Systematic Approach to Reliability and Safety Assessment and Enhancement in Design and Operation of Safe Adaptive Load-Bearing Structures

Dshamil Efinger[a*], Martin Dazer[a]
[a]Institute of Machine Components, University of Stuttgart, Germany

Abstract: Adaptive systems can adjust to changing conditions. When this adaptability is associated with changes in shape, force or stress, the load-bearing structures can be made slimmer, can achieve longer service life and/or cause less CO2 emissions. However, adaptation functions can fail, and in the worst case, they may act contrary to the desired behavior. If safe adaptive structures are to be widely used, a systematic approach to reliability and safety assessment and optimization is required in the design and operation. To this aim, this paper systematically examines the relevant content and the creates generally applicable templates. Based on the findings, it presents a framework for a systematic approach to designing and operating these structures to ensure both reliability and safety. The world's first adaptive high-rise building D1244 serves as an application example.

Keywords: safe adaptive structures, framework for adaptive structures, adaptive load-bearing structures

1. INTRODUCTION

Adaptive systems are characterized by their ability to adjust their behavior in response to changes in the environment [1]. The concept of adaptive systems is used in various fields, including computer science, artificial intelligence and biology [2, 3]. Scientific research into the built world of tomorrow is also looking into it [4]. The findings clearly show improvements in environmental sustainability, increases in service life, material reductions and increases in comfort [5]. The adaptability of the systems also enables them to adapt to during construction unforeseen conditions [6]. Adaptive load-bearing structures are structures that are able to influence the forces generated by external and internal impacts as well as the resulting time-dependent and time-independent deformations in terms of adaptability [7]. A distinction can be made here between influencing the impact itself and influencing the reaction of the structure, whereby both forms of manipulation can also occur simultaneously. However, in addition to the desired effect of adaptation, the adaptation function can also fail. If the load-bearing structure is designed less robustly than a passive one, this might be critical. But in the worst case, adaptation can even take place contrary to the desired behavior. Meaning that the adaptive load-bearing structure damages itself. Consequently, reliability and robustness play a crucial role for safe adaptive load-bearing structures.

The adaptive system consists of actuators, sensors and much more. Each component is required to enable the adaptive system to adapt correctly. However, depending on the functional structure and the current adaptation requirement, a failure of individual components does not necessarily mean the failure of the adaptation function. The functional structure is therefore of great importance. This in turn can change depending on the adaptation requirement, which complicates the consideration in the reliability design. Furthermore, the consequences of a function failure of the adaptation function vary, ranging from no effect to failure of the entire load-bearing structure. Causes include the load combination that occurs, the degree to which the adaptation function takes over the function and the overall structure of the adaptive structure. Due to the diverse influences, the general validity of the handling represents a major challenge.

Nevertheless, if safe adaptive structures are to be widely used, a systematic approach to reliability and safety assessment during design and operation is required. Moreover, a guideline for dealing with unacceptable risks helps to ensure a simple application. This paper addresses both.

2. FUNCTION AND STRUCTURE OF ADAPTIVE SYSTEMS

According to VDI 2221, the definition of a product is:

„*material or immaterial commodity or service which is offered alone or as a system in order to satisfy the need of the market as well as the needs of users in a target-group-oriented way*“ [8].

Based on [8-10], a technical product can also be understood as a system consisting of elements. Technical systems are clearly defined by a system boundary and interact with the environment or other systems through inputs and outputs. Inputs and outputs cross the system boundary. They can be substances, energies and information.

Put simply, an adaptive system is a system with one output and two inputs. The output is the system's response to the input of the instance in combination with the input of the stimulus [11]. Such an abstract adaptive system is illustrated in Figure 1.

Figure 1. Abstract depiction of an adaptive system

When assessing the reliability and safety of a system, the question to be asked is what the purpose of the system is. Again, [8-10] are suitable for this purpose. The purpose of a technical system is to fulfill one or more functions. The same applies to every element and every group of elements in a technical system, as they could be interpreted as a technical system themselves across a system boundary. Functions describe a clear relationship between inputs and outputs. Generalized definitions of functions can be found in the literature. Krumhauer provides these general functions in [10]: *Convert*, *Link*, *Store*, *Route* and *Change*.

The solution-neutral problem formulation is used in product planning to describe the overall function of the system to be developed [10]. The overall function is a combination of main functions. The main functions are to be subdivided into sub-functions and these are to be linked to each other through corresponding material, energy and signal streams [10]. The function structure to be developed should only contain the functions necessary to fulfill the overall function(s) [12].

The central function of an adaptive system is to adjust its behavior in response to changes in the environment. A category of shape- or force-adaptive systems can be defined for the functional properties of a system such as an adaptive load-bearing structure.

For shape- or force-adaptive systems, the behavioral adaptation concerns the optical or geometric shape, the stress distribution or its dynamic behavior. The optical or geometric shape can be changed or maintained by manipulating the force streams despite changing conditions. Manipulating the force streams also allows the stress distribution to be influenced. In the dynamic case, the manipulation can be used to change the stiffness and damping behavior of the adaptive system.

