

Adaptive arch : active stress minimization in a thin arch structure

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International Symposium on "Novel Structural Skins: Improving sustainability and efficiency through new structural textile materials and designs"

Adaptive arch: active stress minimization in a thin arch structure

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Abstract

The concept of adaptive structures is based on the approach that the behaviour of a structure is not established only once during the initial design phase, but the structural response is controlled continuously via the integration of active components. The activation of these components can be used to manipulate the internal stresses, displacements as well as control vibrations. This approach allows the structure to react to variable loads with the goal of optimizing the load-carrying behaviour in real-time. The design of structural elements can thus be carried out for reduced demands, ideally resulting in substantial material savings in comparison with passive structures.

The goal of this research is to develop insights and knowledge about the practical implementation of a control system for adaptive structures. Numerical and laboratory tests are done to minimize the maximum stress in an arch of Plexiglas when externally loaded with varying static loads by active rotation of the supports.

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Keywords: Adaptive structures; Structural optimization; Actuators; Control systems

1. Introduction

The environmental impact of the building industry is large and must be reduced for a sustainable future. This requires new structural optimization methods, limiting the amount of structural material used. Large reductions seem possible when a structure is actively supported and controlled to cope with the rarely occurring extreme loads. With

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active adaptability the structural behaviour can be modified in real-time and further optimize the load carrying capacity when needed.

These “living” structures require a complete new field of expertise on control systems and creating real-time loops for structural interference. This research, is mainly done to develop insights on this new field of active engineering, not to fully optimise the arch structure.

2. Problem description

At the TU/e, numerical and experimental research is done on the structural behaviour of an actively controlled thin arch of Plexiglas (Figure 1). The properties of the arch are shown in Table 1.



Figure 1. Experimental setup

Properties of the arch	
Radius (mm)	567
Start angle (degrees)	28
End angle (degrees)	152
Width (mm)	300
Thickness (mm)	2
Cross sectional area (mm ²)	600
Moment of inertia (mm ⁴)	200
Section modulus (mm ³)	200
Young's modulus (N/mm ²)	3300
Shear modulus (N/mm ²)	1700
Poisson ratio	0.37
Density (kg/mm ³)	1.19e-06

Table 1. Properties of the arch

The active control system consists of two actuators which can rotate the supports. Four strain gauges are placed on the arch to monitor the strains. In Figure 2, the unloaded arch is shown. In the starting situation no rotation and no moment is applied to the arch by the actuators. With the measured strains, the loading pattern and loading value must be determined to calculate the optimum location of the actuators to minimise the stresses in the arch.

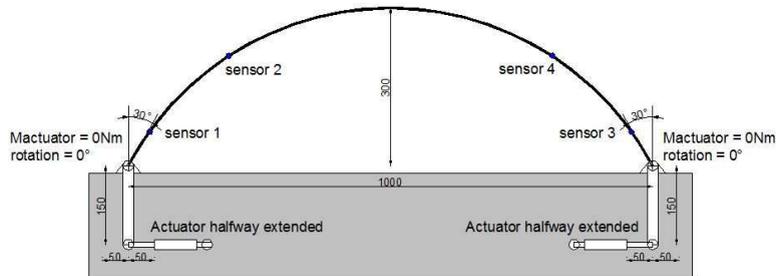
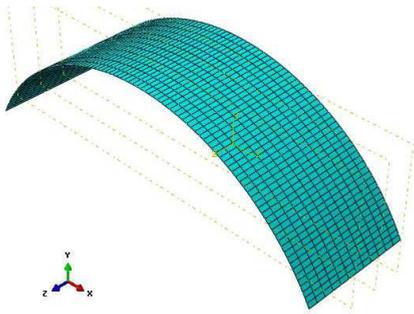


Figure 2. Schematic of the arch in starting situation

3. Numerical optimization

The optimization problem of minimizing the stress in the arch is non-convex. Therefore, finding the global optimum is not straightforward. A simulated annealing algorithm is applied to find the optimal rotation angles which minimize the internal Von Mises stress for a large number of load cases.



