The Eleventh International Conference on
Engineering Computational Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Eleventh International Conference on
Engineering Computational Technology
Edited by B.H.V. Topping and P. Iványi
Civil-Comp Conferences, Volume 2, Paper 4.2
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.2.4.2

Actuator Placement on Structural Test Rigs using Global and Local Optimization

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Abstract

The design of structural testing devices often proves to be a complex technical issue. One of the key questions is how a limited number of force actuators have to be attached to a specimen in order to achieve a desired stress or strain state in the test area. An intuitive placement often does not lead to an optimal solution, which is particularly true for complex stress fields. To solve this problem, the present paper introduces an approach based on numerical optimization. For this purpose, both a global and a combination of local and global optimization methods were selected. The developed optimization framework has been applied to the simple problems of a tensile and a shear test. Since the optimal solutions for these test cases are known, the quality of the results can be easily assessed. It is shown that global optimization by means of evolutionary algorithms leads to very good results for the tensile test and can deal very well with the problem of the opposing goals of a low stress deviation and a low actuation force. In order to obtain the optimal solution to the shear test problem, a combined global and local optimization using evolution algorithms and a gradient-based algorithm has been applied. With this approach, the optimal solution can also be found for the shear test problem. The optimization process presented offers a promising basis for ongoing work on the optimal positioning of actuators on more complex real world structural testing devices.

Keywords: structural test, actuator placement, multi-objective optimization, evolutionary algorithms, gradient-based optimization.

1 Introduction

Despite the increasing accuracy and availability of numerical simulation methods, tests on real components still play an important role during the design and certification process of aircraft structures. Typical examples for this kind of experimental work are buckling and fatigue tests of stringer-stiffened shells, which are representative for fuselage or empennage structures [1, 2, 3, 4]. This type of component tests requires devices that are able to apply appropriate loads to the specimens. These external forces and moments induce internal stress fields, which ideally should be identical to those of the real structures considered. Usually, test rigs or load frames with attached actuators are used for this purpose.

In general, the purpose of structural test rigs is to create specific stress or strain states in specimens, which allow their structural behavior to be examined. The relevant stress distributions are usually available either from previously conducted large-scale tests or from detailed finite element analyses. In contrast, the forces that actuators have to apply to the edges of test specimens in order to create the required stress or strain fields are often unknown. In addition, real test rigs are generally subject to severe restrictions with regard to the load introduction, for example due to the limited number of discrete actuators, their force range, the positioning options and the control capabilities. For every new test device, design engineers therefore have to solve the challenging task of arranging the actuators appropriately to get the required stress fields.

The present paper deals with a numerical approach for the placement of actuators on the edges of structural test specimens in order to meet specific requirements for the stress or strain state in the test area, as shown in Figure 1. Since there is a trade-off between the best match with the desired stress state and the actuation effort, a multi-objective optimization problem has to be solved. In addition, both discrete and continuous design variables must be considered. Evolutionary algorithms are well suited for solving this type of complex optimization problem. Therefore, they have been selected here as the global optimization method. In order to improve the quality of the resulting solutions, this approach is supplemented by a local optimization method.

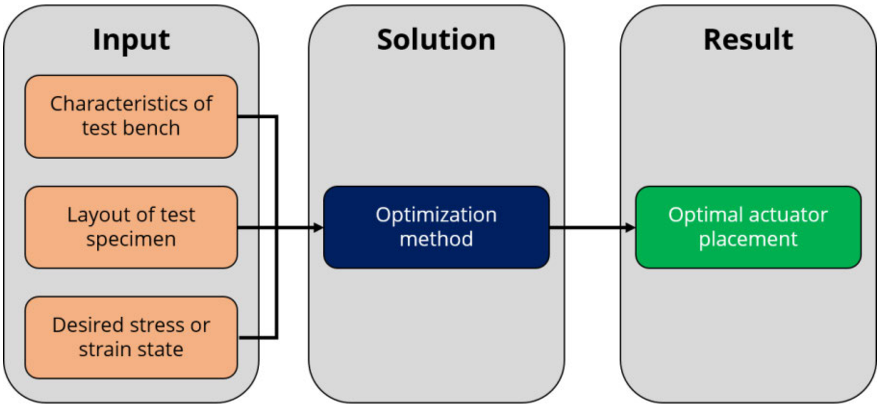

Figure 1: Principle of the actuator placement problem considered.

