling is presented. The focus is on the design of the active prestressing. In addition, different design strategies of adaptive structures are compared with respect to their mass saving potential and the necessary actuation effort.

1 INTRODUCTION

The growing world population, climate-damaging emissions and increasing scarcity of resources pose major challenges for the construction industry. Solutions are being sought to build with less material and thus reduce emissions. The Collaborative Research Center 1244 "Adaptive Skins and Structures for the Built Environment of Tomorrow" at the University of Stuttgart is investigating these problems in a multidisciplinary team since 2017. The main focus is on realizing savings in material and emissions with the help of adaptive structures [1]. Adaptive structures are equipped with active elements, so they can react active to external influences and change its response. Depending on the goal of the adaptation, the stresses in a component can be homogenized, or deformation limits can be respected, even though "not enough" material has been used according to conventional standards. This can be achieved, for example, by strategically change the geometry or stiffness of the structure. Therefore, new challenges arise for structural engineers, such as the consideration of actuator failures or completely different design strategies for adaptive structures. A practical implementation has already taken place within the framework of CRC 1244. The world's first adaptive high-rise building, called D1244, was realized on the campus of the University of Stuttgart [2].

The idea of designing adaptive structures to control static deformations and forces can be found in [3]. The authors of [4] deals with the active control of external influences, such as adaptation of vibrations. Vibration control is also a topic in [5], but the author does not limit

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himself to this. Rather, he presents a comprehensive overview of the application and design principles in various engineering disciplines. Active Civil Structures are examined in detail in [6]. Design strategies are introduced, showing the mass saving potential of adaptive structures compared to conventional structures. An extensive literature review is given in [7] and [8].

With regard to the design of adaptive structures, a rethinking has to take place. Adaptivity must be included in the design process at the earliest possible stage, as shown in [9], [10] and [11]. A holistic optimization approach that includes actuation from the beginning is superior to a strategy that fits actuation to a passively optimized structure. This has been investigated in [12], [13] and [14].

In [15], the authors deal with design strategies for adaptive structures. The underlying idea is to make a structure as stiff as possible against external loads and as flexible as possible against the effect of actuation. This rationale was applied and tested on analytical and numerical examples.

The work presented in this paper is closely related to the findings discussed in [15]. The numerical example, an adaptive ribbed slab, is taken further. The stresses are now integrated into the optimization process, and in this context it is investigated how different design strategies for adaptive structures behave. The expected actuation effort for a given mass saving is analyzed. In addition, the focus is on a more realistic modeling of the actuation. For bridge-type structures, external active prestressing has shown great potential in terms of mass savings ([16], [17]). However, the idea of bridges with an external adaptive tensioning (EAT) system, which can be interpreted as an adaptive underslung, is investigated in [18]. In contrast, an internal adaptive prestressing with compound is modeled in this paper.

2 Numerical Investigation

2.1 Problem Setup

Figure 1 shows the geometry of a ribbed slab. It is supported on all four sides. This is a square slab of side length $L = 10m$ with a system of main and secondary ribs. The stiffer main ribs divide the slab into four subsections, which are supported by the smaller secondary ribs. The height of the secondary ribs is defined as h. The height H of the main ribs is calculated from Δh and h. Like indicated in Figure 2. All ribs have a width of $d_{\text{rib}} = 0.05$ m. As already mentioned in section 1, the goal is to minimize the actuation effort, i.e., it is necessary to tailor the stiffness of the structure to the actuation type and the given load cases. Therefore, h, Δh and the slab thickness d are part of the following optimization problems as design variables.
The position of the actuation is shown in figure 2. In practice, this can be realized as an active prestressing. A conventional prestressing is a steel cable that is loaded with a certain force and then embedded in concrete. If displacements of a ribbed slab under its dead weight are to be influenced by the prestressing, it is necessary that the cable is located in the tension zone of the ribs and is prestressed with a compressive force [19]. Conventional prestressing is normally not reversible, the active prestressing implemented in this paper is only be used if required. For example, if deformation limits are exceeded, the proper force can be applied via the steel cable. In practice, such an actuation could be applied by fluid actuators, as developed in [20]

As can be seen in Figure 1 only the less stiff secondary ribs are actuated. (As a note for Figure 1, only the active ribs for the governing load case are marked in red). Figure 2 shows the location of the steel cable embedded in the secondary ribs. This is located at a constant

