Reliable design of adaptive load-bearing structures with focus on sustainability

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Nowadays large amounts of raw materials are used in the building industry. Conventional design methods for passive constructions are at the limit of what's permissible according to standard and oversized for most of their design life. In order to reduce the consumption of raw material and the environmental impact caused by its production, an actuation of the load-bearing structure is a possible way forward. Such a structure is able to adapt to different load cases by specifically manipulating internal stresses using actuators installed in the structure. This paper introduces a design procedure applied to an adaptive high-rise load-bearing structure demonstrating reliability and includes the changing environmental impact. The trade-off between oversizing, which leads to high reliability and savings of raw material for minimal environmental impact needs to be solved for unique structures with quantity one. By use of a linear-elastic model the effect of wind loads is simulated and actuator forces and tensions were calculated. In the total balance the energy consumption of the actuators and its related greenhouse gas emissions as well as the intended savings due to the reduced need for raw materials in production is included. In conclusion, replacing building material with energy can be a promising way forward on the condition, that electric energy will become increasingly environmentally friendly in the near future, whereas natural resources for materials are limited.

Keywords: Adaptation, Load-Bearing Structure, Ultra-Lightweight Structure, Reliability Analysis, Life Cycle Assessment, Environmental Sustainability.

1. Introduction

In fact, the world's population is growing (UN 2019-1) and living space becomes rare due to urbanization (UN 2019-2). The consumption of construction material is highly increasing (OECD 2015) which will lead to a depletion of natural resources. In addition, the building and construction sector account for 39% of the global greenhouse gas emissions (UN 2017).

One Problem is, that conventional structural design practice usually involves that the strength and the deformation capacity of the structure meets the worst load case. Predominantly, such structures are loaded much lower than the design load assumed, meaning they are oversized for most of their operation life. Reducing construction material is merely possible if the structure is capable to adapt to different load-cases. Based on this ability, these structures are called adaptive structures. Several studies already exist on this subject, mainly by Teuffel (Teuffel2004) and Senatore (Senatore2013), among others.

Overall, adaptive structures can be described as load-bearing structures which are able to manipulate the distribution of their internal forces or influence external applied loads by changing form or shape for example. The adaptation can be in an active way, which needs auxiliary energy or simply passive (Connor2003, Sobek2014).

Previous research at the "Stuttgart SmartShell" proves that for an adaptive shell structure a reduction of the peak fiber stresses is achievable. Furthermore, counteracting vibrations in the system is possible (Weickgenannt2013). Beyond that, Senatore showed, that great material savings are attainable, comparing a passive and an active cantilever under static load (Senatore2013).

To carry out further investigation the German Research Foundation funded the Collaborative Research Centre 1244 (CRC 1244) „Adaptive Skins and Structures for the Built Environment of Tomorrow" (Sobek2016-1) where this research contributes by demonstrating reliability and sustainability. The aim is to meet the demand for living space while preventing the depletion of natural resources.

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Fig. 1. Adaptive High-rise Load-Bearing Structure with Access Tower to be built at the University of Stuttgart. Source: ILEK/IMA

1.1 *Background*

The concept of adaptive ultra-lightweight high-rise load-bearing structures involves replacing mass, this means construction material, with electricity in order to adapt the stiffness of the load-bearing structure to various static and dynamic loads (Sobek2014). The condition is that electricity is available to a large extent in the near future and the continual switch to renewable energy sources leads to a reduction of CO2-emissions per kWh (Gwinner2013).

In order to meet the addressed rising urban migration and the resulting higher population density, a high-rise is considered in the following investigations. Moreover, the mass saving potential is higher compared to e. g. detached houses, due to arising stiffness and vibration issues.

The high-rise, to be built at the University of Stuttgart as pictured in figure 1, will have an adaptive load-bearing structure and will be used as demonstrator building. Over its total height of 36.5 m there are 12 floors, which will be accessible through an access tower built next to the demonstrator. The access tower also ensures an appropriate power and hydraulic fluid supply for the hydraulic actuators adapting the steel structure to external loads.