A Python code is programmed in order to combine the algorithm with a 3D finite element (FE) model of the arch, built in Abaqus (Figure 3). Due to relatively large displacements of the structure, geometrically nonlinear effects are included.

Figure 3. 3D Finite element model of the arch

3.1 Load cases / data base

A load case generator is developed to create a database that contains the relation between external loading, strains and optimal rotation angles. In this research, for each particular load case, four different red neighbouring elements in Figure 4 are used to form one load surface (31 load cases in total). The data base is extended by varying loading magnitudes between 10N and 24N with 2N intervals (8x).

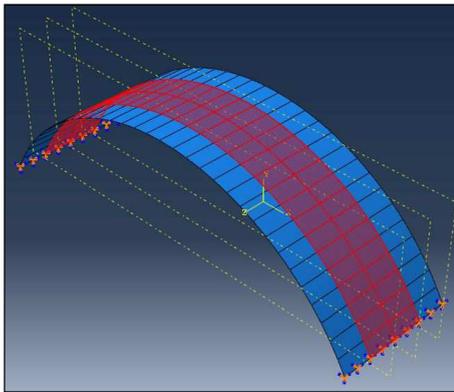


Table 2: Load case generator properties

Load case generator specifics	
Number of load surfaces	31
Number of load magnitudes	8
Total number of load cases	248

Figure 4: Red surfaces are used for load case generator

In table 3 the figures in the database are shown for one load case (LC 2-20). The first row contains the strain values caused by the load case with $\alpha=0$ and $\beta=0$ followed by the target angles for α and β . The last row contains the strain values caused by the load case and α and β equal to the target angles. To keep the actuators rotating to the correct rotation angles, the lines between are added showing the results with intermediate α and β values.

Table 3. Total portion in the database for load case 2-20.

Actual left actuator rotation α (rad)	Actual right actuator rotation β (rad)	$\epsilon_{\text{sensor1}}$ Logarithmic strain [-]	$\epsilon_{\text{sensor2}}$ Logarithmic strain [-]	$\epsilon_{\text{sensor3}}$ Logarithmic strain [-]	$\epsilon_{\text{sensor4}}$ Logarithmic strain [-]	Left actuator target rotation α (rad)	Right actuator target rotation β (rad)
0,0000000	0,0000000	0,0000651	-0,0001055	0,0003470	0,0001049	-0,1496350	-0,1223764
-0,0149600	-0,0122400	0,0000023	-0,0001393	0,0004000	0,0001400	-0,1496350	-0,1223764
-0,0299000	-0,0248000	-0,0000192	-0,0001731	0,0004530	0,0001768	-0,1496350	-0,1223764
-0,0448900	-0,0367000	-0,0000613	0,0002069	0,0005060	0,0002120	-0,1496350	-0,1223764
-0,0598000	-0,0489000	-0,0001033	-0,0002400	0,0005500	0,0002400	-0,1496350	-0,1223764
-0,0748000	-0,0612000	-0,0001455	-0,0002740	0,0006120	0,0002840	-0,1496350	-0,1223764
-0,0898000	-0,0734300	-0,0001876	-0,0003085	0,0006600	0,0003200	-0,1496350	-0,1223764
-0,1047400	-0,0857000	-0,0002298	-0,0003424	0,0007180	0,0003569	-0,1496350	-0,1223764
-0,1197000	-0,0979000	-0,0002719	-0,0003762	0,0007710	0,0003929	-0,1496350	-0,1223764
-0,1347000	-0,1101000	-0,0003140	-0,0004101	0,0008248	0,0004290	-0,1496350	-0,1223764
-0,1496350	-0,1223764	-0,0003561	-0,0004439	0,0008779	0,0004650	-0,1496350	-0,1223764

Additionally, when an external load is released, the control system must return the arch to its original position. Therefore, the database has additional entries with strain values corresponding to the arch without external loading but with actuator rotations. The actuator target points for all these rows are $\alpha=0$, $\beta=0$ (i.e. original situation).