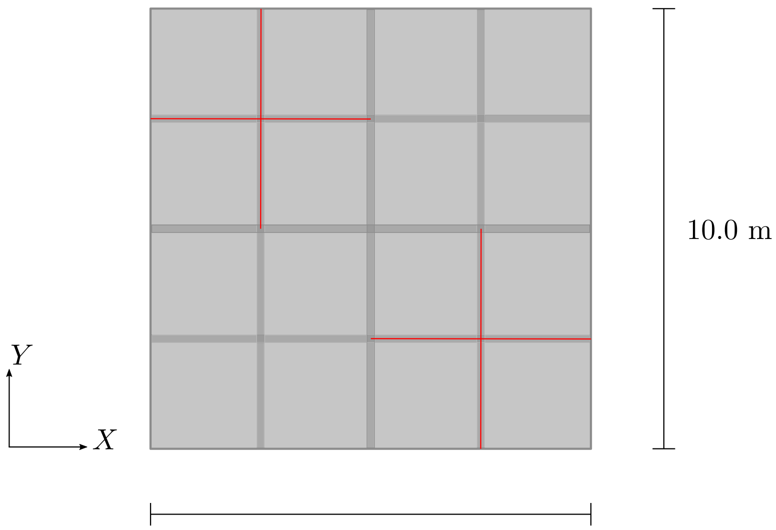

Figure 1: Ribbed slab, plan view

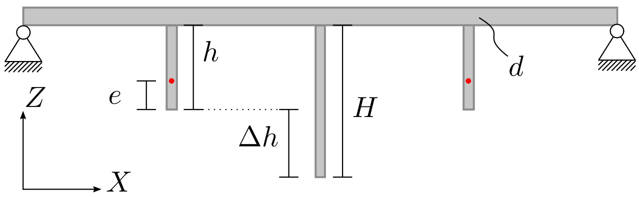

Figure 2: Ribbed slab, cross-sectional data

eccentricity of $e = 0.05$ m from the bottom of the ribs.

The active prestressing is modeled by linear elastic springs. The cable has the same element size as the ribs. So they are continuously coupled to the connected shell elements. Therefore, compound between the cable and the rib is considered. The stiffness K of a linear spring is defined by

$$K = \frac{EA}{l}. \tag{1}$$

As we assume that the cables are anchored at the end of each secondary ribs and at the intersection of the secondary ribs, the cable length is $l = 2.5$ m. The use of a cable with a diameter of $d_{\text{cable}} = 0.02$ m and the young's modulus of steel $E_{\text{S}} = 2.1 \cdot 10^5$ N/mm^2 given in Figure 2 results in a stiffness $K_{\text{cable}} = 26376 \cdot 10^3$ N/m. If we apply a force F_{act} to the spring elements, we can counteract the effect of the external load and keep the displacement and stress limits.

Two load cases considered. A distributed load on the entire slab is called load case 1 (Figure 3). For load case 2 just quarters are loaded, as indicated in Figure 4. The loading for load case 2 is higher, and these checkerboard-type load cases are often the crucial ones. The strategy is only to passively maintain the stress limits $\hat{\sigma} = 3.0 \cdot 10^7 \frac{N}{m^2}$ in both load cases. The first principal

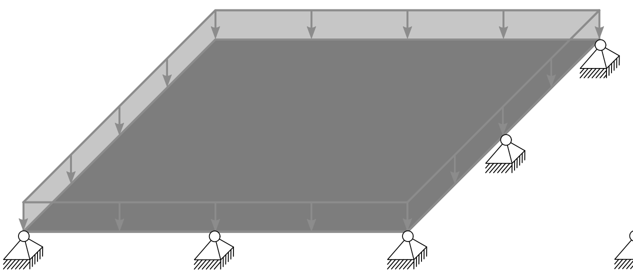

Figure 3: Load case 1

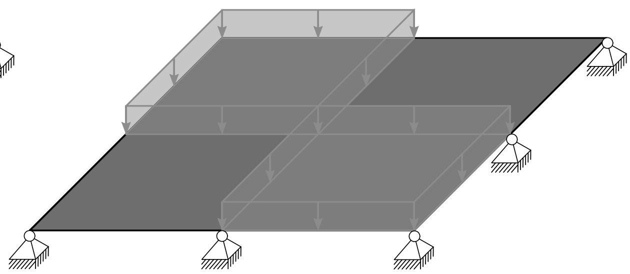

Figure 4: Load case 2

stress has to comply with these limits. Exceeding them would have serious consequences, such as material failure or permanent damage. If an actuator failure occurs, the structure is no longer stable. The displacements are actively controlled and are kept within a limit of $\hat{w} = 0.02$ m by the adaptive prestressing.

2.2 Numerical formulations

The python package *PyAnsys*, which enables a connection between *Python* and the commercial finite element software *Ansys*, is used for the following optimization problems. A 1-D element *LINK11* is employed for the linear spring. Mass and damping are neglected. For the ribs and the slab, shell elements *SHELL181* are used. *SHELL181* is a four-node element based on Reissner-Mindlin shell theory. The constrained optimization problems described below have been solved using sequential least squares programming. In the following optimization problems, the design variables are the geometry parameters d, h, Δh and the actuation force F_{act}.