1.2 *Previous Work and Methodology*

Civil Engineering in Europe uses the Eurocode standard (EN 1990) for the design of load-bearing structures. The standard defines ultimate limit states (ULS) and serviceability limit states (SLS) governed by regional loads and partial safety factors. This leads to a reliable and safe design because of conservative safety factors and load assumptions. For a high-rise mainly, the admissible deflection and fatigue strength is decisive and determines the thickness of the structure.

During product design in mechanical engineering, usually a reliability demonstration is done. Normally this estimate is carried out on the basis of tests or prior knowledge (Bertsche 2008). If the actual end of life occurs considerably earlier than the requirement, the product is highly oversized. In civil engineering, the number of high-rises to be designed and build usually is one. Extensive testing is not possible, so the structures were oversized.

A reliable and safe design has since been ensured by a probability of failure, described by the probability that action effect exceeds resistance of the structure, less than a permissible value. So far, safety and reliability have therefore been a subject of a safe-life design. Saving construction material presupposes a design with more precise location-based load profiles and a more detailed analysis of load cycles than considering only the ULS and SLS. The material savings lead to a slender structure, more sensitive to external loads. Furthermore, the standard design process does not consider the active elements when it comes to adaptive structures.

Several active and passive actuation principles summarized by Connor (Connor2003) exist. The actuation of the load-bearing structure offers the advantage of minimizing deflection, damping vibrations and compensating static loads.

A design method for adaptive structures, including both, the structure and the actuators, was developed by Senatore in (Senatore2018, Senatore2019). By minimizing the embodied energy of the structure, adjusting the actuator layout and the activation threshold and then redirecting the load path, the adaptive structure is optimized, considering the actuation and material energy.

In contrast to the previous work, dynamic loads with higher frequency, such as turbulence from wind loads, must be considered when designing high-rise structures under environmental loads. The mass inertia and the control delay are not negligible. A static or low frequent load can be counterbalanced more easily by the actuators and control, which overestimates the effect of actuation. In addition, the consideration of reliability is necessary if the structure slenderizes. Moreover, an evaluation of environmental impacts needs to contain all aspects of the adaptive structures' life cycle. A necessary actuator replacement, whether due to cycle aging or environmental influences, is to be expected in a typical lifetime.

To consider these dependent parameters, an alternative approach is proposed in the following investigations. The study is demonstrated under the aspect of saving raw material and reducing the Global Warming Potential (GWP). Failures in the adaptation process can occur, which is why a safety and failure analysis is mandatory, publicized by Sobek and the author in (Sobek2016-2, Ostertag2019) and qualitatively discussed in the present paper.

2. Problem Formulation

With adaptive load-bearing structures it is possible to actively counteract vibrations and to specifically stiffen the structure. This can be used for damping vibrations or redistributing loads, to activate less stressed areas or to ensure reliability at all. In the present case reliability describes the functionality of the load-bearing structure under given loads, with regard to stiffness, strength or fatigue strength, which is ensured by the use of actuators, for a desired lifetime (Bertsche2008). For high-rise load-bearing structures, mass savings usually lead to greater deflections, which results in a stiffness or structural fatigue problem (Mufti 2002).

2.1 *Reliability, Safety and Sustainability*

The qualitative correlation of conventional and adaptive load-bearing structures regarding reliability and sustainability is shown in figure 2. Sustainability is here considered as environmental impact for material, manufacturing and electricity for adaptation, compared to the environmental impact of conventional passive structures, related to the structure's lifetime. The qualitative graph shows the reliability of the structure on the vertical axis above the utilization on the horizontal axis. For a conventional structure the reliability is high for a low utilization and decreases with increasing utilization of the structure.

In practice there is a minimum reliability ensuring a certain lifetime and functionality. For safety reason the design of conventional structures, symbolized by the point "Today's Design", aims for a higher reliability, the target reliability. On the point "Today's Design", the distance between minimum and target reliability represents the design safety. To the left, the design safety is increasing with reliability, whereas it is decreasing to the right, as highlighted by the colored area below the reliability curve. Taking the point "Today's Design" as reference, oversizing to the left would increase reliability and also the safety margin. Reducing the reliability to the right, leads to a sustainable design using less construction material, but the safety margin is not sufficient anymore.