To assess and optimize the reliability and safety of a system, both the associated main function itself and the function structure of the system must be addressed. The function structure of the product is developed as part of product planning and development based on VDI 2221 [8], VDI 2222 [13] and VDI 2223 [9]. Divided into the concept phase and the design phase, the following description provide an overview of the development of the function structure and the overall design. The example of a planetary gearbox is used to illustrate this, although in theory the named solution actually emerges during the process.

Concept Phase

In the concept phase, the process begins with the determination of the functions at system level, whereby the main functions of the system are identified. For the example, the transmission and distribution of torques as well as the change in rotational speed and direction of rotation between the input and output shafts. The main functions are then subdivided into sub-functions and these are linked with each other through material, energy and signal flows. This then forms the functional structure. For example, the torque transmission function can be broken down into the sub-functions “Power absorption by the sun gear”, “Power transmission to the planetary gears” and “Power output via the ring gear”. These sub-functions are linked by the mechanical connections and the distribution of forces and movements within the system. The next step is to determine possible solution principles for each of these sub-functions. This involves selecting physical or mechanical operating principles that contribute to the fulfillment of the sub-functions. For example, the power transmission could be realized via the toothing of the gears (effective geometry) and the relative movement of the gears (effective movement). These active principles are combined to form an active structure that describes the solution principle with which the main functions are to be fulfilled. These active structures can be represented by principle sketches or models, which together form one or more principle solution concepts and represent the logical architecture of the product. Finally, the solution concepts are evaluated on the basis of defined evaluation criteria such as efficiency, manufacturability and costs. Following this evaluation, the most suitable solution concept is selected, which may be further detailed and concretized before moving on to the next phase of product development.

Design Phase

In the design phase, the previously developed solution concepts are built upon in order to further concretize the structure of the product and divide it into feasible modules. The division into modules to be realized leads to the system architecture, which is also referred to as a modular structure. Examples of modules could be the sun gear, the planetary gears, the ring gear and the carrier frame. In the next step, the system architecture is further developed by dividing the functional and logical architecture developed in the concept phase into specific groups and elements that are required to implement the solution. The links between the modules are also defined by means of interfaces. This modular structure can be visualized by arrangement sketches or logic diagrams, which show the positioning and interaction of the individual modules within the overall system. Once the modular structure has been defined, the individual modules are designed in detail. This means that preliminary designs are created for each module, considering the specific technical details and requirements. For the planetary gearbox this could include the precise design of the gearing, the choice of material for the gears or the design of the planetary gear bearings. In the final step of this phase, the designed modules are integrated into the overall product. The modules are further detailed and linked together to create the overall design of the planetary gearbox. That overall design ensures that all modules work together to fulfill the desired functions of the gearbox. This could be represented by detailed technical drawings, parts lists and connection diagrams showing the complete integration of the product.

3. FUNCTIONAL FAILURE OF THE LOAD-BEARING FUNCTION OF SHAPE- OR FORCE-ADAPTIVE SYSTEMS

The systematic approach outlined in this section begins with a *function description* that identifies the central function of shape- or force-adaptive systems. Derived from this, the *consequences of a function failure* of this function are dealt with at system level. This is followed by an analysis of the *causes for a function failure*, which determines how a function failure arises for this function and how it can be prevented. Based on the knowledge of the causes of a function failure, the c*ombination of actual loads on the load-bearing structure* is then examined in more detail. To this end, existing possibilities are first determined separately and then systematically varied. The *causes of unexpectedly high actual loads on the load-bearing structure* can then be derived from these.
The procedure developed and the results are universally valid for all shape- or force-adaptive systems and can therefore be applied to any such system.

3.1. Function Description

According to Sobek [7], the exclusive function of the load-bearing structure in lightweight structural design is to transfer loads. In lightweight system construction, this main function is supplemented by additional functions, such as the space closure or insulation function.
Ostertag formulates in [14] "the function of protecting the occupants or the contents from adverse environmental conditions [...]" for the system of an adaptive high-rise structure, which also serves as an application example in this paper. He also defines the load-bearing capacity – and thus the transfer of loads – as the main function for the adaptive structure.
The "load-bearing capacity" or "load transfer" as the main function corresponds to the generally applicable "guiding" function from section 2. Regardless of what other functions a shape- or force-adaptive system may have, this function of "force transmission" represents an elementary basis for these systems. A function failure of this function must therefore be easy to assess in terms of consequences, causes and possible measures.

3.2. Consequences of Function Failure

If the main function, in other words the transfer of loads, fails at system level, the load-bearing structure collapses. In the case of the high-rise building, this means the building collapses. This is caused by a local failure in the transfer of forces, which is functionally relevant for the current load condition at system level. For this fundamental correlation, it is irrelevant what type of load is present or what type of load the design was based on. Such a condition may arise in one case solely due to the existing dead weight, or in another case it may not occur even under the most extreme loads. In any case, the only decisive factor is whether or not the function of load transfer at system level is fulfilled at all times.

