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SAFETY AND REDUNDANCY OF ADAPTIVE BUILDINGS STRUCTURES

Mark Slotboom [2], Arnold Robbemont[2], Arjan Habraken[1], Patrick Teuffel[1]

[1] Department of the Built Environment, Eindhoven University of Technology
5600 MB Eindhoven, The Netherlands
e-mail: P.M.Teuffel@tue.nl ; A.P.H.W.Habraken@tue.nl
web page: http://www.tue.nl/sd

[2] Zonneveld ingenieurs b.v.
3006 AJ Rotterdam, The Netherlands
e-mail: Slotboom@zonneveld.com

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ABSTRACT

The last three decades there has been extensive pioneering research done on adaptive structures. Studies on buildings and civil structures that are able to adapt to different environmental conditions. The application of an adaptive structure gives new elements in the design of a structure compared to a traditional structure. There are components added that must be checked on safety and reliability. A fail-safe concept for a structure means that a structure must not fail due to the failure of single elements and alternative load transfer mechanisms must be available. For adaptive structure this means in addition to the individual structural elements also the active system must be fail-safe. Even if it loses the active control, the stability must be ensured. The second additional safety consideration is according to the NEN-EN 1991. On buildings in consequences class CC3, the probability and consequences of any unfortunate event must be considered. Within the analysis of unfortunate events, the active frame can contribute in dealing with exceptional load cases. These considerations are discussed and presented with a case study of a high-rise building.

1. INTRODUCTION

The term 'adaptive structure' has come to mean any structure which can alter either its geometric form or material properties and has been recognized as one of the most challenging and significant areas of structural engineering[1]. Four different states can be distinguished when explaining an adaptive structure. The passive state is defined as the state as conventional buildings are known, without manipulation and only burdened with external loads. Passive-adaptive state is also without manipulation but optimized to be used as an adaptive structure. The activated state is defined as the condition where the structure only is burdened by the actuators, the last state is the adaptive state which is defined as the superposition of the passive-adaptive and the activated state[2].

Passive-adaptive + activated = adaptive

The focus of the presented study is on actively adaptive structures in line with the definition of Yao[3] and the Load Path Management concept of Teuffel[4]. Load Path Management concept (LPM) is a method to design an adaptive structure. Under LPM is meant the manipulation of the properties and / or the internal forces of the structure, i.e. it considers the whole load transfer mechanism. This LPM concept is applied on a realistic building design. The selected case study is a slender high-rise office building existing of 27 levels. The main structure of the building consists of a steel frame (S355), where the stability in the slender direction is governed by six stability frames. Over two third of the total steel weight is localised in these stability frames, where the stiffness was a decisive issue. These facts make the stability frame in this building a potential ideal application for an adaptive structure. The clear profit of the adaptive frame is the 67% reduction of steel weight, which is mainly the outcome because of the regulation of the horizontal displacement.

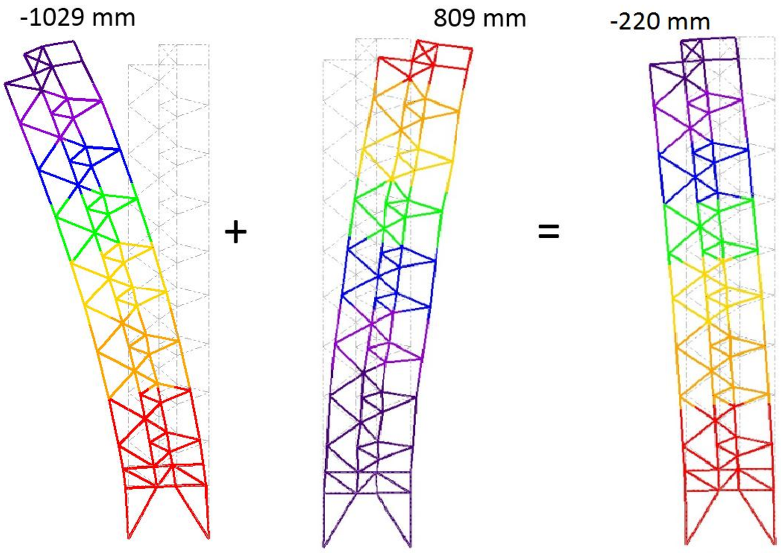


Figure 1. Passive + active = adaptive

2. FAILURE ACTIVE ELEMENTS

Safety is the state of being "safe", the condition of being protected against types or consequences of failure, damage, accidents or any other event which could be considered non-desirable.