Paralleled to the passive structure's reliability curve, the second curve describes the reliability of an exemplary adaptive load-bearing structure. The adaptation installed in the structure improves the reliability by supporting the structure. A reliability growth is achieved described by the vertical arrow, pointing to the point "R+". The new point "R+" is here considered unsustainable, as additional raw material for actuators and electricity for actuation is needed to provide the adaptation.

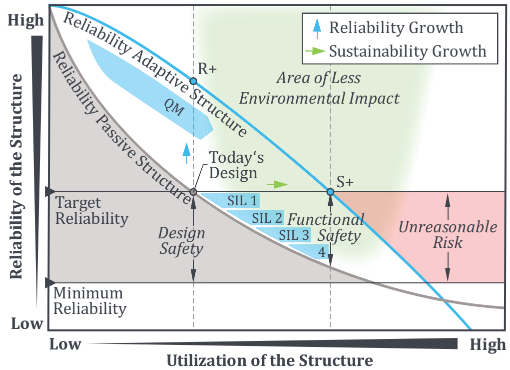

Fig. 2. Correlation between Reliability, Safety and Sustainability for Passive and Adaptive Structures

Depending on the type of structure, a significantly lifetime extension might in turn compensate the need for more material and electricity and can be promising for a lifetime extension of e.g. bridges with a small number of actuators, mainly loaded unidirectional.

Setting the same boundary conditions and aiming for a comparable target reliability as of "Today's Design", the horizontal green arrow describes the growth of environmental sustainability, leading to the point "S+" for an exemplary adaptive load-bearing structure. In this point there is only a minimal design safety left, highlighted by the colored area below the passive structure's reliability curve. Considering the distance between minimum reliability and target reliability as the safety margin where a reduction is not acceptable, a safe design has to be ensured otherwise. The more tasks, ensuring stability, damping and stiffening were transferred to the adaptation with decreasing design safety, the more safety-relevant the functioning becomes. This means, the less safety from a safe design, the more safety related the adaptation function. Under the consideration of functional safety standards as EN 61508 (EN 61508), the maximum risk reduction for safety assurance is exploited with safety integrity level 4 (SIL). An unacceptable residual risk would remain if safety is further reduced. In general, also for less safety relevant adaptive structures quality measures (QM) were recommended.

As shown, the structure's reliability depends on the dimensioning and degree of adaptation, affecting each other and in turn sustainability and safety, which is why an iterative design method is proposed. The design method described in the following considers structural reliability and sustainability in the design of load-bearing structures. Further steps include a reliability analysis of the components needed for adaptation and a functional safety analysis, both beyond the focus of this paper.

3. Design Approach and Modelling

Activating the structure, one question that arises is the influence of the actuators on the building's deflection and dynamic behavior. The deflection correlates with component cross-sections and therefore the mass of the building. Thinner cross-sections can be actuated more easily, but the less mass, the more actuators are needed for damping and stiffening, as their maximum forces are limited. In addition, the placing of the actuators in the load-bearing structure is important, because their impact on deflection and their energy consumption varies. To investigate these effects, a design method using a simulation model and a load spectrum including dynamic loading, caused by e.g. wind loads, is introduced below.

3.1 *Iterative Design Approach*

Within the context described, an iterative design approach for adaptive load-bearing structures is proposed. The procedure starts from an architectural design with a given topology and material as pictured in figure 3. To investigate the effect of external applied loads on the load-bearing structure, a linear-elastic model with a linear-quadratic regulator (LQR), described in (Wagner 2019a) was modelled using MATLAB. On the basis of the second order differential equation of motion (1) with vector $q(t)\epsilon\mathbb{R}^n$ for degrees of freedom, a manipulation of the system is done by actuator forces $u(t)\epsilon\mathbb{R}^m$.

$$\bar{M}\ddot{q}(t) + \bar{D}\dot{q}(t) + \bar{K}q(t) = \bar{F}u(t) \qquad (1)$$