Using this approach, the control system finds the closest match in the database to the current combination of strain measurements and then rotates the supports accordingly.

The strain in table 3 can increase in a certain point when α and β are moving towards the target value. This is because the goal is not to minimize the stress in the 4 locations but to minimize the maximum occurring stress in the entire arch.

Figure 5 shows, for both the passive and active arch, the maximum stress for the 31 load cases with magnitude of 20N. The activation always reduces the maximum stress, but the amount of reduction depends on the specific load case.

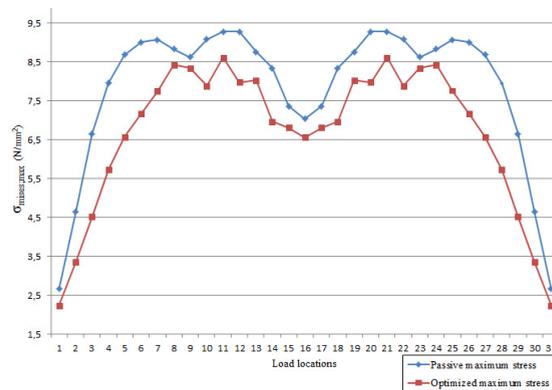


Figure 5. Optimization results for all load cases with magnitude 20N

If the load magnitude or load location quickly changes, α and β are not zero. The control system must still be able to find the correct entry in the database. This is done because a search method is applied which finds the row in the database with the smallest difference with the measured sensor values. When actuators change toward the target value, stresses will change in a way that different target values are found. The control system iteratively converges to the correct target value and a new optimized state related to the changed external loading. The case study in chapter 5 shows this research. But, adding all possible combinations of angles in each load case will result in a smoother and more direct movement towards the target angles. It will only increase the size of the database drastically.

4. CASE STUDY

Several laboratory tests are done with different loadings and different speed of loading adjustments. The hardware that is used only deals with static loading. It is not able to respond to faster dynamic loads. Sensor measurements are updated every 0.1 second and compared to the database. The best matching index in the database is found, after which the target points on the corresponding row are sent to the actuators using an Arduino board.

The tests are done with and without active control and compared to the numerical results. The key points to satisfy are:

- the correct α and β index in the database is found belonging to the applied load,
- the actuators move to the corresponding target positions,
- the actuators must stop when the target positions are reached,
- when the arch is unloaded, the actuators must move back to the starting positions,
- when the arch is not in the starting position, and a different load is applied, the actuators must move to the new correct target positions.