For a first evaluation, the presented optimization approach has been applied to simple academic structural test problems. Since the corresponding optimal solutions are known, the potential and limits of the proposed procedure can be explored. On this basis, it is possible to derive a path for the further development of an actuator placement optimization procedure that is suitable for more practical applications.

2 Methods

Figure 2 shows an example of a simple test structure that is loaded by discrete actuators. The desired stress state is defined as the reference state that is to be obtained during the structural test. Therefore, a number of n_{Act} actuators have to be placed on the edges of the sample in order to achieve the minimal difference between the resulting and the desired stress state with minimal actuation effort.

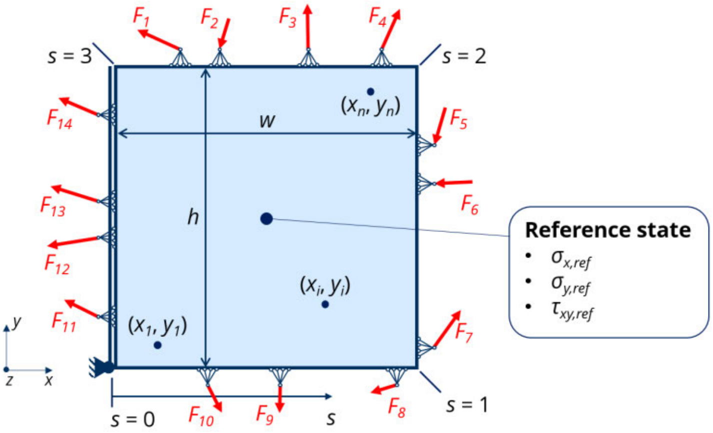

Figure 2: General layout of a test structure with discrete actuators.

For the numerical optimization, the difference between the actual and the constant reference stress state $\sigma_{x,ref}$, $\sigma_{y,ref}$, $\tau_{xy,ref}$ is calculated as the mean absolute deviation of the plane stress components $\sigma_{x,i}$, $\sigma_{y,i}$, $\tau_{xy,i}$ at the discrete points (x_i, y_i), $i = 1, \ldots, n$:

$$\Delta\sigma = \frac{1}{3n} \sum_i \left(\left|\sigma_{x,i} - \sigma_{x,ref}\right| + \left|\sigma_{y,i} - \sigma_{y,ref}\right| + \left|\tau_{xy,i} - \tau_{xy,ref}\right| \right) . \tag{1}$$

The actuation effort is described by the summed force magnitudes of all $j = 1, \ldots, n_{Act}$ actuators:

$$F_{total} = \sum_j \left|F_j\right| . \tag{2}$$

The optimization problem is defined by the two objective functions

$$\min(\Delta\sigma(\mathbf{x})) , \tag{3a}$$

and

$$\min(F_{total}(\mathbf{x})) , \tag{3b}$$

where $\mathbf{x}_{\min} \leq \mathbf{x} \leq \mathbf{x}_{\max}$ are the design variables. Figure 3 outlines the developed framework to solve the problem described.

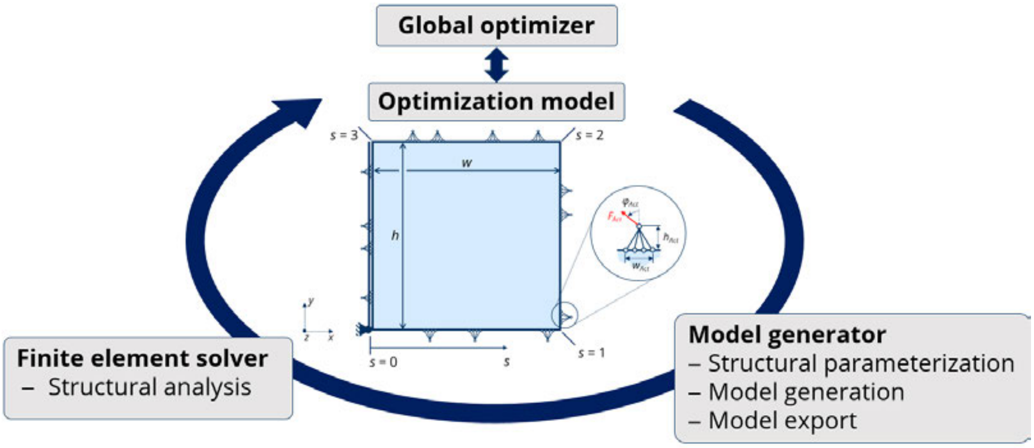

Figure 3: Outline of the global optimization approach.