The application of an adaptive structure gives new elements that has to be elaborated in the design of a structure compared to a traditional structure. These additional active components must be checked on safety and reliability, but at the same time these active elements can also provide an additional safety options. A fail-safe concept for a structure means that a structure must not fail due to the failure of single elements and alternative load transfer mechanisms are available. For adaptive structure this means in addition to the individual structural elements also the active system must be fail-safe. Even if it loses the active control, the stability must be ensured. The first considered safety issue is the possibility that the active elements do not function correctly at the time that the load case occurs where actuations is required.

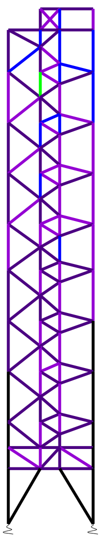
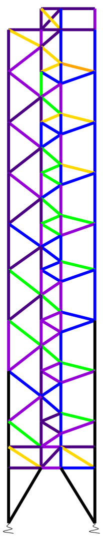
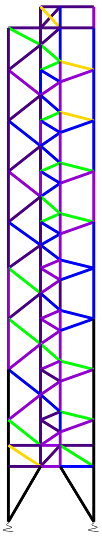
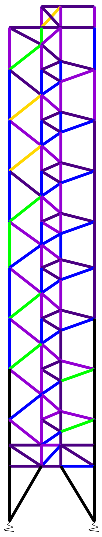
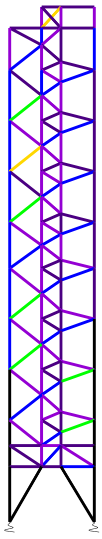
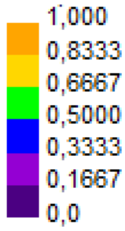
2.1 Failure of all active-elements

A possible situation during the lifetime of a structure is a large-scale power outage where the conventional power supply is not functioning at all. During this power outage the active system is no longer able to support the structure. A possible solution is a power backup system consisting of emergency generators (gasoline generators), as nowadays is applied in, for example, hospitals. But even if this backup system is not working or not present, the safety of the structure must still be guaranteed. This can be done by checking the passive-adaptive state: the situation in which the optimized frame is loaded by the maximum load cases without being able to make use of the active elements.

The chance that a large-scale power outage is occurs at the same time that decisive load case occurs and there is no working backup system can be considered extremely small. The improbability of this accumulation of events is therefore estimated as an extreme load case. When an extreme load case is checked, the safety factors of the different loads are set to 1,0. Furthermore, during an extreme load case is there no restriction for the maximum horizontal displacements. In the standards are also transient load factors listed in the case of accidental load cases. Because the possibility of a power outage in combination with less extreme loads is bigger, these transient load factors for the failure of the active system are also considered at 1,0. With these load combinations is the passive-adaptive state of the case study checked on strength, stability and displacements.

In the table below are the five normative load combinations for the stability frame checked. The first load combination has only vertical loading, the second and third combination is with wind from the positive direction with maximum and minimum vertical loadings and the fourth and fifth combination with wind from the negative direction with also variable vertical loadings. The results are listed in Table 1.

Table 1: Results passive-adaptive state

	Load combination 1	**Load combination 2**	**Load combination 3**	**Load combination 4**	**Load combination 5**	
Steel utilisation *(axial and buckling combined)*						
Maximum stresses (N/mm²)	84,9 -134,2	186,9 -149,3	159,7 -117,0	92,34 -130,4	91,37 -118,5	
Horizontal displacement (mm)	94,68	507,4	479,6	-317,5	-345,3	

With these results from the calculation of the adaptive passive state can be concluded that the failure of the active system will not lead to unsafe situations. The strength and stability are enough even without the actuations. Only the horizontal displacements are larger than 1:500, but given the accidental situation is this accepted as long as the frame remains intact.

