

# TOPOLOGY OPTIMIZATION METHOD FOR THE ADAPTATION OF EXISTING STRUCTURES TO NEW REQUIREMENTS, THRU ADDITION OF FRAMEWORK STRUCTURES

Saad Hafsa

BMW Group  
Research and Innovation Center,  
Munich, Germany

Axel Schumacher

University of Wuppertal  
Chair for Optimization of Mechanical Structures  
Wuppertal, Germany

e-mail: [saad.hafsa@bmw.de](mailto:saad.hafsa@bmw.de), [schumacher@uni-wuppertal.de](mailto:schumacher@uni-wuppertal.de)

**Key Words:** *topology optimization, adaptation, reinforcement, framework structures.*

**Abstract.** Besides designing a component from scratch, there are situations where it is advantageous or wished to reuse an already existing structure and adapt it to fulfill new requirements. The reasons can be financial, practical or because of the heritage value of the original object. This situation is encountered in different disciplines like in civil engineering where buildings are retrofitted to new safety norms or in biology where implants are used to re-establish or improve the function of an organ. Also, for the design of some motorsports vehicles, a series vehicle is used as a basis and adapted to the specific needs of racing operations.

When topology optimization methods are used to solve an adaptation problem, most of the added material is spread into layers to reinforce the existing members. These results cannot be easily interpreted into a component and a control over the topology of the added material is required. In the case of a motorsport vehicle, the main structural adaptation measure is the addition of a roll cage. Therefore a method is developed which provides a framework-like reinforcing structure as a result of a topology optimization applied on an adaptation task.

## 1. INTRODUCTION

Numerical optimization methods have proven to be efficient for finding solutions to structural layout problems. Numerous studies have been published concerning the design of new structures but a small number can be found about the optimal adaptation of an existing one. Diaz and Kikuchi formulate a reinforcement topology optimization problem in which a given structure is reinforced using a prescribed amount of material [1] but no control over the topology of the added elements is included. Wang investigated the relationship between rigidity improvement and material reinforcement of a car body shell [2]. The design space is restricted to the thickness of the existing structure.

The content of this paper is the first investigation for optimizing added structure components which have connections to the basic structure at few places.

## 2. DEVELOPED METHOD

Matlab is a well-known tool for easily implementing own optimization routines. Several Matlab codes for educational purpose have been published for topology optimization. A comprehensive list can be found in [3]. The research group on Topology optimization of the Technical University of Denmark has published some of them, for example the 99-line program for two-dimensional topology optimization [4] or the 88-line efficient version of it [5]. Based on these software programs we developed a method for optimizing added structures called *AdOpt*.

### 2.1. Sensitivities penalization of boundary zone elements

The goal is to achieve reinforcement with few material adjacent to the basis structure. To do so, the underlying idea of the method is to apply a special treatment to the elements on the boundary of the basis structure during the optimization loops. These elements are next referenced to as *BZE* (boundary zone elements) while the remaining elements of the design space are called *nBZE* (non-boundary zone elements). The sensitivities of the *BZE* are penalized in order to remove a high amount of them. In the same time, enough elements must be kept in order to make the necessary connection between the basis and the reinforcing structure.

The penalization factor  $Q_e$  for the sensitivities of the *BZE* is chosen dependent on the actual element density  $\rho_e$  and calculated by equation 1:

$$Q_e = \rho_e * F. \quad (1)$$

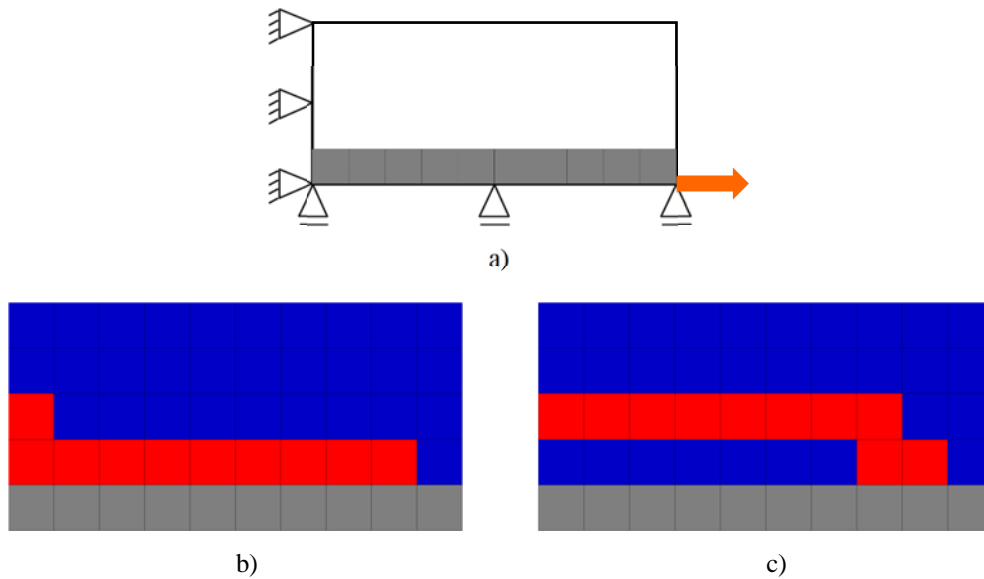
The factor  $F$  is used to define under which density values, the penalization factor  $Q_e$  becomes smaller than one and thereby lowering the sensitivity values of the corresponding elements (respectively greater than 1 and increasing their sensitivities). For example, by setting  $F = 1,5$ , all elements with a density value smaller than  $\rho_e = 0,66$  will have their sensitivities decreased. The modified sensitivity values  $\left(\frac{\partial c}{\partial \rho_e}\right)_Q$  are calculated as:

$$\left(\frac{\partial c}{\partial \rho_e}\right)_Q = \frac{\partial c}{\partial \rho_e} Q_e, \quad (2)$$

with  $\frac{\partial c}{\partial \rho_e}$  the sensitivity value before sensitivity penalization.

An effect of the use of sensitivity penalization can be found in Figure 1. The load case corresponds to a uniaxial traction and symmetry is used in the example. With the standard method, all added elements are on the boundary of the basis (Figure 1b), which is not the case when the sensitivity are penalized (Figure 1c).

The size of the layer of boundary zone elements can be defined by the user. At least two elements are necessary to avoid connection thru the corner nodes only, between basis and reinforcing elements. Furthermore, a filter has to be applied to suppress checkerboard effect.



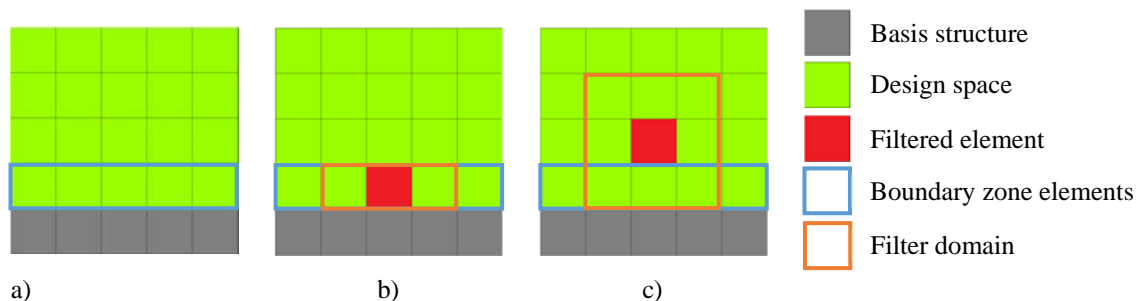
**Figure 1:** Tensile beam a) Design domain, basis structure, boundary conditions, and external load, b) Result without penalization of sensitivities, c) Results with penalization of sensitivities

## 2.2. Filtering

During topology optimization, filtering techniques are used to prevent results in checkerboard fashion. A whole range of them are described in (Sigmund 2007). For an adaptation optimization, the operating mode of a filter has a great influence on the results.

If the loadcase for the adaptation task is close to one used for generating the basis structure, the sensitivities of the elements of the basis structure will be high. If they would be considered during the filtering of the design space, they would increase the sensitivities of the surrounding elements, namely the BE. This would finally lead to a high amount of material added on the boundary which is the kind of result we want to avoid. Therefore, they are not considered during filtering.

For the filtering of the BZE, the nBZE are also not considered as this would also increase their sensitivities. For the filtering of the nBZE, the BZE are considered. Thereby, elements of the nBZE close to BZE having low sensitivity will have decreased values and the other way around (Figure 2).