The in-house optimization tool GEOpS^2 [5], which is based on evolutionary algorithms, is used as a global optimizer. It is connected to a model generator that provides a finite element mesh of the test arrangement. Finally, the in-house static finite element solver FiPPS^2 is used to determine the stresses in the loaded test structure, which are required to calculate the values of the objective function (3a).

To improve the process, a second optimization approach is considered, which includes an additional local optimization method, as shown in Figure 4.

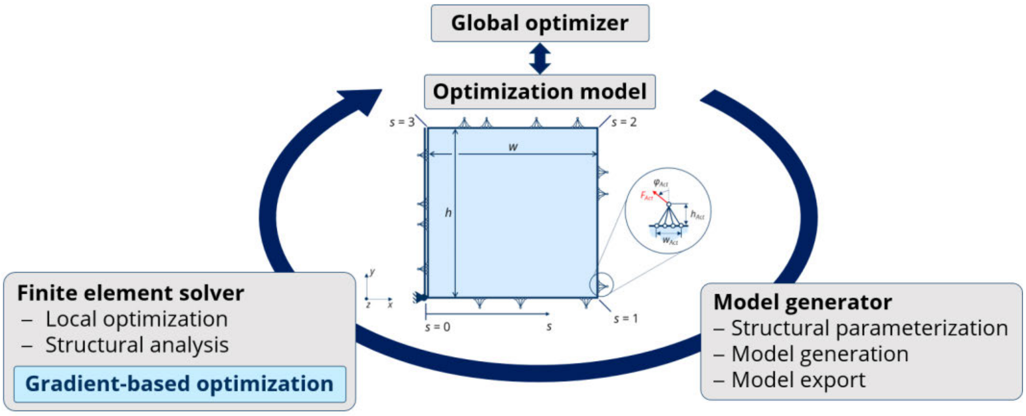

Figure 4: Outline of the combined global and local optimization approach.

Therefore, a gradient-based optimization algorithm is used to vary the actuator force magnitudes and directions in order to minimize $\Delta\sigma$ in a single-objective problem. For this purpose, the open source optimization library NLopt [6] is linked to the finite element solver at source code level, which enables a highly efficient implementation. The very time-consuming Cholesky factorization of the stiffness matrix is only carried out once for each local optimization. The remaining variables are included in the outer global optimization loop, which solves the two-objective problem of minimizing $\Delta\sigma$ and F_{total}.

3 Results

The uniaxial target stress state ($\sigma_{x,ref}$ = 50 MPa, $\sigma_{y,ref}$ = 0, $\tau_{xy,ref}$ = 0) for a rectangular plate with dimensions w = 200 mm, h = 50 mm and a thickness t = 1 mm is defined as indicated in Figure 5.

A fixed number of n_{Act} = 12 actuators with width w_{Act} = 5 mm and height h_{Act} = 20 mm is used.

The aim is to find an optimal actuator placement, which is defined by the design variables

- position s_j
- force magnitude $F_{Act,j}$ and
- force direction $\varphi_{Act,j}$

for each actuator j in order to match the reference stress state in the area marked in green.

Only the global optimization approach (Figure 3) is used for this example. Since the optimal solution to this academic problem is known, an initial, well-founded evaluation of the results can be carried out before dealing with more complex problems.