2.2 Failure of control system

Another safety risk occurs when the active elements are active when no actuation is needed. Instead of helping the structure it can increase the internal stresses and displacements. This can happen by an error in the digital control system or the incarceration of an actuator. Another possibility is when a load suddenly disappears and the active system cannot respond quickly enough. An example is the wind that suddenly drops down. As a result, the loads (the pretension) following from the actuations of the active elements remains. These remaining loads can at all times not mean that the frame brakes down. The possibility that certain actuations are present in the frame even though they are not (anymore) needed is considerably higher estimated then the probability that all active elements do not work. The actuations of the active elements in the safety check are seen as variable loads with the corresponding safety factor ($1{,}65 \ * Q_{k,1}$).

The steel frame is studied on strength, stability and displacements. This is done for the five normative load combinations in which the needed actuation is taken in to account, but the wind load is multiplied by zero. With these load cases the active elements may never create a too high pre-stress in the frame.

Table 2: Results internal actuations

	Load combination 1	**Load combination 2**	**Load combination 3**	**Load combination 4**	**Load combination 5**
Maximum stresses (N/mm²)	84,9 -134,2	186,9 -149,3	159,7 -117,0	92,34 -130,4	91,37 -118,5
Horizontal displacement (mm)	94,68	507,4	479,6	-317,5	-345,3

As also is concluded with the failure of all elements, it can be seen that the structure has sufficient capacity for safety situations. In this situation it means that the frame can withstand the standalone actuations, in other words, the actuations will never cause the failure of the structure. The horizontal displacements are quite high, but considering the low possibility that a situation occurs where the actuations are normative these displacements can be accepted.

2.3 Failure single active-elements

The active failure of any, standalone, active element is always a possibility (thus the failure of the active part of the element, it will remain passive). Due to poor maintenance or unexpected breakage of components of the active elements, the active elements are no longer able to achieve the desired forces and length changes. This omission of one or two active elements should not mean that a building becomes unsafe or unusable.

The active elements in an adaptive structure are selected on the efficiency on the internal forces in all elements and the efficiency on the deformation of the selected degrees of freedom. From the 21 selected active-elements, the two most efficient elements on the internal forces in the frame and the two most effective elements on the horizontal displacements of the frame are selected as failing active elements. The LPM procedure is recalculated with the fixed locations of the active elements, but now with less active elements. The results are shown in the table below. The results are part of the ULS load combinations.

Table 3: Different situations with failing active elements

	Maximum compressive stress (N/mm^2)	Maximum tensile stress (N/mm^2)	Load comb.	Maximum displacements (mm)	Total actuation (mm)
All elements work (21 active elements)	**-184,5**	**230,6**	**l.c. 1**	**127,0**	**88,5**
			l.c. 2	**405,0**	**290,9**
			l.c.3	**370,0**	**232,2**
			l.c.4	**360,0**	**143,0**
			l.c.5	**399,0**	**76,8**
Element 18 and 34 fail (19 active elements)	-209,9	278,2	l.c. 1	145,3	84,3
			l.c. 2	653,6	307,3
			l.c.3	626,3	166,3
			l.c.4	451,7	136,8
			l.c.5	510,4	74,0
Element 43 and 32 fail (19 active elements)	-558,8	324,4	l.c. 1	199,2	123,8
			l.c. 2	99,5	563,4
			l.c.3	110,9	390,9
			l.c.4	626,7	193,1
			l.c.5	439,0	89,4

What becomes clear from table 3 is that the failure of some decisive active elements means that the structure does not meet the requirements on strength and displacements. Both the stresses as the displacement requirements are exceeded in the case of failure of the most decisive active elements. Further research showed that in the case of failure of less decisive active elements, the effects are much less severe and can sometimes even be neglected.

Backup systems

For the occurrence that some of the active elements fail there must be a backup system that prevents the failure of the entire frame or parts of it. This system must ensure that the effect of missing actuations are limited. In this paper two different systems are discussed:

- by placing spare actuators;
- by placing spare active elements.