**Figure 2:** a) Elements groups with highlight of the boundary zone elements, b) Filtering domain for a boundary element, c) Filtering domain for a non-boundary zone element

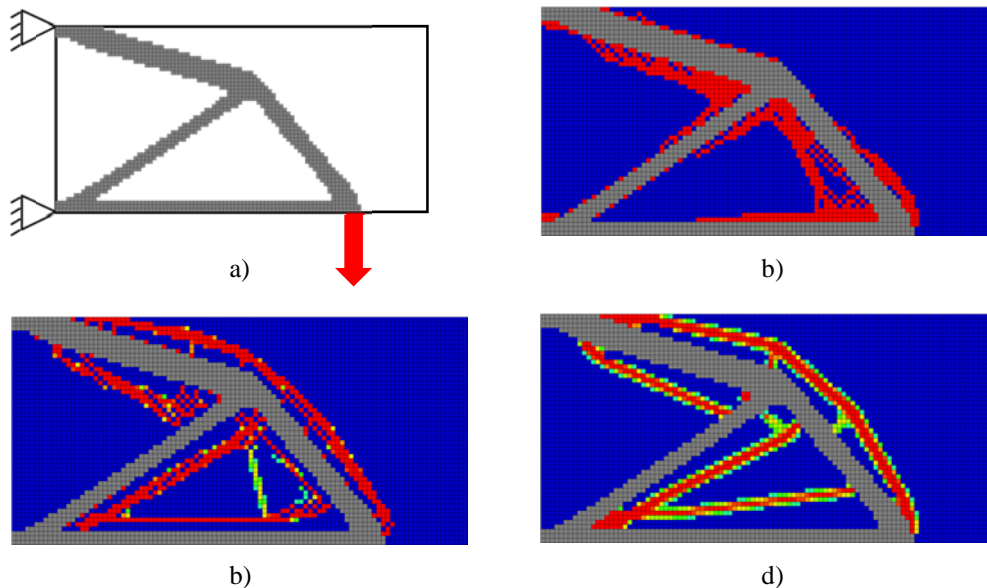
### 3. NUMERICAL EXAMPLES

The developed method is applied in the following on several example problem formulations. The basis structure has been generated with a constraint on the volume fraction of 0,2. During adaptation, the same load case is used and the goal is to minimize the compliance with a new constraint on the volume fraction of 0,3.

#### 3.1. Cantilever plate 1

##### 3.1.1. Optimization process and results

The problem is solved with different settings. First, the topology optimization is done without modification of the sensitivity values or filtering (Figure 3b). For the second run, the penalization of sensitivities is activated (Figure 3c). The third run is done with the described filtering method additionally.



**Figure 3:** Cantilever plate: a) Initial design domain, b) Without penalization of sensitivities and without filter, c) With penalization of sensitivities and without filter, d) With penalization of sensitivities and with filter

The first run delivers a results where the material is mostly added on the boundary of the basis. Also, a new member is created. When the sensitivity penalization is activated, few elements on the boundary have high density. Still, checkerboard effect is present. The use of the filters enables an aggregation of the elements having high density.

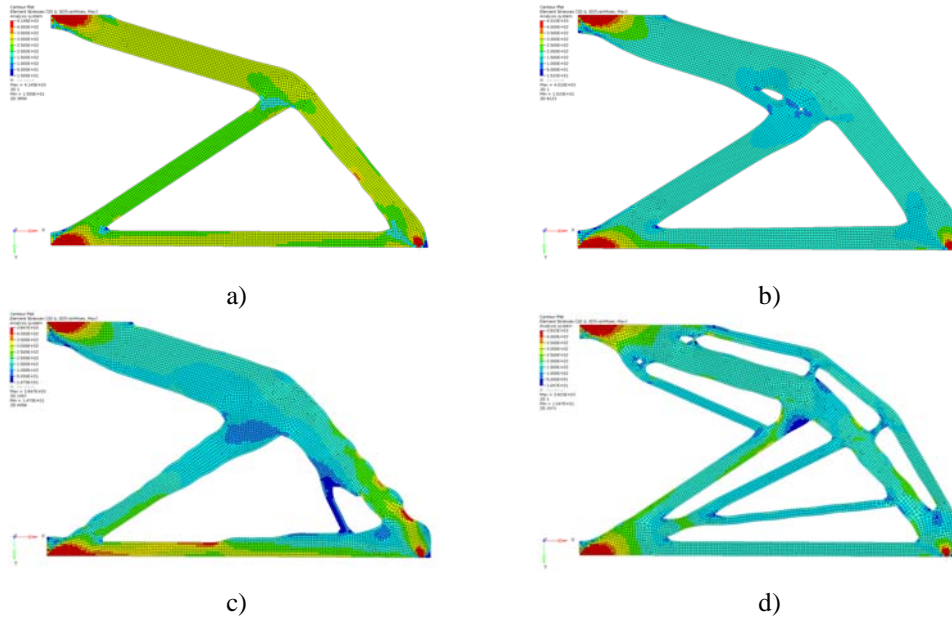
At the end of the optimization with *AdOpt*, the reinforcing structure consists of beam-like elements, connected to the basis structure at a few locations.