3.3. Cause Analysis for Function Failure

Both globally and locally, external and internal forces, some of which change over time, constantly act on the load-bearing structure and its components. The actual load on the support structure is formed from these forces. If the load exceeds the load-bearing capacity, the local stress becomes too great, which leads to local failure. However, such a local failure does not necessarily result in a global function failure of the load-bearing function. A local function can be taken over permanently or temporarily by another element or load path. This corresponds to redundancy. However, the failed local function element can also be transformed into a different function, which is a fail-safe mechanism, for example. Furthermore, the local function, permanent or temporary, may not be essential for the global main function and essentially serve secondary functions. For the adaptive high-rise building, this could be the load-bearing function of a partition wall. A global failure only occurs if the failed local function is required globally, no alternative load path can transfer the load and there is no sufficient possibility for temporary transfer via the failed local load path.
Sources of external and internal force effects on the load-bearing structure and its components are the actions on the one hand and the manipulation by the actuators on the other.

3.4. Combinations of Actual Loads on the Load-Bearing Structure

The occurrence of the individual force effects can be divided into six cases for the actual load on the supporting structure. Viewed over time, these cases can alternate in any order, but a single case can also occur permanently. The cases can be related both globally to the entire load-bearing structure and locally to individual elements. Different cases of force effects can exist simultaneously for different elements. Table 1 provides an overview of the six cases. They are formed from the combinations of the respective table row listed in the columns for the *actions* and *manipulation by actuator*. Impacts may be present or not. Manipulation by the actuators can (partially) compensate for the impacts, not influence them or (partially) amplify them. In the special form of case 6, the manipulation by the actuators acts on the support structure or the element, although no impacts are present. Case 6 is particularly suitable for system identification and calibration. This is used by Prokosch et al. in [15] for instance. Apart from such a purpose, this case is to be classified as unintentional.
The lowest probability of failure of the load-bearing function is to be expected if Case 1 is present. However, in most cases it will not be possible to generate Case 1 globally and locally everywhere and to maintain it without interruption even with changing actions.
Case 5 is one of the worst conceivable scenarios, in which impacts are present and these are amplified by manipulation of the actuators. Globally, this case represents an undesired behavior of the adaptive system. Nevertheless, such a case may be intended locally if the aim is to generate Case 1 or Case 2 globally or for other local areas – for example as a protection function or safety function for individual elements of the supporting structure. However, it must then be ensured that particularly stressed areas can withstand the increased loads.
Case 4 is a milder form of Case 5, which is also globally undesirable.
Partial compensation (Case 2) or amplification (Case 4) can have various system-related, intended and unintended causes. Intended causes include the previously mentioned protective function or safety function, while system-related causes may include physical limits of the actuators (displacement, force, dynamics) or the actuator system (inertia of the control loop, actuating power, dynamics). Unintended causes include control deviations, signal errors and failures of components in the actuator system [16, 17].
If impacts are present but are not manipulated by the actuators, this results in Case 3, where the adaptive support structure acts as a passive structure. This may be intended if only low loads are present. However, with high impacts, this case is particularly conceivable if the actuators are not functional.

Table 1. Overview of combinations of actual load on the supporting structure

Case	Impacts	Manipulation by actuators
Case 1	Present	Compensates impacts
Case 2	Present	Compensates impacts partially
Case 3	Present	Does not compensate and does not amplify impacts
Case 4	Present	Amplifies impacts partially
Case 5	Present	Amplifies impacts
Case 6	Not present	Acts on supporting structure/element

3.5. Causes of Unexpectedly High Actual Load on the Load-Bearing Structure

For the objective of reliable and safe adaptive load-bearing structures, the question now arises as to what new causes there are for unexpectedly high actual loads on the load-bearing structure compared to passive systems so that these can be addressed. For this purpose, the six cases developed in the previous section for the actual load on the load-bearing structure are analyzed in more detail in terms of their causes.
No new influences can be identified on the impact side. As with conventional systems, unexpectedly high actual loads may be caused by unconsidered, incorrectly or incompletely represented impacts.
Manipulation by the actuators allows a generalization from the six cases. The desired state is considered first. This is "Actuators compensate globally and locally for all effects" (special form of Case 1).

In contrast, there are less desirable or undesirable states. They are formed from cases 2 to 6, when the actual state deviates from the target state. These are:

- Actuators do not fully compensate (Case 2),
- Actuators do not compensate (Case 3),
- Actuators overcompensate (Case 6),
- Actuators amplify impacts (Case 4+5).

These can be summarized as: "*Actuator does not work/works insufficiently/works incorrectly*".
This corresponds to inadequate adaptive behavior, which is examined in more detail in the next section.