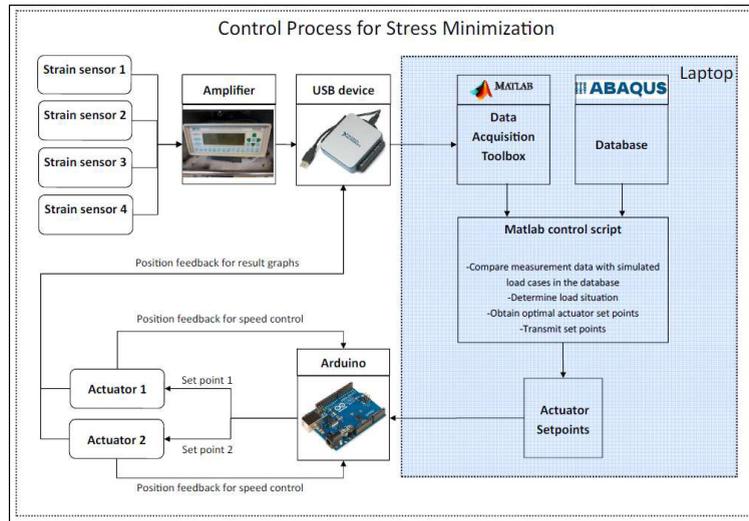


Figure 6. Control process of the laboratory test for stress minimization

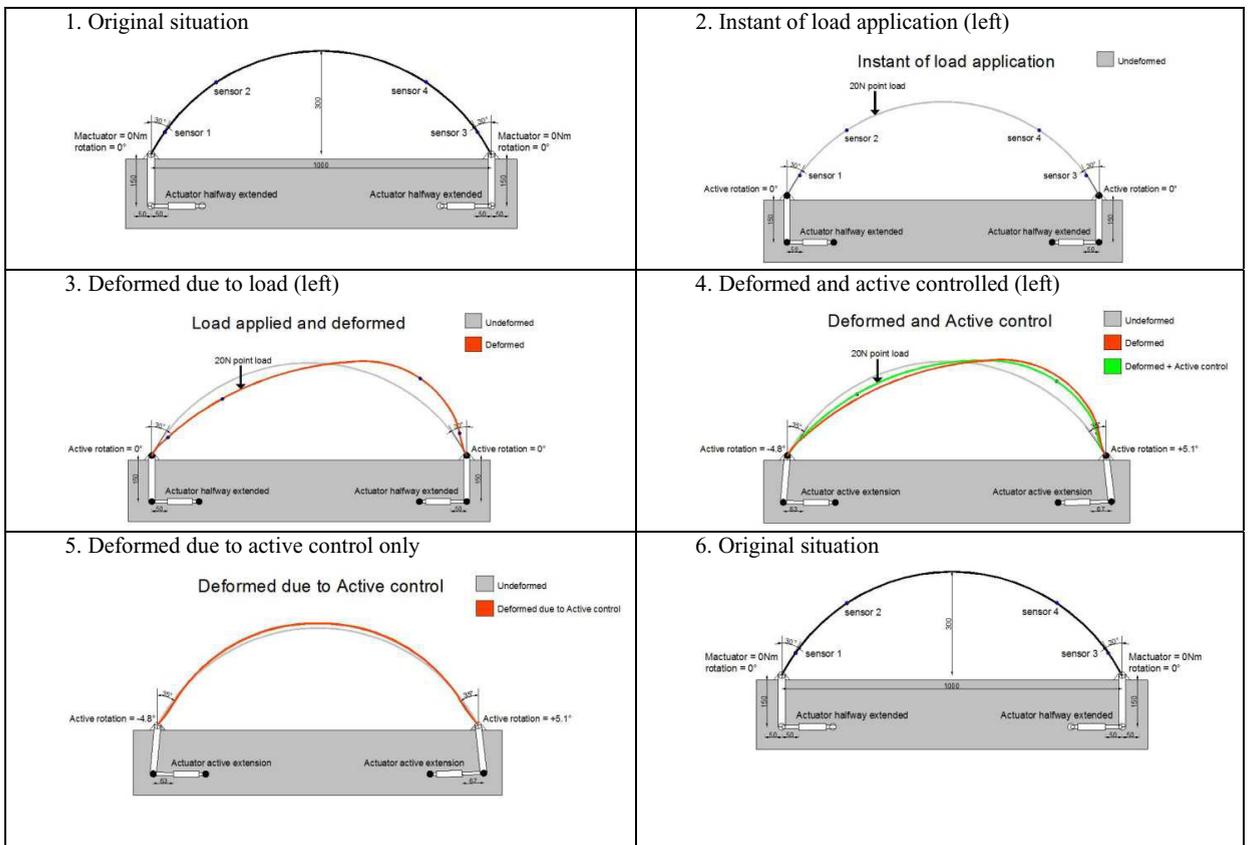


Figure 7: Steps of the case study

A case study is performed in section 4.1 with the control system switched off and in section 4.2, the control system is switched on.

4.1 Passive case study

Figure 7-1 + Figure 8-1) and sensor strains are on their initial values. Note that each sensor has a slightly different (non-zero) starting strain value due to installation tolerances.

Figure 7-2 + Figure 8-2). At this instant, the sensor values shoot up because the arch deforms.