The initial conditions are set to $q(0) = q_0$ and $\dot{q}(0) = q_1$. The Rayleigh damping matrix $\bar{D}\epsilon\mathbb{R}^{n\times n}$ is assumed to be of the form

$$\bar{D} = \alpha_1\bar{M} + \alpha_2\bar{K} \qquad (2)$$

with coefficients α_1 and α_2 determined from literature. In the modal analysis the mass matrix $\bar{M}\epsilon\mathbb{R}^{n\times n}$ and the stiffness matrix $\bar{K}\epsilon\mathbb{R}^{n\times n}$ are determined by a finite element analysis of the structure. In the subsequent step potential actuator elements were chosen, considering boundary conditions as controllability, wind direction and symmetrical actuation, which limits the number of possibilities drastically. In case of wind loads, the wind direction is difficult to determine, which requires the possibility to counteract wind loads from any direction.

For the following disturbance simulation, a dynamic, site-specific wind load spectrum is simulated, acting unidirectional on the façade of the demonstrator. The result is constrained by strength, stiffness, fatigue and buckling according to the preset design limits. Based on the wind load simulation the lifetime estimation and the calculation of the expected energy consumption is done, whether an actuation is needed or not.

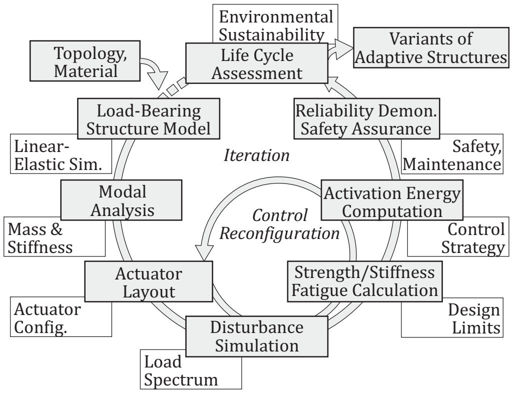

Fig. 3. Design Approach for Adaptive Load-Bearing Structures under Dynamic Loading

The energy consumption is calculated out of the simulation as operational power W_s with the force applied by the actuators $u(t)$ and the stroke $\Delta s(t)$ over time t and every actuator k. Energy gained by the actuators return stroke is conservatively neglected by summarizing only $W_k(t) > 0$.

$$W = \frac{1}{\eta_t} \cdot \sum_{k=1}^{n_{act}} \left(\sum_{t=0}^{T_s} \big(u_k(t) \cdot \Delta s_k(t)\big) > 0 \right) \qquad (3)$$

A total efficiency of $\eta_t = 0{,}85$ is assumed to be sufficient including energy conversion, pressure loss in the pipelines and valves and pump efficiency. The total yearly operational energy consumption per load profile p is calculated using a site-specific distribution with a related frequency of occurrence O over simulation time T_s per year in kWh.

$$W_{tot,p} = W_s \cdot O_p \cdot \frac{365 \cdot 24}{T_s \cdot 10^3} \quad [kWh] \qquad (4)$$

Stand-by energy is neglected and depends on the application. For example, pressure reservoirs can compensate the starting time of the hydraulic pump.

In the next step a reliability demonstration follows, to determine the maintenance interval of the adaptation system, here simplified by a fixed actuator exchange interval of 20 years. Likewise, the safety assurance needs to be done. If the actuation principal is for example serial, several investigations for pressure loss and slacken of the corresponding element or maximum and minimum stroke of the actuator need to be considered in a sufficient safety analysis.

Out of the use of raw material and energy the environmental impact is determined in a life cycle assessment (LCA). Several variants were simulated varying in the number of actuators, their placement and material consumption, which were compared afterwards.

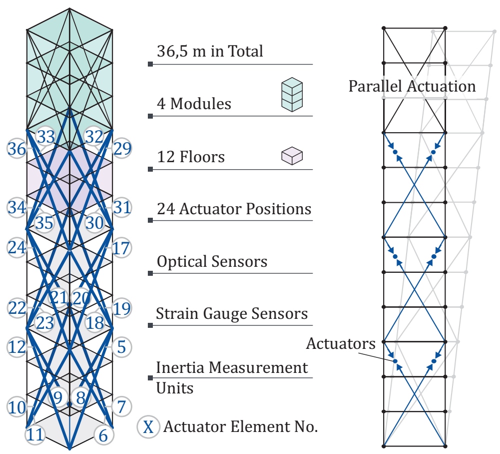

Fig. 4. Adaptive Load-Bearing Structure of the Large-Scale High-Rise Demonstrator (Weidner2018)