3.6. Logic path to the failure of a shape- or force-adaptive systems

For ease of use, the logic path in Figure 2 provides an overview of the contents of the previous subsections. It starts with a global focus with the actual loads on the structure. If these are too generally greater than the load-bearing capacity, a global failure is inevitable. Otherwise, the loads can then be observed on a local focus, whereby a locally excessive load leads to a local failure. The consequences of a local failure depend on the function structure at a global level. This is described using a simple scenario with the example of the adaptive high-rise building from [18]. For this purpose, the four column supports are considered. If actions lead to a load that is greater than all four supports can withstand in total, the load exceeds the load capacity globally and a global failure and thus a collapse is inevitable. However, if the load is only greater than the load capacity for a single support, a failure occurs for the individual support on local level. If there is a global compensation option for the failing support, no global failure is caused – but if this cannot be compensated for, a global failure resulting in a collapse occurs.

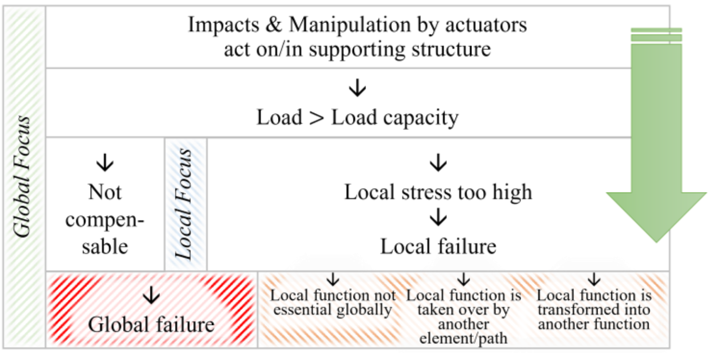

Figure 2. Logic path to the failure of a shape- or force-adaptive systems

4. CHARACTERISTICS AND CAUSES OF INADEQUATE ADAPTIVE BEHAVIOR

The previous section clarifies what an inadequate adaptive behavior means for the adaptive support structure and why such behavior should be prevented. It is now necessary to clarify how an inadequate adaptive behavior manifests itself. This is the characteristics of inadequate adaptive behavior. Based on this, the causes of such behavior must be determined to be able to derive corrective measures if necessary.
For this purpose, the Fault Tree Analysis (FTA) [19] is used based on the main malfunction "*actuator does not work/works insufficiently/works incorrectly*". This is flanked by a Failure Mode and Effects Analysis (FMEA). The FMEA is used to determine the causes and consequences of failure based on the malfunctions identified in the FTA, to assess the risk arising from a failure and to define optimizing measures.
While the first level of the fault tree can be created universally, the subsequent levels are very specific to the individual system. For this reason, the universally valid first level is dealt with first and then an example of a specific solution is described.

4.1. Generally Valid

The first level of the fault tree is completely independent of the exact system, actuator or control technology or mechanical solutions. This first level can be formed for exactly two different scenarios. One is force control, and the other is displacement control. They are presented separately in the next two subsections.

4.1.1. Force Control

For a force-controlled shape- or force-adaptive system, the first level of the fault tree is shown in Figure 3. Inappropriate adaptive behavior can occur purely in a static state (path 6), purely in a dynamic state (path 5) or in both a static and a dynamic state (all paths with the exception of path 5 and path 6).

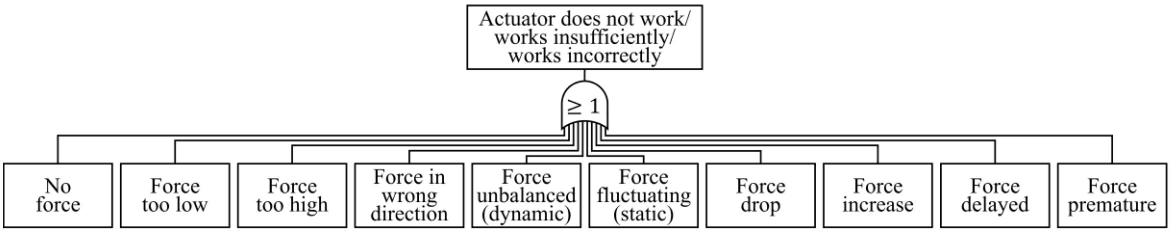

Figure 3. Fault tree with the universally valid first level for a force-controlled adaptive system

4.1.2. Displacement Control

For a displacement-controlled system, the states are slightly modified from those of force control. Cases without a desired and at the same time without an occurring displacement change (stress adaptation) cannot be represented in the control and in the fault tree. However, further distinctions are required elsewhere, which is why there are a total of eleven causes of malfunction on the first level in Figure 4.