Multiple actuators:

By placing multiple actuators (cylinders) in each necessary element, which can deliver more power than is absolute necessary, the missing actuations in one active element can be compromised. The backup-system is in this case within the same bar and therefor it does not change the structural system. A requirement for this backup-system is that the different actuators within the same element are controlled independent, to minimise the possibility of the failure of multiple actuators in the same bar at the same time. Additional safety can be created by placing multiple actuators in series: even if the entire actuation of one element in the series can't take place, there is always a part of the actuation possible with the remaining actuators.

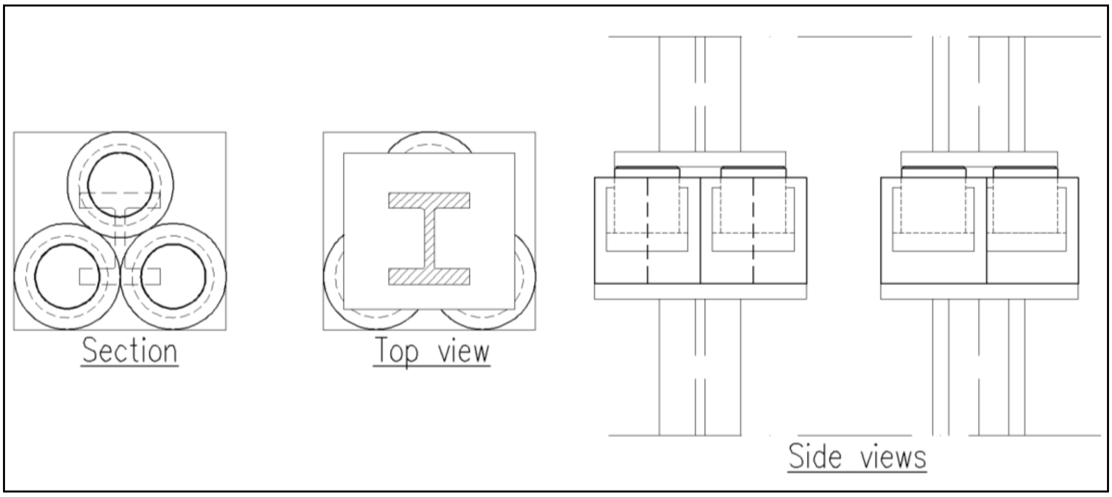


Figure 2: Multiple actuators parallel in one element

Spare active elements:

The other method is by having additional active elements. This is a backup-system that can compromise the failure of another active element. The structural system is in this case also changed. A modified distribution of the active elements means also a modified control of the internal forces. There are alternative elements needed which can become (more) active when the situation occurs that some active elements are no longer able to work active. Research on many combinations of failing active elements showed that many elements have the same 'backup' elements. In the case studies in which both the most effective active-elements on internal forces are deactivated and in which the most effective active-elements on displacement are deactivated the same backup elements are needed. This is because in the structural system some elements have more effect on the forces and displacements of the frame than most other elements.

In figure 3 the steel stability frame, with the active elements in red, is shown three times (with the dimensions in millimetres). The first frame represents the 'normal' situation without the spare elements and with the active-elements in the blue circles as the most effective active-elements regarding the horizontal displacement of the frame. The second frame shows the distribution of the active-elements pictured without the two most effective active-elements on the displacement of the first frame, but with the backup active-elements in the blue circles. The same is done with the two most effective active-elements regarding the internal forces of the frame (the green circles in the first frame), which results in the same backup active-elements (the green circles in the third frame).

By using these alternative elements, the same forces and displacements are reached. The only difference is the actuation, which is somewhat more in the different load cases with the alternative active-elements compared to the 'first choice' active-elements.

