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Influence of Variable Support Conditions on Topology Optimization of Load-Carrying Parts

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Abstract: The paper addresses the importance of proper modeling of boundary conditions in preparing a FEA model for topology optimization of load-carrying structural parts. More specifically, the focus is on possible variations of support conditions during the service life of a structural part. Such variations emerge from various reasons, for example, from a fixing screw becoming loose. Since such variations are not deterministic and may cause the structural part to operate within a wide range of various conditions, this paper aims to improve the insight into this problem and to suggest a way to mitigate it. For this purpose, a bracket intended to carry a hydraulic motor is used as a test example and the topology of its design is optimized under various support conditions. The results are then analyzed in order to evaluate the consequences, caused by variations of the supports. Furthermore, a novel optimization procedure scheme is proposed based on selective load cases activity. This procedure aims to reduce the computational effort that may otherwise increase by an order of magnitude due to addition of all possible support variations. It is shown that adequate preparation of load cases that include all possible support conditions is of extreme importance since otherwise the part may behave badly in practical application even if its design looks to be quite reasonable. The new proposed optimization procedure also proves to reduce the needed computational effort substantially.

Keywords: lightweight design; load-carrying structure; topology optimization; variable support conditions

1 INTRODUCTION

Design and construction of load-carrying parts is an ever more challenging task for engineers. The reasons for that are steadily increasing requirements related to longer lifespan, reduced material consumption, and specific demands of manufacturing technologies. Fortunately, the development of structural design and optimization procedures is more or less able to follow those increasing demands. The most vital tools in this context are the procedures for numerical analysis of structural response and the corresponding numerical optimization procedures, see for example [1-3]. Unfortunately, proper engagement of all these tools may be quite tricky in real-life applications, which may lead to disappointing results. In many cases, the reason for a bad result is insufficient knowledge about the modeling of boundary conditions and inadequate understanding of their actual role within the optimization process.

Topology optimization can result in substantial benefits when compared to other optimization types, [4, 5]. Nevertheless, its development was rather slow in the past, because topology optimization procedures were plagued by quite some numerical difficulties, [6]. On top of that, topology optimization often generates designs, which are practically impossible to produce with conventional technologies. However, these circumstances are currently changing practically daily due to the impressive development of modern multi-axis CNC machines and additive manufacturing (AM) technologies.

By engaging AM processes, almost every custom design can be produced and excellent new materials have been emerging frequently in the past few years. This specific circumstance created new potentials for employing topology optimization procedures in the design of load-carrying parts. In fact, those procedures have become vitally important since AM produced parts are typically sensitive to crack initiation, which can cause early and unexpected structural failure of a mechanical part. In order to minimize the risk of potential structural failure of such parts, probably the most important requirement is to lower the stress levels as much as possible and to remove stress concentrations.

Design of a load-carrying part with limited volume, low stress levels, and without stress concentrations is an extremely demanding task, which requires the employment of adequate numerical procedures, typically FEA combined with topology optimization, e.g., [7]. What is often underestimated in these procedures is the importance of accurate modeling of boundary conditions (supports and loads) and the need to understand fully what the optimizer is actually doing. Consequently, maybe two of the most exposed reasons for bad topology optimization results can be outlined briefly as follows:

- **Misuse of standard FEA modelling practices.** In standard FEA procedures it is quite reasonable to engage many simplifications or procedures that may reduce the modeling and computation time, while preserving reasonable accuracy. For example, variable size finite elements are used in mesh generation, or, in a bolt fastening situation the nodes being in contact with the bolt are simply fully fixed. This introduces errors that may often be neglected in standard FEA. In topology optimization, however, these errors may quickly cause the optimizer to generate a bad design.
- **Insufficient understanding of the optimization process.** What is often forgotten is that a topology optimizer will generate a design that is totally and exclusively adapted to the underlying boundary conditions. This requires an extremely careful analysis of all possible supporting and loading situations that might (maybe accidentally) appear during the life time of a part. Any failure in capturing all possible situations may result in designs that will not fulfill the expectations. In the context of optimization, a particular support/loading situation of a part is termed a *load case*. Proper identification and inclusion of all possible load cases is therefore of the most vital importance.