Figure 7-3 +Figure 8-3). Between (3) and the moment of load removal, the arch stays in this deformed shape because the active control system is not switched on yet. However, the sensor values do change slightly because the flexible arch deforms a little bit more over time. At the moment of load removal, the sensor values shoot down again and the arch returns to its original situation (Figure 8-1).

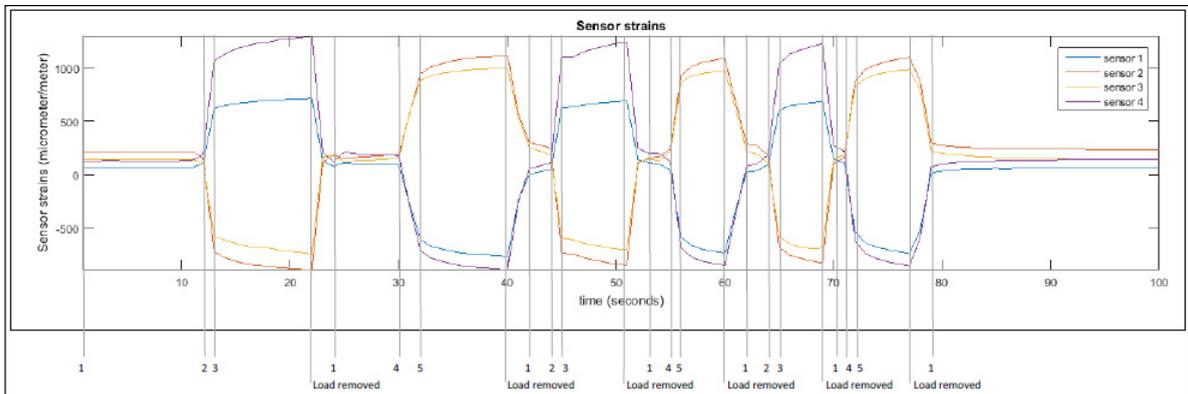


Figure 8: Passive case study. Sensor measurements over time.

When the load of 20N is applied on the right side, the sensor values immediately shoot up again. Since the arch is symmetrical and the load is exactly mirrored, this time sensor 2 and 3 measure higher values and sensor 1 and 4 measure lower values as opposed to the previous situation. The load is removed and the entire process is repeated two times with a shorter interval between load removal and load application. For now, this has no effect since the control system is turned off. In section 4.2 it becomes obvious that this does have an effect since the control system responds with a slight delay.

4.2 Active case study

In Figure 9A (top), the sensor measurements for the active case study are plotted along with the actuator target points in Figure 9B (bottom). In these figures, a white background stands for no external loading, blue stands for load on the left and orange stands for load on the right. It must be noted that the actuator target points are not the actual actuators positions at that time, because it takes time for the actuators to move towards a new target point. This also means that the sensor measurements in Figure 9A start changing a short time after new actuator target points in Figure 9B are received.

After 7 seconds, the 20N load is applied on the left side of the arch (Figure 9-2) The sensor measurements change instantly and the actuator target points change slightly later. The load is hung from the arch slowly so there is not a sudden jump in sensor values (as in the passive case study). The deformation due to the external load is reached (Figure 9-3). Slightly later again, the control system calculated new actuator target points. Then the actuators start moving to the new optimal positions, which causes another kink in the sensor strains. Next, the optimal rotation

angles are reached for this specific load case (Figure 9-6) and the sensor values remain horizontal until the load is removed.

As mentioned before, the found strains after adaptation can be higher for some sensors because the verification method is indirect. A direct verification of the maximum stress in the experimental structure is not possible, since the location of maximum stress always changes and only a limited number of sensors can be applied.

Load removal corresponds with a sudden change in sensor strains. At this time, there is no load applied to the arch but the actuators are still in the rotated positions (Figure 9-8). The control system recognizes this change and actuators move back to the original position a little later. This corresponds with the sensor values slowly returning to their initial values (Figure 9-1).