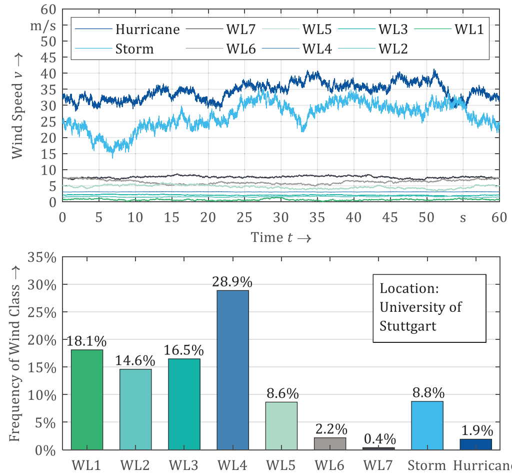

Fig. 5. Wind Speed and Frequency of Occurrence (LUBW2019)

3.2 *Demonstrator Layout and Loading*

The introduced high-rise demonstrator building serves as application example for the proposed design method. It consists of four modular constructions. Each module reinforced with eight bracings, two crossing on every side. The resulting structure is pictured in figure 4.

The actuation principal is a parallel actuation for the hydraulic actuators installed in the bracings. Several sensors measuring tension and deflection to enable a control to actively counteract deflections caused by wind loads. Also, a torsional deformation can be counterbalanced by placing and activating actuators in the bracings diagonally opposite. The highlighted elements are potential positions for the placement of the actuators in the load-bearing structure, providing space for a total number of 24. A light façade with 100 kg/m² is assumed. Moreover, storey and roof loads were considered.

The deflection of high-rise structures is limited due to tolerances and user comfort. According to the Eurocode standard (EN1990) the maximum permissible deflection has to be specified by those responsible. In this study a deflection of 40 mm is assumed. Larger deflections are considered as failure. For demonstrating reliability, a location-based representative wind load spectrum, shown in figure 5 was set up. The wind speed profiles were generated according to a mean wind speed belonging to the related wind class and a variance parameter. The wind profiles last 60 s, which is assumed to be a representative time period for the disturbance simulation. The wind force acting on the adaptive structure is modeled as dynamic pressure and stationary wind velocity as function of the height z, air density ρ and reference height z_0, described in [Gienger2018].

On the basis of the wind class frequencies WL1-WL7 with the additional classes storm and hurricane and their related wind profiles reliability is demonstrated. The structural fatigue is determined by an analysis of the most critical notch types using rainflow counting of the load cycles. For the presented load-bearing structure the considered critical notch types according to Eurocode are listed in Table 1.

Table 1. Critical Notch Types (EN1993)

	Screw Connect.	Flange Connect.	Cross Joint
Notch Type $\Delta\sigma_c$	50 N/mm²	71 N/mm²	71 N/mm²
Load Cycles N_c	$2 \cdot 10^6$	$2 \cdot 10^6$	$2 \cdot 10^6$
Location	Vertical Supports	Vertical Supports	Vertical Bracings

For the examination of the SLS including the permissible deflection of 40 mm the maximum wind load, in this case a hurricane with mean wind speed of 34.5 m/s, is used. As a conservative estimation, the wind direction is kept constant for the simulation. Nevertheless, since the wind direction can change, an actuator placement independent of the wind direction is used. Initial investigations showed, that an asymmetric placing of the actuators to the wind load is counterproductive as activating results in additional torsional deformations and induces load cycles negative for reliability. In the following, the results of the previously described procedure were shown.

4. Simulation Results

Starting from the dimensioning according to Eurocode standard, the load-bearing structures cross-sections were reduced. The maximum deflection under wind loads was the decisive criteria within the present investigations. By varying the cross-sections for mass reduction and the number and placing of the actuators, multiple simulations have been performed. What can be stated is, that configurations with more equally distributed actuators require less energy, although more actuators were installed.