An example illustrating the importance of adequate load cases is shown in Fig. 1. The load-carrying arm is supported by two pins and carries a vertical load. If the part is optimized only with respect to the prescribed vertical load, the optimal design would be highly sensitive to possible transverse (horizontal) loading. Additional transverse loading is therefore needed to generate a more robust design that is resistant also against accidental transverse loads.

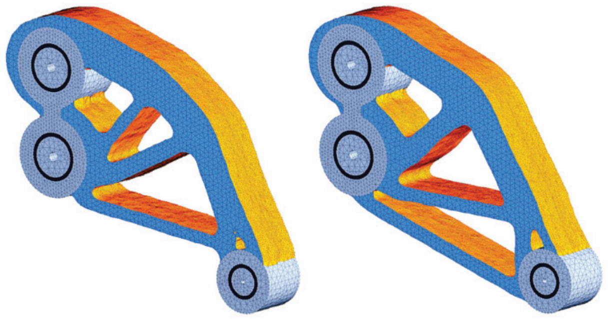

Figure 1 Optimal design of a load-carrying arm obtained by prescribed loading only (left) and by various more realistic loadings that may occur accidentally (right)

Unfortunately, the need to introduce additional load cases results in substantially increased computational effort. In real-life application this additional effort may quickly reach completely unacceptable levels since the needed FEA models are often enormous, exhibiting tens of millions of degrees of freedom (DOF). To address this problem, in this work a special procedure is proposed based on selective load case activity.

This paper aims to improve the understanding of topology optimization processes of load-carrying parts. More specifically, it addresses the problem of identifying properly all possible support conditions in case of a screw fastening of a part. Special attention will be given to the consequences of changed support conditions caused by a screw becoming loose. In addition, a new procedure is proposed to mitigate the problem of increased computational effort. The outline of the paper is as follows. Section 2 presents the proposed procedure of managing and inactivating potentially irrelevant load cases in order to speed up the optimization process. Section 3 presents briefly the investigated example structure. In Section 4 the optimization model is described in detail with focus on variable support conditions. In Section 5 the optimization results are presented and accompanied by an analysis of the design performance. Based on the results Section 6 outlines the conclusions valuable for a designing engineer.

2 SELECTIVE LOAD CASE ACTIVITY

A topology optimization process is inherently a computationally demanding task. This is because, firstly, the underlying FEA models must be densely meshed, which leads to enormous number of DOFs. Secondly, the process is iterative, typically requiring many cycles. And thirdly, the number of load cases is also typically quite high. If one denotes the number of cycles by N, and the number of load cases by M, the complete optimization process will require $N \times M$ full analyses of a large FEA model. This is by itself a large computational effort, but things get much worse once we start thinking about all possible variations of boundary conditions. As it turns out, this may increase the number of load cases by a factor of $K$and the number of needed analyses will easily increase by an order of magnitude to $N \times M \times K$. Just to illustrate the involved orders of magnitude, quite usual numbers N, M and K are 100, 20 and 5 respectively, resulting in a total of 10^4 required FE analyses.