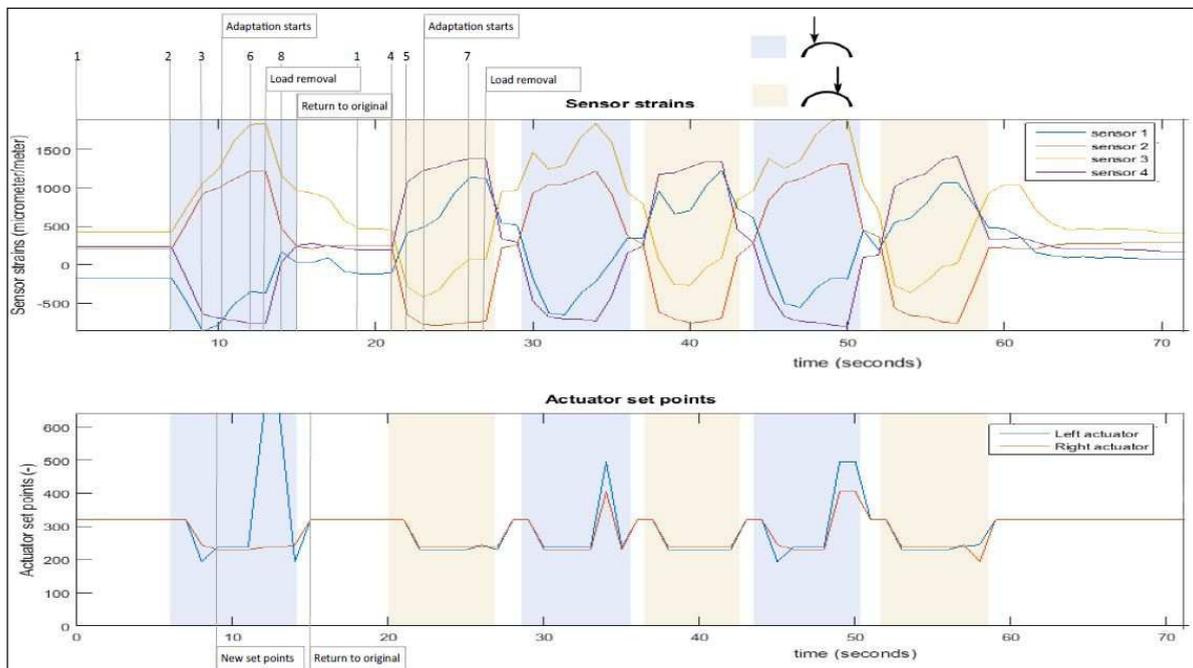


Figure 9: Active case study. A) Sensor measurements over time. B) Actuator target points (vertical axis shows actuator rotation angle, where 0 is full extension i.e. -18° for left actuator and $+18^\circ$ rotation for right actuator).

Next, the 20N load is applied on the right side. Only now when the load is removed again and sensor values start dropping, the load is applied on the left side with a very short pause, not allowing the control system to fully move back to the original position before the new load is applied. From this scenario, the same actuator target points must be found because the new load situation is identical to the first one. Now this must be found starting from a non-initial situation. In a brief iterative process, the control system converges on the new optimized shape because the control system continuously finds a better match with the current sensor values.

4.2.1 Comparing results

To verify that the correct load scenarios are indeed found and the actuators rotate the supports to the optimal rotation angles for each specific load case, the index found in the database for each load is verified to the simulated load scenario corresponding to this index.

Figure 10 shows the passive deformed experimental model due to the 20N load on the left. From retracing the index found in the database, it can be concluded that load scenario 6-20 is found (Figure 10-B). In Figure 10-C, the deformation due to this load in the FE simulation is shown. The deformation closely matches the experimental deformation in Figure 10-A.