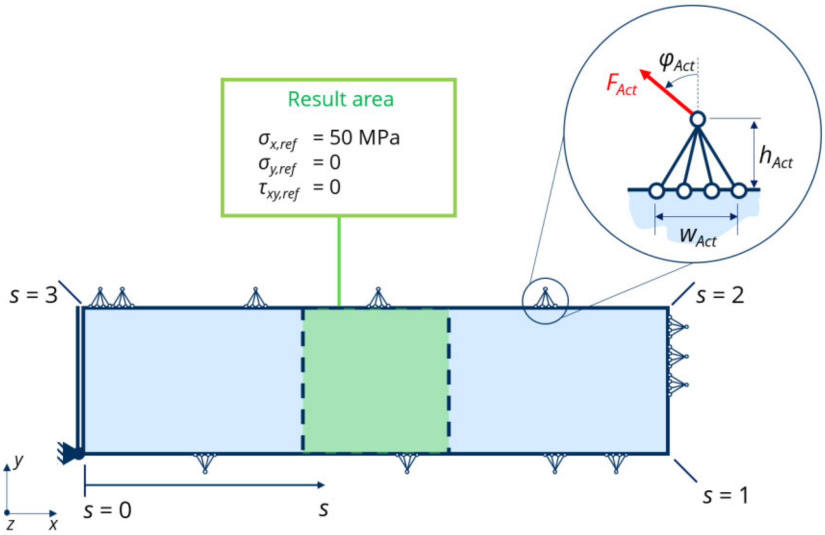

Figure 5: Layout of the tensile test problem.

Figure 6 shows the resulting Pareto front and the individual with the lowest stress deviation. The solution fits very well with the expected result.

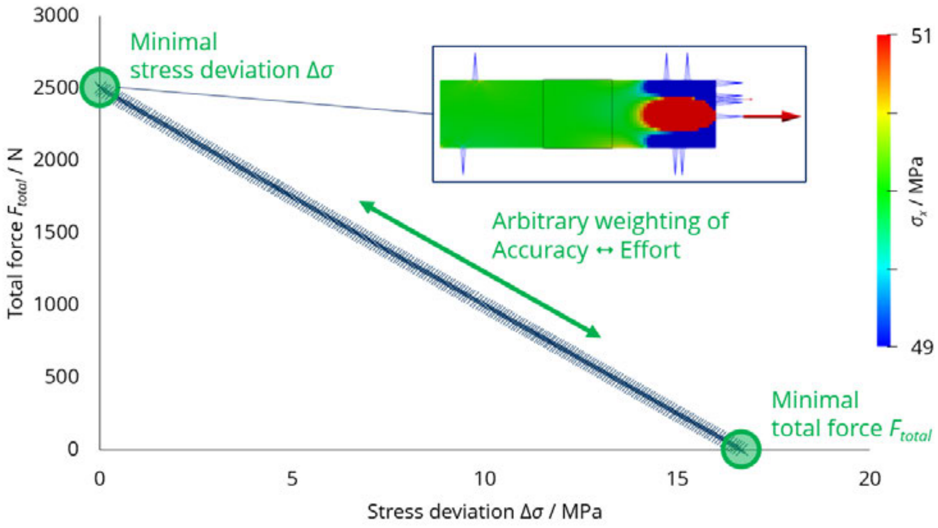

Figure 6: Resulting Pareto front for the tensile test problem with the individual having the lowest stress deviation $\Delta\sigma$.

As a second, more complex example a shear test is considered. In this case, the actuators are modeled as segmented line loads, which are defined by the design variables

- number of actuators n_{Act}
- position s_j
- length $w_{Act,j}$
- force $q_{Act,j}$ and
- force direction $\varphi_{Act,j}$ of each actuator j

as shown in Figure 7.

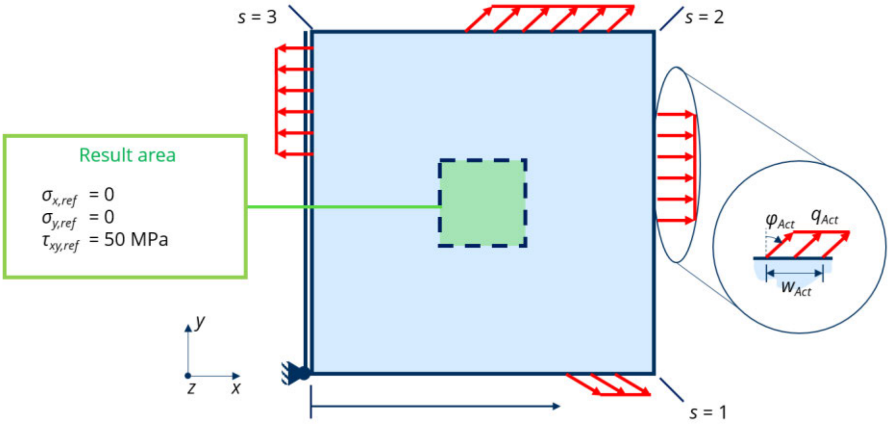

Figure 7: Layout of the shear test problem.