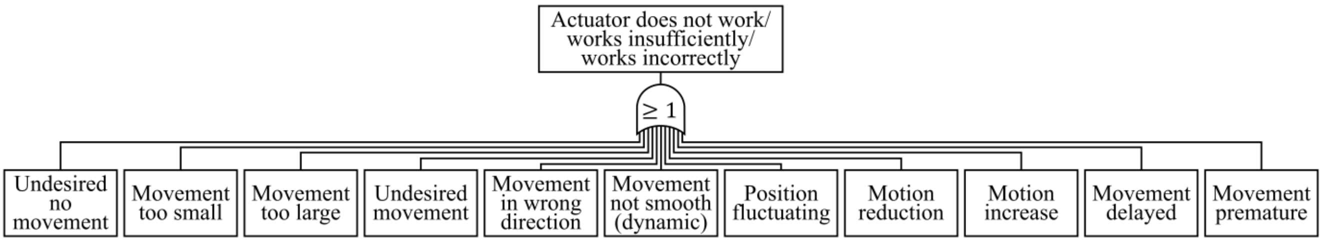

Figure 4. Fault tree with the universally valid first level for a displacement-controlled adaptive system

4.2. Solution-Specific

All levels after the first level are dependent on the exact system, actuator technology, control technology and/or mechanical solutions. They must therefore be supplemented on a case-specific basis to the first level of either

the force-controlled or displacement-controlled system. In addition, the application of an FMEA is suitable as a bottom-up supplement from the lowest level.
For the application example of an adaptive high-rise load-bearing structure system according to [20], Figure 5 provides the addition of the 2nd level to the fault tree. Further levels are omitted here for reasons of space. The application example uses hydraulic actuators, some of which are mechanically integrated into the structure in series and some in parallel. The actuators are controlled via proportional valves, and pressure reservoirs are installed near the cylinders to ensure constant and rapid pressure availability. Sensors can be used to monitor the pressures and flow rates of the hydraulic system, the dynamics of the load-bearing structure, expansions in measuring points on the load-bearing structure and the paths and forces of the actuators. The aim of the implemented fault tree structure is to automatically detect the causes of faults during operation via the sensor signals and to warn of possible consequences before they occur or, if necessary, to enable the control strategy to be adapted accordingly.