##### 3.1.2. Results validation

For analyzing the performance of the generated structures, the optimization results are smoothed using the capabilities of a commercial software (Optistruct) and submitted in a finite element analysis.

Four models are compared:

- basis structure
- direct optimization (without the basis structure in the model)
- adaptation without AdOpt
- adaptation with AdOpt



**Figure 4:** Stresses for the cantilever plate: a) Basis structure, b) Direct optimization, c) Without AdOpt, d) With AdOpt

For the basis structure and the direct optimization, the stresses are uniform within the model (Figure 4a). When the adaptation is done without *AdOpt*, some area of the added elements are very little loaded while some areas of the basis structure experience high stress values (Figure 4c). With *AdOpt*, all members of both the basis and added structure are evenly stressed which is an indication of a meaningful material distribution (Figure 4d). The models with the new constraint have the same mass of 1,5 times the mass of the basis. Therefore, a direct comparison of the model performances can be done by evaluating the increase in stiffness relative to the value for the basis structure (Table 1).

The stiffness obtained with *AdOpt* is close to the one of the direct optimization although the problem formulation has the additional constraints to keep the basis structure and enforce a distant added structure. Furthermore, in this example it has an even better performance then without *AdOpt*.

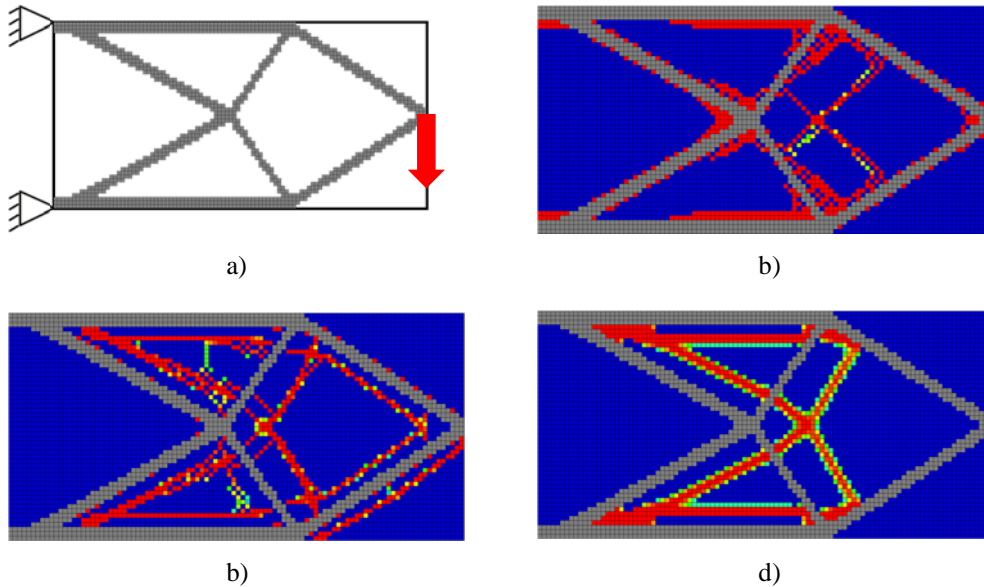
**Table 1:** Relative stiffness for an equal mass increase of the basis structure

	Relative mass	Relative stiffness
Basis structure	1	1
Direct optimization	1,5	1,29
Adaptation without AdOpt	1,5	1,24
Adaptation with AdOpt	1,5	1,26