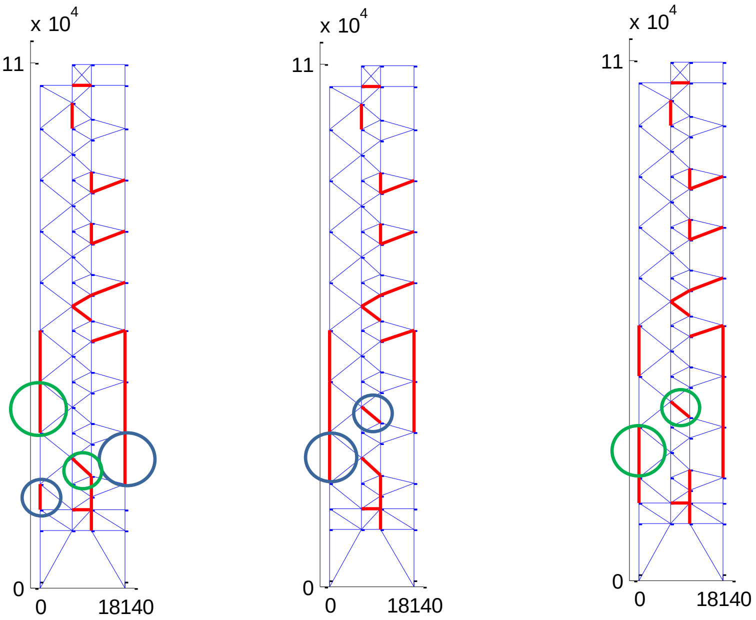


Figure 3: 1. Active elements 'normal' situation 2. Spare 'displacement' elements 3. Spare 'force' elements

3. ACTIVE REDUNDANCY

According to the NEN-EN 1991-1-7, the case study is a consequences class CC3 building, which means that a risk analysis has to be performed in the design process. This analysis must consider the probability and consequences of any unfortunate event. Design analysis is made to avoid disproportionate damage to the structure from an accidental cause. Within the analysis of unfortunate events, the active frame can contribute in dealing with exceptional load cases.

3.1 Strategies in the Eurocode

Within the Eurocode[5] a difference is made between strategies for known accidental actions and accidental design situations (unknown accidental actions). Some known accidental actions are impact loads from vehicles, gas explosions in buildings and loads caused by extremely increased (ground-) water levels.

The two strategies given by the Eurocode for known accidental actions are preventing or reducing the action, e.g. protection measures and design the structure to sustain the action. One of the given approaches is designing structural members to have sufficient ductility, capable of absorbing significant strain energy without rupture. This approach is incorporating sufficient redundancy in the structure to facilitate the transfer of loads to alternative load paths during an accidental event.

According to the Eurocode the potential damage of the structure arising from an unspecified cause, should also be minimised, taking into account its use and exposure. For localised failure (unknown accidental situations) are three strategies given:

- enhanced redundancy, e.g. alternative load paths;
- key element designed to sustain notional accidental actions (A_d);
- prescriptive rules, e.g. integrity & ductility.

The third strategy is comparable to the named approach with known accidental actions, designing enough ductility in the structure. The first strategy is designing the structure such that when the case of local failure occurs (for example the failure of a single element) the stability of the whole structure is not endangered. This can (almost only) be done by creating other load paths. This strategy of creating alternative load paths is the most interesting strategy for adaptive structures and will therefore be further elaborated in this paper.

The load combination of an accidental situation (known and unknown accidental loads) is:

$$1{,}0 * G_{kj,} \;+\; 1{,}0 * A_d \;+\; 1{,}0 * \Psi_{1,i} * Q_{k,1} \;+\; 1{,}0 * \Psi_{2,i} * Q_{k,i}$$

3.2 Creating alternative load paths

The creation of alternative load paths in the passive frame is done by the use of three connected vertical trusses. Also plastic deformation is allowed and the loads and load factors are reduced. This is not any different in the adaptive frame, only that the amount of steel in the adaptive frame is significantly less and therefore has less ‘reserve’ for alternative load paths. But on the other hand the adaptive frame does have the capability to control the internal forces. By applying the same force path optimization principles used in the ‘normal’ active frame, the aim is to use the active elements to ‘steer’ the forces around the location where a certain bar has failed. By redirecting the forces away from the local failure, the consequences of the local failure is possible less significant. This can prevent further failure of other elements in the frame. This part of the research is done on basis of two examples of missing elements in the stability frame. These bars where chosen on their importance within the frame, they transfer relatively high loadings and are also one lowest bars in the frame which cannot restrain the prescribed accidental load A_d of 34 kN/m^2. Because of the extreme situation, are there no requirements for the displacements when analysing accidental load combinations. The results of the frame with the void elements 43 and 44 are listed in the following table.