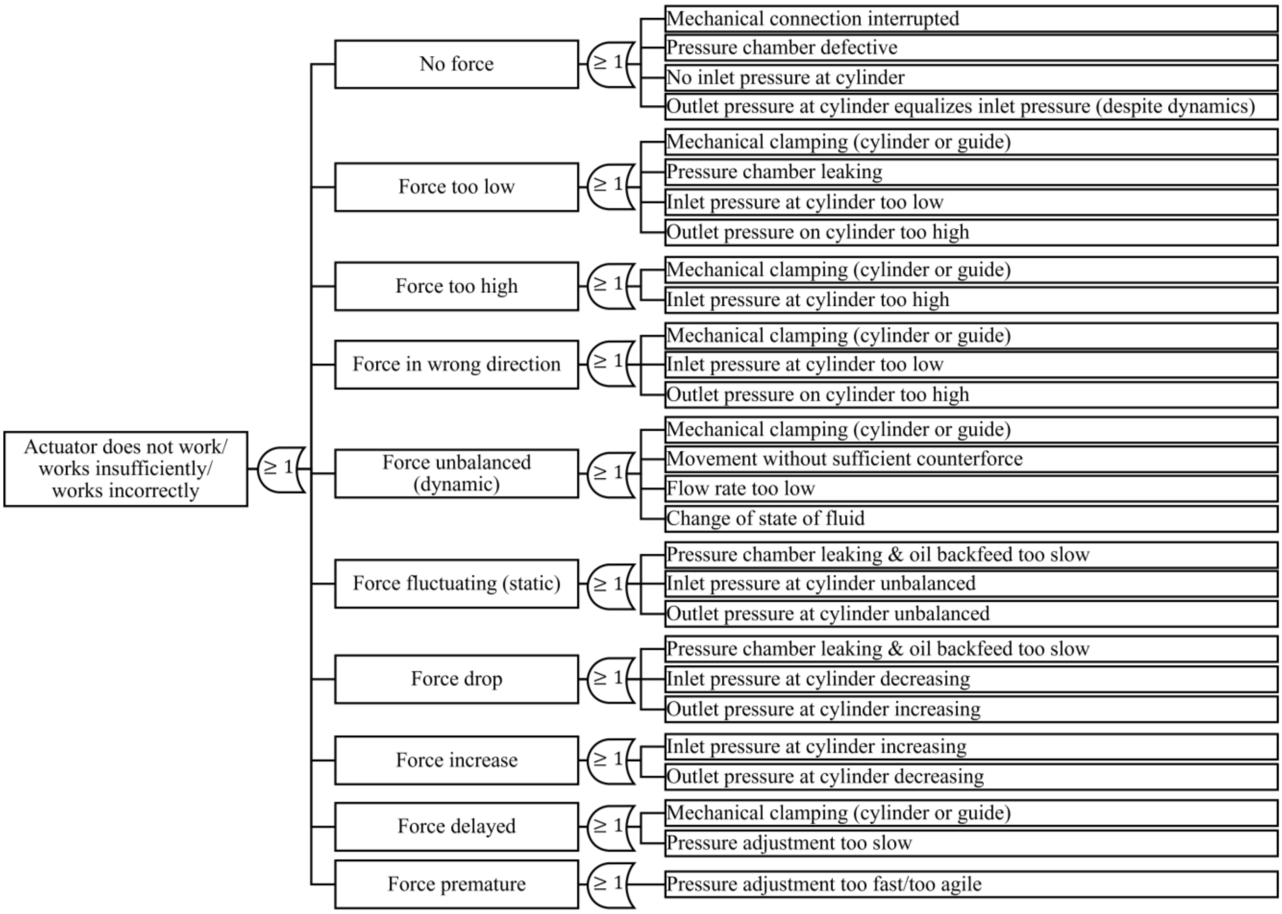

Figure 5. Fault tree with the universally valid first level and a solution-specific second level of the force-controlled hydraulically actuated adaptive system of a demonstrator high-rise building D1244

5. SCHEME OF MEASURES FOR MAINTAINING THE FUNCTION AND INCREASING THE ROBUSTNESS OF THE ADAPTIVE SYSTEM

The scheme of measures addresses the development of the adaptive system on the one hand and its operation when corresponding situations occur on the other. The scheme of measures addresses the effective structure and influences the function structure. The measures taken during development serve to reduce the probability of potentially critical events occurring. Such a scheme of measures for maintaining the function and increasing the robustness of an adaptive high-rise structure is depict in Figure 6. The process always starts with a "*yes/no*" question, with "*yes*" as a green path to the left and "*no*" as an orange dashed path to the right. If the question is answered positively, the next question follows. If the question is answered negatively, measures are outlined that can be considered during development and then applied during operation. During operation, the implemented measures can then be used individually or sequentially as required to maintain functionality. On the one hand, the measures include various forms of redundancy. These can be homogeneous or diverse redundancies. Homogeneous redundancy includes actuators, sensors, switching and control devices or circuits,

storage or load paths of the same type, which can functionally replace each other in the event of a failure. Diverse redundancies are components or subsystems of different types that take over the function of the other in the event of a failure – for example, electrically operated actuators in addition to hydraulic actuators.
On the other hand, there are fail-safe concepts or emergency measures. Examples include locking actuators in the best possible position in the event of an actuator failure, reducing effects such as wind by creating temporary openings or isolating collapsing areas.