### 3.2. Cantilever plate 2

#### 3.2.1. Optimization process and results

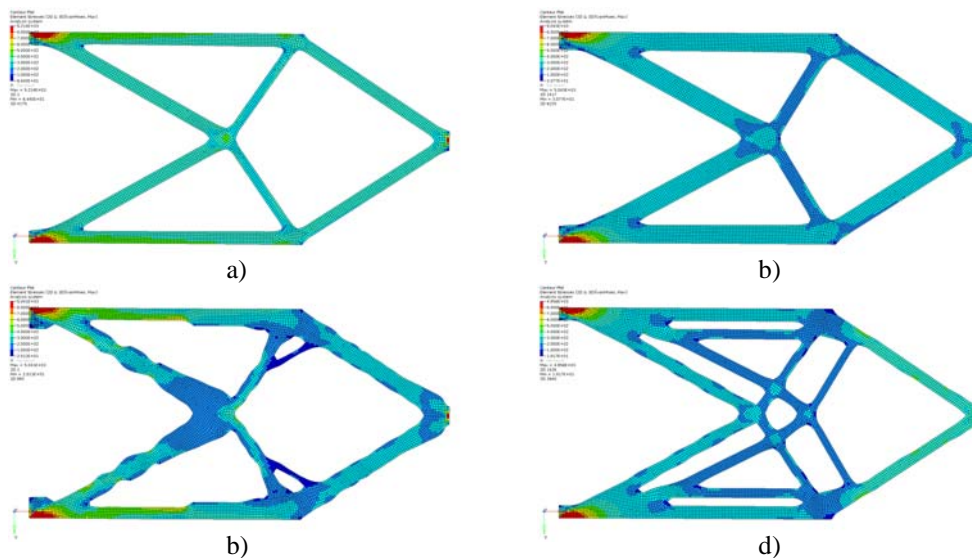
In this example, the location of the load is different which leads to a new topology of the basis (Figure 5). Similar effects to the ones of the previous examples are observed for the different optimization settings. The use of *AdOpt* delivers the required framework reinforcing structures.



**Figure 5:** Michell truss: a) Initial design domain, b) Without penalization of sensitivities and without filter, c) With penalization of sensitivities and without filter, d) With penalization of sensitivities and with filter

#### 3.2.2. Results validation

The adaption without *AdOpt* results like in the previous examples in higher stressed regions of the basis structure and little stressed members within the added material (Fig.6).



**Figure 6:** Stresses for the cantilever plate: a) Basis structure, b) Direct optimization, c) Without *AdOpt*, d) With *AdOpt*

On the other side, the stresses in the model obtained with *AdOpt* are more even.

When comparing the relative stiffnesses (Table 2), the performance of the adaptation with *AdOpt* is again close to the one of the direct optimization.

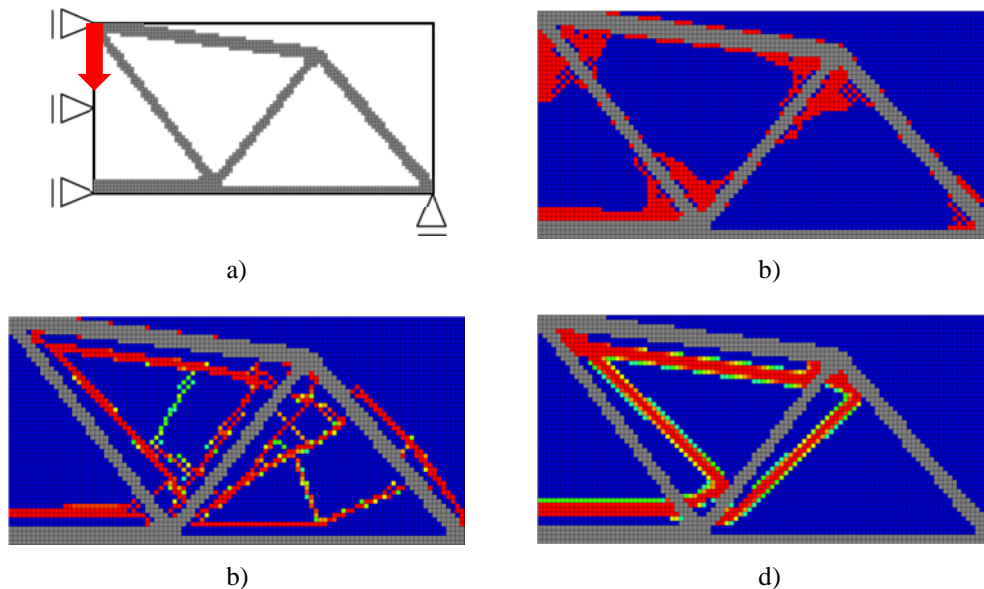
**Table 2** Relative stiffness for an equal mass increase of the basis structure