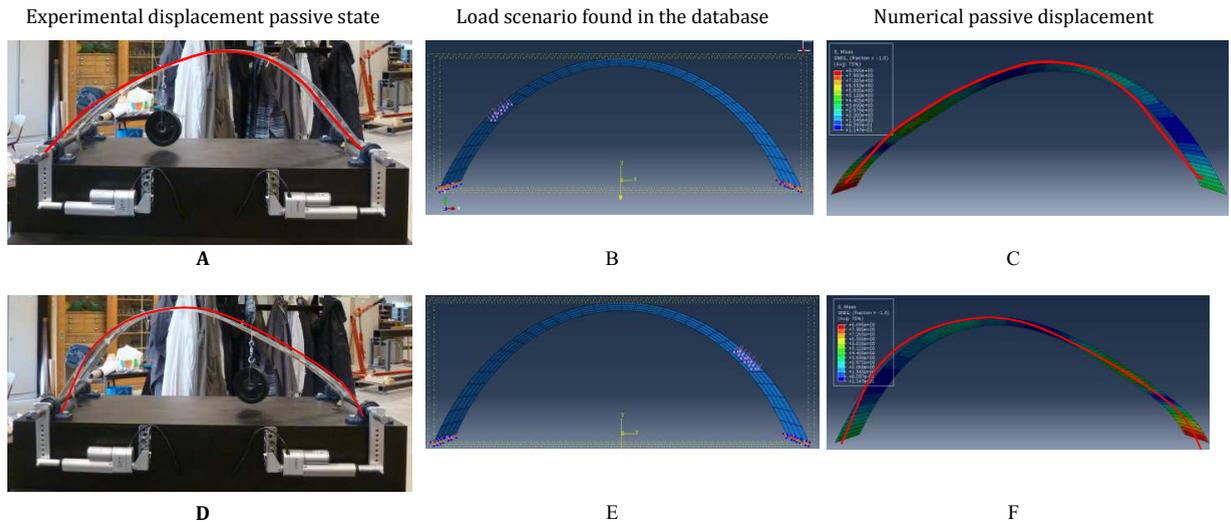


Figure 10: Case study, Passive results

Table 4 shows that the “passive” measured strains have comparing patterns with the “passive” Abaqus strains in the database. This is of course also the reason why this index in the database is found.

Table 4. Comparison measured strains with Abaqus strains. Load 6-20

Load case 6-20		Sensor 1	Sensor 2	Sensor 3	Sensor 4
		Logarithmic strain [-]	Logarithmic strain [-]	Logarithmic strain [-]	Logarithmic strain [-]
		(x10 ⁻³)	(x10 ⁻³)	(x10 ⁻³)	(x10 ⁻³)
Measured strains	Passive	4,95	-6,47	-11,3	9,21
	Active	9,01	-6,45	-4,10	12,05
Abaqus strains in database	Passive	4,18	-6,49	-8,17	10,99
	Active	9,45	-6,48	-3,65	12,29

The active controlled deformation is shown in Figure 11A and is similar to the numerically optimized arch shape Figure 11B.

In order to verify that the experimental optimized shape is close to the numerically optimized shape, the measured strains in the “active” state show comparing patterns with the strains found in Abaqus (Table 4).

Also here, some strains in the active state actually show larger strains compared to the passive state (sensor 1 and 4). Again, minimizing the maximum strain in the entire arch, does not necessarily mean that the strain at all four sensor locations decreases. This is clearly shown in Figure 12. The maximum Von Mises stress according to the FE calculation is 9.00 N/mm² in the passive state and 7.16 N/mm² in the active state. A maximum stress reduction of 20.45% is achieved.