In real-life applications, this is a serious problem that needs to be addressed. For that purpose, in this work a special procedure was implemented aiming to reduce this high number of FE analyses. This procedure is based on a presumption that as the number of load cases increases, the possibility of a particular load case to become irrelevant for the final optimization result also increases. The idea is to try identifying irrelevant load cases during the optimization process and skip those load cases to reduce the computational effort. For this purpose, a so-called activity factor $a_i \in [0, 1]$ was defined as

$$a_i = \frac{n_i}{n} \tag{1}$$

where $i = 1, \dots, M \times K$ is the load case index, n is the total number of design variables (parameters, associated with material density at a particular point of the structure) and n_i is the number of design variables, that will be updated based on the sensitivity coefficients s_j resulting from the i-th load case

$$s_j = \max_i \left(s_{ij} \right), \quad j = 1, \dots, n \tag{2}$$

where s_{ij} is the sensitivity coefficient corresponding to the i-th load case and j-th design variable. It follows that an activity factor of $a_i = 0$ means that the i-th load case is irrelevant to the design process in the current cycle; on the contrary $a_i = 1$ means that the design changes in the current cycle will depend solely on the i-th load case. In other words, a_i reflects the current design relevance of the i-th load case. Based on these quantities the optimization procedure was modified to operate in the following way.

2.1 Optimization Procedure with Selective Load Cases Activity

1. Initialize the optimization procedure by marking all load cases as active.

2. Start new cycle: run FEA of all active load cases; inactive load cases are skipped.

3. Compute activity factors of all active load cases; if any activity factor a_i is less than some predefined activity trash value ε, that is if $a_i < \varepsilon$, mark the corresponding load case as inactive.

4. If any inactive load case was inactive for more than some predefined inactivity number m of optimization cycles, mark this load case as active again.

5. Perform the usual design step by updating the design variables on the basis of active load cases.

6. Check the convergence criteria:

(a) if met and all load cases are active, go to step 7
(b) if met and we have inactive load cases, mark all load cases as permanently active and go to step 2
(c) if not met, go to step 2.

7. Terminate the optimization.

The activity trash value ε should be chosen between zero and a few percent. The inactivity number m should be somewhere between a few and up to ten.

By implementing this procedure, load cases that currently look as irrelevant for the design process are simply skipped, meaning that we save the computational effort that would be otherwise needed for the corresponding FEA. This may result in significant savings in the total computational effort and time.

3 INVESTIGATED EXAMPLE STRUCTURE

The load-carrying structure used in this numerical investigation is a bracket mounted to a frame of a construction machine. The bracket carries a hydraulic motor and a wheel of the vehicle, which means that it has to carry all loads transmitted from the wheel to the frame. It is therefore a highly loaded and critical part of the vehicle, [8].

The initial design of the bracket, which is actually a maximum-volume design, is shown in Fig. 2. The bracket is mounted to the vehicle frame by four screws (red markers). In addition to the screws, the bracket is supported also by a contact along a thin strip that is pushed towards the frame by the applied loads (red strip). The loading, coming from the wheel, is applied at two larger borings (green areas) that hold the wheel pivot axle in position.

During vehicle operation, the amplitudes and directions of the applied loads vary significantly. Since the stress levels are very high, this raises the danger of possible fatigue crack initiation and structural failure. Such a part requires careful design to keep the stress concentrations low in the whole range of operation.