In the following four variants with different material savings and number of actuators were exemplarily chosen as shown in Table 2.

Table 2. Properties of the investigated variants.

Variants	Stan-dard	LW	Active 8	Active 24
Mass [t]	38,3	28,0	21,1	19,6
Mass Saving	0%	28,8%	44,8%	48,9%
Actuators	0	0	8	24
Energy [kWh/a]	0	0	319	230
Hydraulic Fluid [l]	0	0	500	1500
Deflection Max. [mm]	31	40	40	40

The first and second variant are passive variants and represent the consideration of the design according to standard and as light-weight (LW) structure. Variants three and four represent active ultra-lightweight adaptive structures, once with eight and once with 24 actuators. The actuator placing for the active variants was done according to figure 4, where only the lowest module was completely equipped for “Active-8” and all available actuator elements were used for the configuration “Active-24”. As wind direction can change randomly only fully symmetrical configurations were chosen to counteract loads of any direction and to avoid inducing load cycles by unbalanced actuation.

The passive structure following the standard includes all partial safety factors according to Eurocode. The wind load specifications of the Eurocode standard are generalised for larger territories and therefore result in different load assumptions for the site. However, the requirement was to endure a deflection of 40 mm with fatigue strength. Material savings with an actual maximum deflection of 40 mm was the optimization criteria for the remaining variants. For the calculated mass of all variants, an additional 10 % was added. This includes connection details such as bolts and joints.

The structural material savings are exhausted with 48,9 % with a maximum number of 24 actuators in the configuration “Active-24”. In this dimensioning the wind load “storm” also needs to be actuated, to stay below the prescribed deflection of 40 mm. The variant “Active 8” only needs actuation energy for wind load “Hurricane”, as the structure is still able to bear the load.

The variants described are being examined for their environmental impacts. The standardized method of LCA (EN15978) is used to calculate the environmental impacts. The aim of the LCA is to quantify the environmental impacts along the entire life cycle of products, buildings, services and processes. The software “GaBi” (sphera2019), including a parameter database was used for the calculation of the LCA. The environmental impacts are represented by greenhouse gas emissions in the form of the impact category Global Warming Potential (GWP) in kg CO_2-equivalent. The reference area of the calculation is the described structure with a maximum deflection of 40 mm and a gross floor area of 2.551 m² (4,75 m x 4,75 m, 12 floors). The system boundary of the LCA comprises the production phase, actuation in the use phase and the end of life.

Based on the four variants the calculation in the LCA was done. Tall structures require forces which currently only hydraulic actuators can provide. Therefore, hydraulic fluid was considered. As maintenance interval for the actuators, a fixed service life with continual exchange every 20 years was assumed. Both shares were often neglected in the analyses, making adaptive structures appear much more beneficial. The material for all investigated variants is construction steel S355. The calculation of the GWP for electrical energy, needed for actuation, is based on the German electricity mix. The four variants are compared in figure 6.

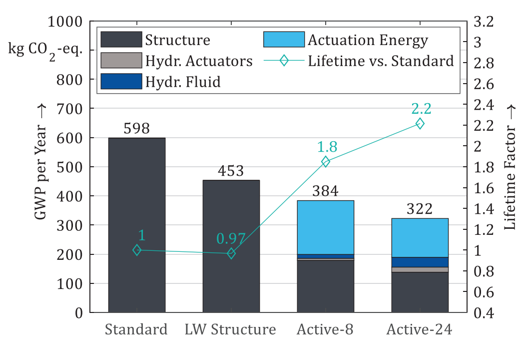

Fig. 6. Categorical GWP per year of Active and Passive Structures related to the lifetime

For the first two variants, the GWP of the load-bearing structure is represented by the single black bars. In addition to the GWP of construction steel, the two active adaptive load-bearing structures show the values for actuators, hydraulic oil and actuation energy. The difference between the standard and LW structure are the partial safety factors and different load assumptions in design, according to standard. Reliability of the variants, expressed by the lifetime factor is indicated on the right. It can be stated that the lifetime of the passive LW structure compared to the passive standard structure diminishes slightly, because of the material savings. On the contrary, the active configurations extend the lifetime, even though only wind load "Hurricane" is actuated in the presented case.