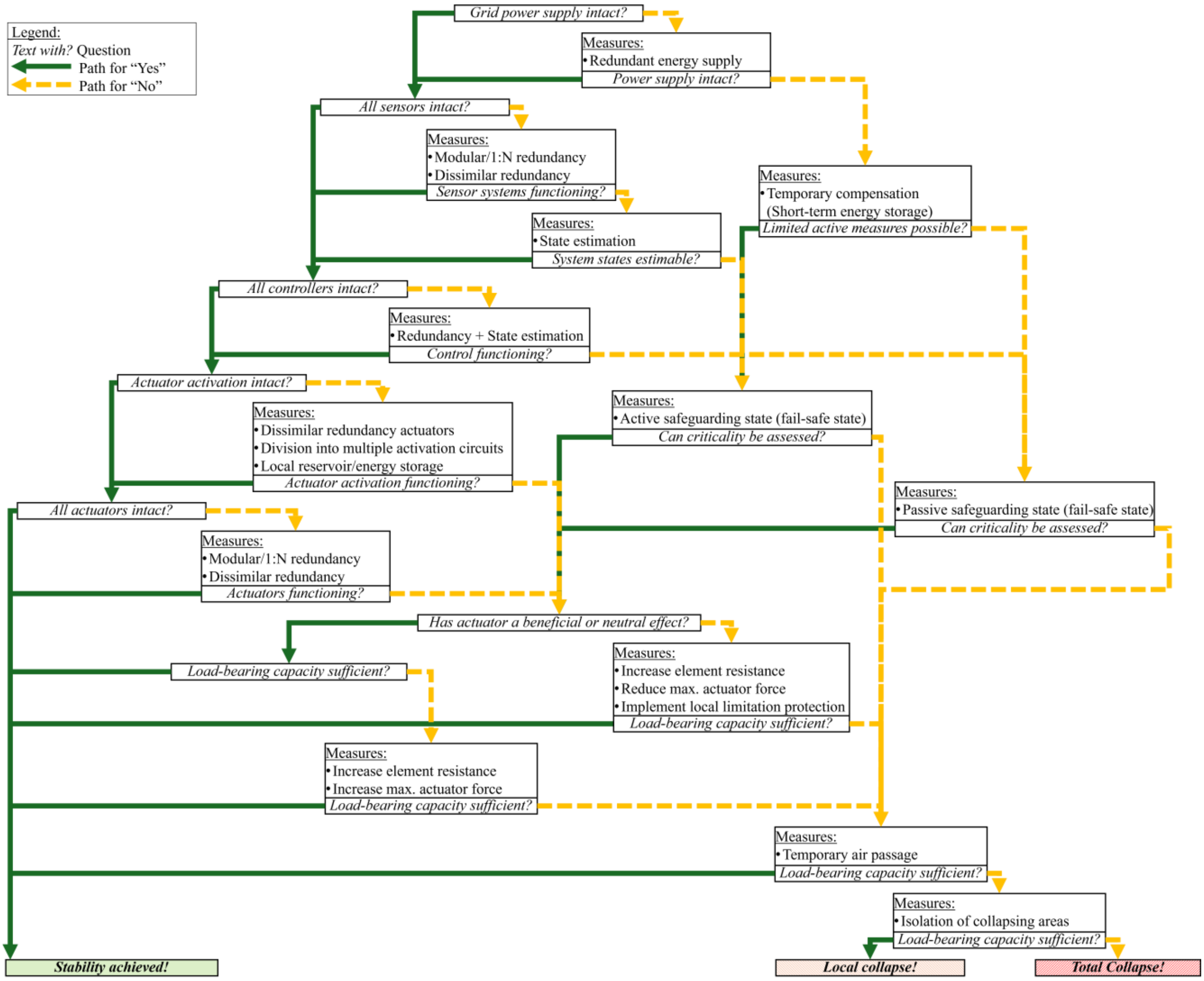

Figure 6. Scheme of measures for maintaining the function and increasing the robustness of an adaptive high-rise structure

6. FRAMEWORK FOR APPLICATION SUPPORT

The previous sections have systematically worked out the causes, influences and correlations for the reliability and safety of shape- or force-adaptive systems. These can be used for the future development and operation of such adaptive systems as part of a framework. The following two-part procedure should be used for this purpose.

It starts with the assessment and evaluation of reliability and safety for the main function of load transfer of the shape- or force-adaptive system. The procedure can be realized in six steps:

1. System analysis of the entire adaptive system
2. Complete the fault tree (from subsection 4.1) from the 2nd level onwards for each individual system
3. Determine, calculate and complete probabilities of occurrence in the fault tree for each individual actuator

4. Determine/calculate probabilities of occurrence for cases 1-6 (from subsection 3.4) (this also requires the information that would also be required for a passive system, e.g. frequencies of occurrence and, if applicable, times of occurrence for the impacts) (locally and globally)
5. Examine mechanical system for resistance for cases 1-6 and determine consequences if necessary (locally and globally)
6. Globally compare the probability of failure of the main function with the permissible limit values

If the sixth step delivers a satisfactory result, the process can be ended at this point. However, if there is a need for action, two directions can be used in the second part, or they can also be combined.

7. Adjust the system
    a. Reinforce mechanical supporting structure
    b. Apply measures from the scheme of measures (from section 5)

The assessment can be updated after each adjustment. For 7.a., start at step 5, for 7.b. from step 3. Using the example of an adaptive high-rise structure, [20] provides additional input regarding the action analysis, design and maintenance optimization, which must be considered from the fourth step onwards.

The framework provides a predefined structured procedure. A further advantage is that all possibilities are already considered both in the fault tree and in the combinations of possible loads on the supporting structure. This prevents anything from being forgotten, reduces the demands on the user of the framework and assists in forming an understanding of the system.

7. CONCLUSION

The paper addresses the major challenge of assessing and improving adaptive load-bearing structures in terms of reliability and safety. Following a systematic examination of relevant content and the creation of generally applicable templates, it presents a framework for a simple, systematic approach.

To this end, the second section first examines the nature of adaptive systems. In addition, the category of shape- or force-adaptive systems is formed and the adaptive load-bearing structures are assigned to this category.

In the third section, the central function of "force transfer" is determined on the basis created above and the consequences of a function failure are determined. In the cause analysis, it is shown that a local function failure either leads to a function failure of the adaptive load-bearing structure or not, depending on the functional structure. By systematically varying the force effects, six universally valid possible cases are then defined, which form the actual load on the load-bearing structure. This shows that different states can exist locally and globally and that some locally less preferred states can still make sense on a global level. Furthermore, general situations of inadequate actuator behavior are determined from the scenarios identified. In summary, the logic path provides the sequences from the force effects to the failure of the load-bearing function at a local and global level.

With the results on inadequate behavior of the actuators, generally valid fault trees are formed in the fourth section by applying FTA and FMEA. These contain one level, as further levels are application-specific due to the principle. Such an advanced example is shown in the application to the adaptive high-rise structure of the D1244.

In the fifth section, a developed scheme of measures provides recommendations for improving reliability and safety in system design. In system operation, it provides recommendations for measures in the event that a part of the system does not work as intended.

To support the application, the findings and results have been incorporated into a framework, which is discussed in the final section. The procedure and templates developed are generally valid for all shape- or force-adaptive systems and can therefore be applied to any such system.