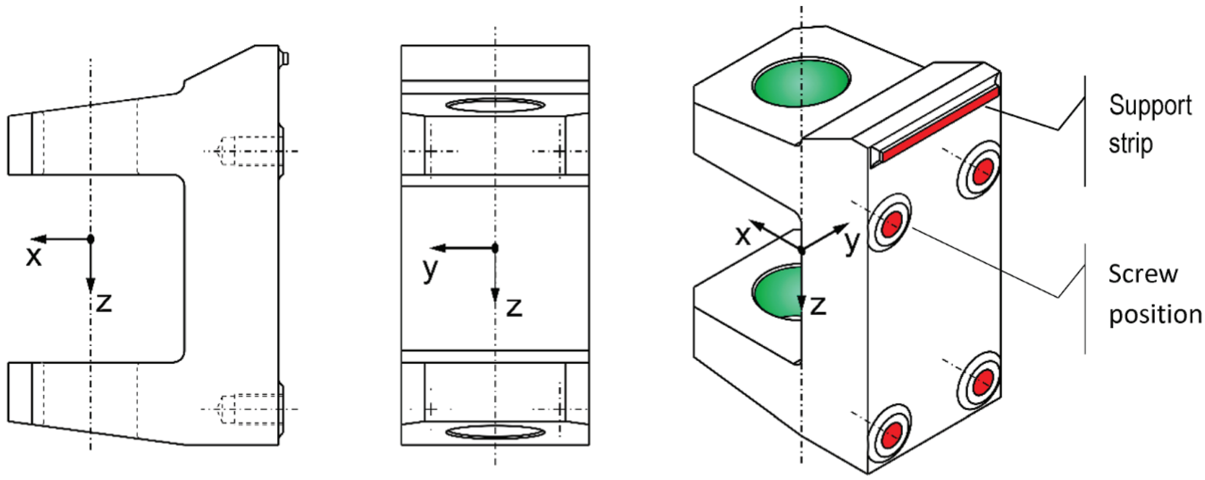

Figure 2 Example structure - a bracket carrying a hydraulic motor (various views)

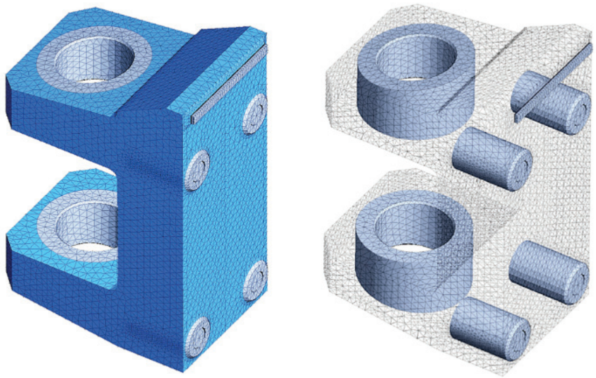

Figure 3 Optimization model of the bracket: free domain (blue) and fixed domain (gray); a thin contact layer is modeled along the thin supporting strip

4 OPTIMIZATION MODEL DEFINITION

The first step in preparing an optimization model is related to partitioning the domain of the part into volume regions so that one can exactly specify which regions have to remain fixed and which are declared free for optimization by material removal. In addition to this, contact regions also have to be defined in order to enable accurate modeling of loading and support conditions. In our case the bracket was partitioned as shown in Fig. 3. As can be seen the fixed regions are defined around the large borings for the wheel pivot axle and around the screws. A contact region was also defined as a thin layer connecting the part with the thin supporting strip. The rest of the part is considered to be free for optimization.

4.1 Loading Conditions

The bracket is loaded by: (i) vertical forces related to the vehicle weight and vertical impacts from the wheel, (ii) force couples (moments) caused by vehicle acceleration/deceleration, and (iii) force couples (moments) caused by driving through a right/left bend. In this way 5 basic load sets $B1$-$B5$, shown in Fig. 4, were created, as given in Tab. 1.

Table 1 Basic load sets $B1$-$B5$

Set name	Description	Resultant magnitudes (kN, kNm)
$B1$	Vertical load	$Fz = 7.5$
$B2$	Acceleration	$Mx = 4.2(2\times40\ \text{kN})$
$B3$	Deceleration	$Mx = 4.2(2\times40\ \text{kN})$
$B4$	Left bend	$My = 4.2(2\times40\ \text{kN})$
$B5$	Right bend	$My = 4.2(2\times40\ \text{kN})$

Table 2 Combined load sets $C1$-$C6$ used in the optimization process

Set name	$B1$	$B2$	$B3$	$B4$	$B5$
$C1$	x	x			
$C2$	x		x		
$C3$	x	x		x	
$C4$	x	x			x
$C5$	x		x	x	
$C6$	x		x		x

These basic load sets were combined into realistic load sets used in the actual optimization process. Tab. 2 lists all 6 combined load sets with marks indicating which of the basic load sets are included within a particular combined load set.