The bars show the GWP per year which in this case is referred to the resulting service life, expressed by the lifetime factor. Due to the extension of service life, the structural share for the active variants is reduced drastically. The share for operational electricity accrues annually and is independent of it. Comparing the two active variants, the increased use of actuators rises the GWP for actuators and hydraulic fluid, but the service life extension partly relativizes this. The difference in service life between the two active variants is caused by a more balanced actuation and further cross-section reduction, which facilitates the influence of the actuators on the structure and diminishes total weight. It can be seen, that the adaptive structure with 24 hydraulic actuators has the lowest GWP. When compared to the passive variants, the savings are in the range of 131 – 276 kg CO_2-eq. per year, which equals about 46% at best. Under the assumption that electricity will increasingly include renewable energies in the future, the share of GWP for actuation energy will become even smaller. This will also slightly affect the GWP for construction steel. On the basis of this diagram the actuation of structures is reasonable with certain limitations.

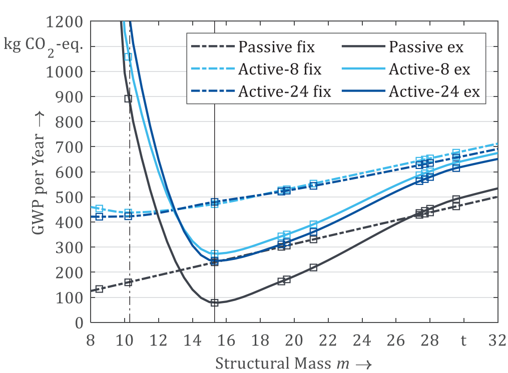

Fig. 7. Comparison of GWP for Design Points

Independent of a deflection limit figure 7 shows the progression of GWP along the structural mass. The graph shows the GWP of the "Passive", "Active-8" and "Active-24" configuration. The dashed line expresses the GWP related to a fixed service life of 50 years, whereas the continuous line relates to the extended service life. As proposed in different design methods, usually the optimal design point is the minimum, which results from embodied and operational energy, here at a mass of about 10,3 t. Regarding the curves for the extended service life, at some point the structures lifetime decreases rapidly, which is reflected in a strong increase in GWP for lower masses. The optimal design point considering structural reliability results here at about 15,2 t. Because of a longer service life, the GWP per year decreases further, compared to the fixed service life. For an extended service life, the actuator exchange is equivalently considered. With increasing mass, the structural weight governs and a shortened service life worsens the GWP. The gap between the passive and active curves is the expenditure for adaptation. Of course, the passive variant reaches deflection limits earlier.

5. Summary and Outlook

Activating the load-bearing structure of a building is a promising way to save construction material and diminish the GWP to reduce environmental impact. Limits are defined by the number of actuators installed in the structure and their maximum actuation force.

The introduced design method is capable to find the optimal actuator configuration and placing for a structure which is sufficient for specified boundary conditions regarding deflection, GWP and service life. For the present case, it has been shown, that the optimal solution depends on whether the service life is fixed or depleted, which improves environmental impact. Hydraulic fluid and actuation energy worsen the GWP with higher numbers of actuators, what is often neglected in the analyses. The consideration of random load directions, restricted actuation forces, limited installation space and design and structural reliability requirements are defining the borders of sustainable adaptive structures, which is why a simple correlation of operational energy and embodied energy is not sufficient and results in a different optimal design point. The proposed design method considers these factors in an iterative approach.

For the future, the underlying German electricity mix is expected to contain more and more renewable energy sources, which will result in further decrease of the GWP, mainly for electricity. To reduce the GWP, alternative actuators can cut the share for hydraulic fluid.

In this paper the focus was on structural lifetime of active and passive variants with a fixed service life for the hydraulic actuators. Parallel actuation comes with the advantage of fail-safe, as if the actuator is incorrectly powerless, a minimum stiffness of the element is still given. On the contrary, more energy for activating the structure is necessary. Further investigations therefore include safety issues and also reliability modelling of the components needed for adaptation, to determine service intervals and demonstrate overall reliability.

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