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References

[1] Bruha I. Defining adaptive and learning systems. Cybernetics and Systems, 20, 77-88, 1989. https://doi.org/10.1080/01969728908902194
[2] Broy M, Leuxner C, Sitou W, Spanfelner B and Winter S. Formalizing the notion of adaptive system behavior. Proceedings of the 2009 ACM symposium on Applied Computing, 1029-1033, 2009. https://doi.org/10.1145/1529282.1529508
[3] Feigh K, Dorneich M and Hayes C. Toward a Characterization of Adaptive Systems. Human Factors: The Journal of Human Factors and Ergonomics Society, 54, 1008-1024, 2012. https://doi.org/10.1177/0018720812443983
[4] Sobek W et al. Adaptive Hüllen und Strukturen – Aus den Arbeiten des Sonderforschungsbereichs 1244. Bautechnik 98, H. 3, 208-221, 2021. https://doi.org/10.1002/bate.202000107
[5] Borschewski D et al. Ökobilanzierung adaptiver Hüllen und Strukturen. Bautechnik, Volume 99, Issue 10, 731-745, 2022. DOI: 10.1002/bate.202200067
[6] Efinger D, Mannone G and Dazer M. Applying Prognostics and Health Management to Optimize Safety and Sustainability at the First Adaptive High-Rise Structure. European Conference of the Prognostics and Health Management Society, 2024.
[7] Sobek W. Entwerfen im Leichtbau. Themenheft Forschung, University of Stuttgart, 70-82, 2007. Available at: http://www.uni-stuttgart.de/hkom/publikationen/themenheft/03/sobek.pdf (02.05.2024)
[8] VDI Verein Deutscher Ingenieure e.V. VDI 2221 Blatt 1:2019-11, Design of technical products and systems - Model of product design. Beuth Verlag GmbH, Berlin, 2019.
[9] VDI Verein Deutscher Ingenieure e.V. VDI 2223:2004-01, Methodisches Entwerfen technischer Produkte. Beuth Verlag GmbH, Berlin, 2004.
[10] Bender B and Gericke K. Pahl/Beitz Konstruktionslehre. Methoden und Anwendung erfolgreicher Produktentwicklung. 9th edition. Springer Vieweg, Berlin, Heidelberg, 2020. https://doi.org/10.1007/978-3-662-57303-7
[11] Bruha I. DEFINING ADAPTIVE AND LEARNING SYSTEMS. Cybernetics and Systems, 20(1), 77–88, 1989. https://doi.org/10.1080/01969728908902194
[12] Hackl J. Wirkmodell der Eigenschaften modularer Produktstrukturen. Springer Vieweg, Berlin, Heidelberg, 2022. https://doi.org/10.1007/978-3-662-65263-3
[13] VDI Verein Deutscher Ingenieure e.V. VDI 2222 Blatt 1:1997-06, Konstruktionsmethodik - Methodisches Entwickeln von Lösungsprinzipien. Beuth Verlag GmbH, Berlin, 1997.
[14] Ostertag A. Zuverlässigkeit, Sicherheit und Nachhaltigkeit adaptiver Tragwerke. PhD thesis, 2021.
[15] Prokosch T, Stiefelmaier J, Tarín C and Bischoff M. Detection and Identification of Structural Failure Using the Redundancy Matrix. ECCOMAS Thematic Conf. on Smart Structures and Materials, 2023.
[16] Loose T. Angewandte Regelungs- und Automatisierungstechnik. Ingenieurwissenschaftliche Grundlagen mit Beispielen und industriepraktischen Anwendungen. Springer Vieweg, Berlin, Heidelberg, 2022. https://doi.org/10.1007/978-3-662-64847-6
[17] Blanke M, Kinnaert M, Lunze J and Marcel Staroswiecki. Diagnosis and Fault-Tolerant Control. 3rd edition. Springer-Verlag, Berlin, Heidelberg, 2016. https://doi.org/10.1007/978-3-662-47943-8
[18] Borschewski D, Albrecht S, Bischoff M, Blandini L, Bosch M, Dazer M, Efinger D, Eisenbarth C, Haase W, Kreimeyer M, Leistner P, Nitzlader M, Roth D, Sawodny O, van den Adel F, Voigt M and Weber S. Ökobilanzierung adaptiver Hüllen und Strukturen. Bauphysik, 45: 107-121, 2023. https://doi.org/10.1002/bapi.202300102
[19] DIN Deutsches Institut für Normung e. V. DIN EN 61025:2007-08, Fehlzustandsbaumanalyse. Beuth Verlag GmbH, Berlin, 2007.
[20] Efinger D, Ostertag A, Dazer M, Borschewski D, Albrecht S and Bertsche B. Reliability as a Key Driver for a Sustainable Design of Adaptive Load-Bearing Structures. Sustainability, 14(2):895, 2022. https://doi.org/10.3390/su14020895