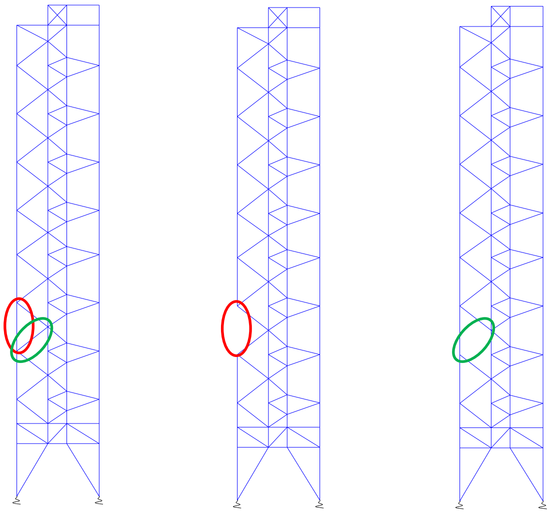


Figure 4: The failure of bar 43 (red) and 44 (green)

Table 4: Comparison different situations of failing elements

	Maximum compressive stress (N/mm^2)	Maximum tensile stress (N/mm^2)	Max. unity check	Maximum displacements (mm)	Total actuation (mm)
No failing elements (19 active elements active)	-183,6	207,7	0,91	136,1	208,7
Element 43 fails (18 active elements active)	-579,1	436,3	**2,62**	861,0	277,4
Element 44 fails (18 active elements active)	-165,9	139,1	**1,63**	349,9	153,5
Element 43 or 44 fails (passive-adaptive)	-277,5	117,9	0,98	257,3	0

From the results became clear that the adaptive frames in these accidental load cases yield significantly worse results than the passive-adaptive frames. The results are the opposite of what is sought to be reached with the adaptive structure. These deterioration results by using the active elements can be explained by analysing the used optimization process. The process is initially made to distribute the forces optimally in the initial structure, thus with all elements present. From this optimization the cross-sections of all elements are determined and thus the stiffness of the frame and therefore broadly the load-bearing path.

In the new incidental situation, where a complete element is removed, the changes in the stiffness distribution of the frame are big. If then this new stiffness distribution in the frame is combined with the constraints of the previously determined cross-sections of the elements, the optimization process cannot find a correct solution. And this optimization procedure makes sure that the, in addition to limit the stresses in the elements, the equilibrium within the frame is guaranteed. The consequence is that the results of the optimization process for the optimal distribution of forces within the frame are not correct. The active elements are nonetheless still trying to achieve this force distribution, which deteriorated the situation instead of improving it.

These results would not necessarily mean that active structures in accidental situations, as the failure of an element, do not have any beneficial effect or even a worse effect. These results indicate that the current Force Path Optimization of the Load Path Management cannot be used for finding other alternative load paths. Therefor a new optimization process must be written, an optimization which finds a load path that minimises the elements with the cross-sections known in advance. A Stress Path Optimization[6].

When the passive-adaptive situation of the stability frame is examined, it is seen that the frame can withstand the two examples of accidental situations. By designing the frame with three vertical zones, the structure is also safe in extreme situations, without any actuation and with the material reduction.

4. CONCLUSION

In order to ensure the safety of an adaptive structure, more components need to be checked compared to the same passive structure. The active system can fail in several ways. Total outage of all active elements can occur, or refusal of some single active elements. And even if the active elements work, they can provide the wrong actuations due to a malfunction. Although there are extra parts in the adaptive structure that can fail, the case study does not require any additional steel to ensure the safety. And by applying some spare active elements and / or spare actuators the building does even not become less usable when some single active components stop functioning. Another side of the story is the redundancy of the structure. The active elements may provide additional load bearing routes in order to increase the safety of the structure in case of an extreme situation. This can be for predetermined situations but may also be possible for unknown situations. If this option is possible, it would be another advantage and thus another reason for further research into adaptive structures.

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