As a benchmark, a configuration of the ribbed slab is first calculated which complies with the stresses and displacement limits of both load cases completely passively. σ_{q1} and w_{q1} are the largest values for the stress and displacement, which occur on the slab for load case 1. The same yields for σ_{q2} and w_{q2} for load case 2. The passive configuration is obtained through volume minimization. Therefore, the objective function is the volume of the entire ribbed slab structure. The formulation of this optimization problem is:

Objective function:	$V(h, \Delta h, d) = dL^2 + 2LHd_{\text{rib}} + 4Lhd_{\text{rib}}$
Design variables:	h, Δh, d
Constraints:	$w_{\text{q1}} \leq \hat{w}$ and $w_{\text{q2}} \leq \hat{w}$
	$\sigma_{\text{q1}} \leq \hat{\sigma}$ and $\sigma_{\text{q2}} \leq \hat{\sigma}$
	$0.1 \text{ m} \leq \begin{Bmatrix} h \\ \Delta h \end{Bmatrix} \leq 1.0 \text{ m}$
	$0.01 \text{ m} \leq d \leq 0.1 \text{ m}$

The optimization process yields the following solution:

Slab thickness:	$d = 0.02357$ m
Height of secondary ribs:	$h = 0.27868$ m
Height difference to main ribs:	$\Delta h = 0.39491$ m
Overall volume V:	$V = 3.85\ \text{m}^3$

Two different design strategies are now compared. On the one hand, the approach that the displacement w_{q2} in load case 2 (this is crucial due to the much higher load) is minimized and then the remaining displacement above the limit is handled with the actuation. We certainly exceed displacement limits (or stress limits) because we set the volume $V = 3.2\ \text{m}^3$ as a constraint.

For this strategy, which minimizes the largest displacement and compensate actively the difference to satisfy the displacement limit, is reformulated as

Objective function: w_{q2}
Design variables: h, Δh, d
Constraints:
$$V = 3.2\ \text{m}^3$$
$$w_{\text{q1}} \leq \hat{w}$$
$$\sigma_{\text{q1}} \leq \hat{\sigma}$$
$$\sigma_{\text{q2}} \leq \hat{\sigma}$$
$$0.1\ \text{m} \leq \begin{Bmatrix} h \\ \Delta h \end{Bmatrix} \leq 1.0\ \text{m}$$
$$0.01\ \text{m} \leq d \leq 0.1\ \text{m}$$

The obtained solution is:

Slab thickness:	$d = 0.02106$ m
Height of secondary ribs:	$h = 0.24718$ m
Height difference to main ribs:	$\Delta h = 0.35257$ m

As expected, the deflection limit of 0.02 m is violated. The objective function w_{q2} results to 0.028 m. Satisfying the deflection limit under load case 2 requires an active prestressing force $F_{\text{act}} = 357.9$ kN.

As a second approach, a holistic optimization strategy is introduced. In this approach, the actuation force is directly minimized. The corresponding optimization problem results in:

Objective function: F_{act}
Design variables: h, Δh, d, F_{act}
Constraints:
$$V = 3.2\ \text{m}^3$$
$$w_{\text{q1}} \leq \hat{w} \text{ and } w_{\text{q2}} \leq \hat{w}$$
$$\sigma_{\text{lq1}} \leq \hat{\sigma} \text{ and } \sigma_{\text{q2}} \leq \hat{\sigma}$$
$$0.1\ \text{m} \leq \begin{Bmatrix} h \\ \Delta h \end{Bmatrix} \leq 1.0\ \text{m}$$
$$0.01\ \text{m} \leq d \leq 0.1\ \text{m}$$

And the Solution yields to:

Slab thickness	$d = 0.02184$ m
Height of secondary ribs:	$h = 0.21251$ m
Height difference to main ribs:	$\Delta h = 0.37869$ m
Actuation force	$F_{\text{act}} = 207.9$ kN

It can be seen that the holistic optimization approach requires less actuation effort than the other strategy. F_{act} is only about half as large, although the configurations differ only slightly. There is also a little more material in the main ribs, which was also seen for the pure displacement controlled strategy in [15].

3 CONCLUSIONS

In this paper, a ribbed slab with an adaptive prestressing is modeled. With this adaptive ribbed slab, different optimization strategies for adaptive structures were calculated, and we found that the findings from [15] could be verified. Even if stresses are taken into account, a holistic optimization approach is superior to the idea of passively optimizing a structure and then actuating it.

Another very interesting observation is that for strategy 1 the stress boundary condition is completely satisfied. The displacement limit is slightly overfulfilled with $w_{\max} = 0.018$ m.

For strategy 2, the maximum displacement is $w_{\max} = 0.02$ m and thus becomes active as a boundary condition. The maximum stress is $\sigma_{\max} = 1.6 \cdot 10^7 \frac{N}{m^2}$ and does not become governing.

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