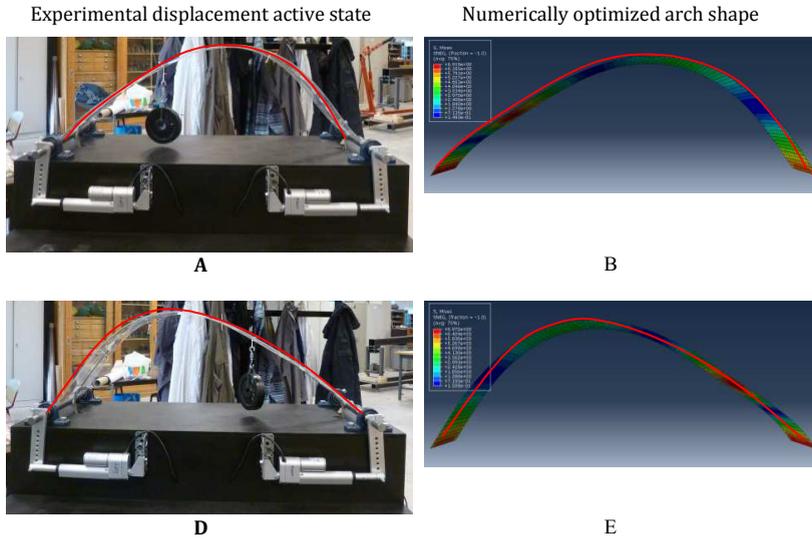


Figure 11: Case study. Active results

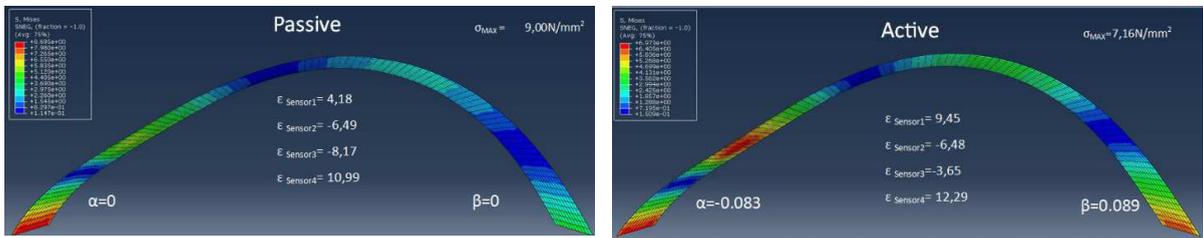


Figure 12: Von Mises stress in the arch. Passive and Active state. Load case 6-20

A similar procedure is performed for the load applied on the right side (Figure 11 D+E). In Table 5, sensor measurements are compared for both passive and active states. The maximum Von Mises stress according to the FE calculation is 9,06 N/mm² in the passive state and 7.74 N/mm² in the active state. A maximum stress reduction of 14.6% is achieved.

Table 5: Comparison measured strains with Abaqus strains. Load 25-20

Load case 25-20		Sensor 1 Logarithmic strain [-] (x10 ⁻³)	Sensor 2 Logarithmic strain [-] (x10 ⁻³)	Sensor 3 Logarithmic strain [-] (x10 ⁻³)	Sensor 4 Logarithmic strain [-] (x10 ⁻³)
Measured strains	Passive	-6,71	12,16	3,59	8,0
	Active	-2,64	13,32	8,97	7,89
Abaqus strains in database	Passive	-8,17	10,99	4,18	6,49
	Active	-3,65	12,29	9,45	6,48

5. Conclusions

In this research, active control on a small scale lightweight arch structure of Plexiglas is investigated numerically and experimentally. A control concept is developed for the experimental structure using numerical optimization results.

The thin arch structure can be actively controlled when subjected to varying static loads. Significant stress reduction is achieved using the active control system compared to the same passive structure. On average for all load cases, the maximum stress is reduced by 18%, with a maximum of 26%.

This research has led to new insights and knowledge about the practical implementation of a control system for adaptive structures. This knowledge involves communicating and translating sensor data directly to Matlab, sending commands from Matlab over the serial port to the Arduino, translating the received commands into actuator positions, and making the actuators move to these positions accurately.

A novel approach using a database with simulated load scenarios is implemented because real-time calculations to determine optimal actuator positions take too much time and computational power.

A basis for the practical implementation of active control in lightweight structures is developed. However, much more research is required to make the control system more robust and implement it on a full scale structure and also to extend the capabilities of the control system to react quicker, for example to dynamic loads, such as wind.

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