	Relative mass	Relative stiffness
Basis structure	1	1
Direct optimization	1,5	1,30
Adaptation without <i>AdOpt</i>	1,5	1,24
Adaptation with <i>AdOpt</i>	1,5	1,25

### 3.3. Symmetric MBB beam

#### 3.3.1. Optimization process and results

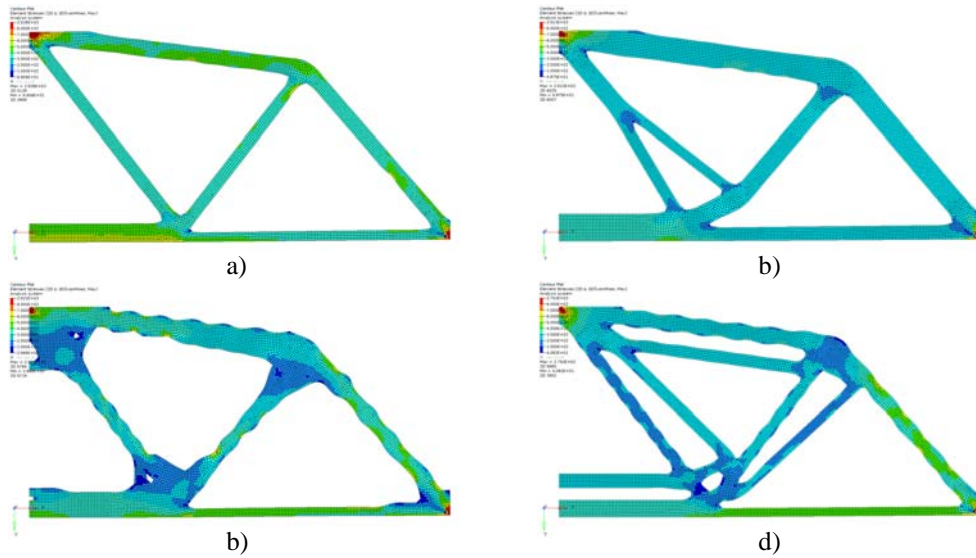
The symmetric MBB is a classic example in topology optimization. A study of the adaptation results is performed next. For the symmetric MBB beam, similar effects to the ones for the cantilever beam are observed (Figure 7). On the Figure 7b, it can be seen that reinforcement is done on the corners of the basis members. With *AdOpt*, the material usage is completely different because new members are used to strengthen the basis.



**Figure 7:** Symmetric MBB Beam: a) Initial design domain, b) Without penalization of sensitivities and without filter, c) With penalization of sensitivities and without filter, d) With penalization of sensitivities and with filter

#### 3.3.2. Results validation

The stress distribution without *AdOpt* is better then in the previous examples because fewer areas have low stress values (Figure 8b). When using *AdOpt* the added member have even stress distribution with values close to the ones of the basis.



**Figure 8:** Stresses for the cantilever plate: a) Basis structure, b) Direct optimization, c) Without AdOpt, d) With AdOpt

The relative stiffness value with the latter results is slightly higher than without *AdOpt* (Table 3). The stiffness of the direct optimization is only 9% higher than with the proposed method.

**Table 3** Relative stiffness for an equal mass increase of the basis structure

	Relative mass	Relative stiffness
Basis structure	1	1
Direct optimization	1,5	1,46
Adaptation without AdOpt	1,5	1,32
Adaptation with AdOpt	1,5	1,34

#### 4. FINAL REMARKS

The shown numerical examples illustrate that the developed *AdOpt* method is able to deliver the required topology of reinforcing structures. Furthermore, it has been seen in the application examples that the performance is close and sometimes better than for results obtained with an actual state-of-art method applied on an adaptation task.

Further research activities will be the implementation of an algorithm to account for multiple constraints. Thereby, a control over the amount and shape of the connecting elements between basis and reinforcement is expected. Furthermore, stress constraints could be considered

The use of a commercial solver in the optimization loop to gain in computation speed is required. Finally, a better understanding of the factor used for penalization and effect on the result is necessary



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