The shear test problem is solved using the global approach (see Figure 3) as well as the combined global and local approach (see Figure 4). For local optimization, the low-storage BFGS (L-BFGS) [7, 8] algorithm is used to vary $q_{Act,j}$ and $\varphi_{Act,j}$ while the remaining variables are part of the global optimization.

Figure 8 shows the resulting Pareto fronts and the corresponding individuals with the lowest stress deviation $\Delta\sigma$.

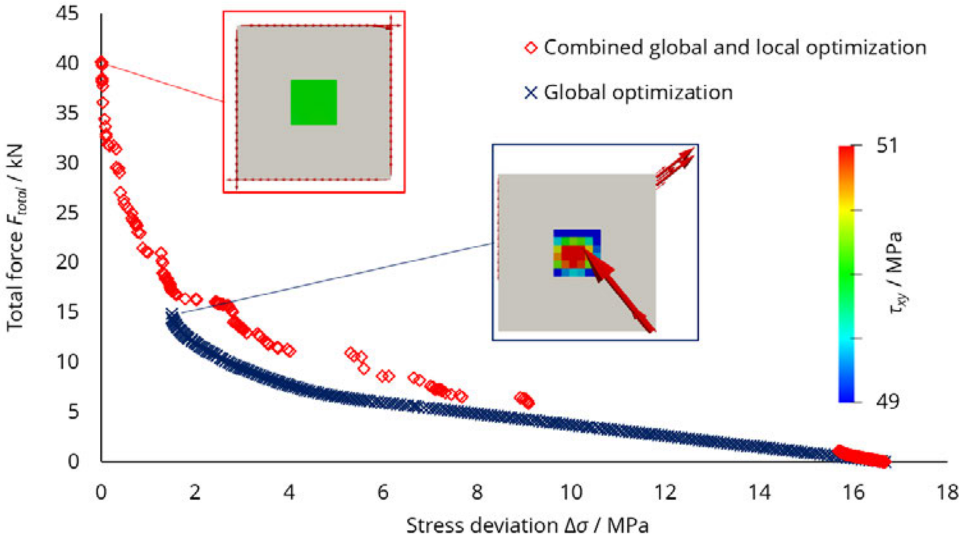

Figure 8: Resulting Pareto fronts for the shear test problem and the corresponding individuals with the lowest stress deviation $\Delta\sigma$.

It can be clearly seen from that diagram that the pure global optimization approach results in a continuous Pareto front for the two-objective problem, but is not able to find the optimal solution. The combined global and local approach, however, provides the optimal solution, but shows discontinuities in the Pareto front.

4 Conclusions and Contributions

The present work deals with the problem of placing actuators on the edge of flat structural test specimens in order to achieve a desired stress state. A suitable optimization process has been developed and applied to two standard test problems of rather academic nature. It has been shown that the global optimization approach with evolutionary algorithms can find the optimal solution for a tensile test problem. For the more complex test case of a shear-loaded sample, however, the global optimization could not identify the expected optimum. Combining the global optimization with a local gradient-based optimizer has resolved this deficiency and allowed to find the optimal stress state also for the shear test problem.

A drawback of the latter method is that the Pareto front of the two-objective problem has significant discontinuities. The explanation for this observation is the fact that the gradient based optimizer is unable to handle multi-objective problems.

The analysis of the results obtained permits to derive important basic knowledge about the problem of actuator placement on structural test specimens. Further research will be carried out to improve the optimization approach for dealing with real life problems when placing actuators on structural test benches. For example, a modification of the target function for the stress and strain deviation will be considered in order to enable evaluations of predefined stress and strain states that are not constant in the test area. In addition, a more precise modeling of the actuators as well as variable thicknesses and sizes of the support structure surrounding the test object will be examined.

Acknowledgements

This research was funded by the German Federal Ministry for Economic Affairs and Energy under grant number 20Q1716B. The responsibility for the content is with its authors. The financial support is gratefully acknowledged. The numerical calculations have been performed on the Bull HPC-cluster of the Zentrum für Informationsdienste und Hochleistungsrechnen (ZIH) of the Technische Universität Dresden.

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