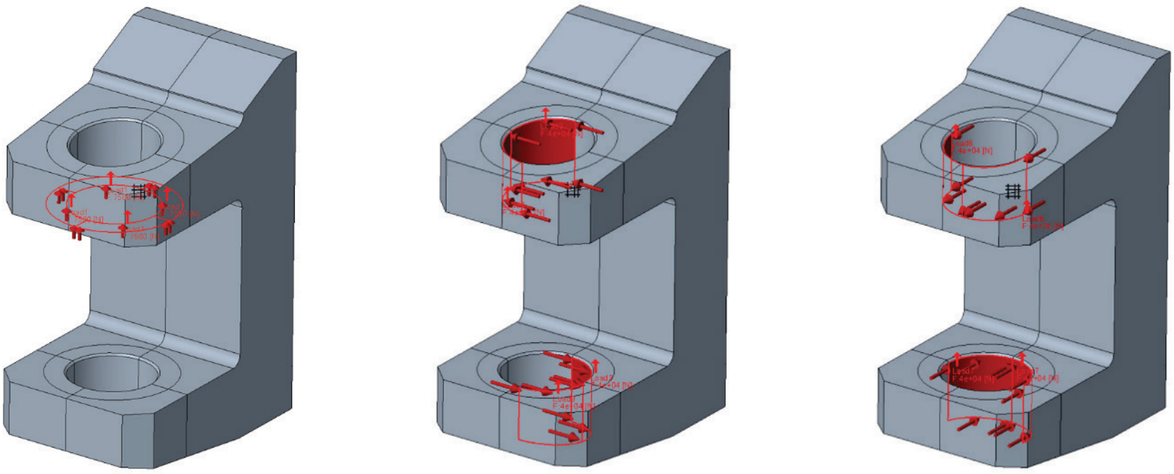

Figure 4 Basic load sets *B*1 (left), *B*2 (middle), and *B*4 (right); load sets *B*3 and *B*5 are symmetrical to *B*2 and *B*4 respectively

4.2 Ideal Support Conditions

The bracket is fastened to the vehicle frame by four screws. Under normal circumstances all of the four screws are tight, which means that all four screw cross-sections can be fully supported in the FEA model. This ideal support situation, shown in Fig. 5, is denoted as S1.

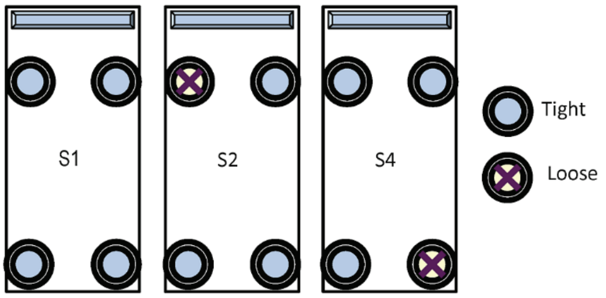

Figure 5 Bracket support conditions: ideal *S*1 (left) and worst-case *S*2 (middle) and *S*4 (right); conditions *S*3 and *S*5 are symmetrical to *S*2 and *S*4 respectively

4.3 Loose Support Conditions

In reality a screw connection is not exactly the same as prescribing zero displacements (fully supported) to the corresponding FE nodes. Instead, it is a rather sophisticated contact situation that may vary substantially once a particular screw tends to become loose. Under such circumstances, the support situation and consequently the stress field within a load-carrying part may change dramatically. For a fully optimized part this is a dangerous situation since the stress levels may very quickly rise to critical values.

To prevent such dangerous situations, a careful analysis of all possible support conditions is necessary in order to identify the most critical support situations and to include these critical situations into the optimization problem.

In our case two such worst-case support situations were identified as follows: (i) one of the upper fixing screws becomes completely loose, and (ii) one of the lower fixing screws becomes completely loose. The first worst-case support situation is denoted here as *S*2 and the second one is denoted as *S*4, Fig. 5. To promote better symmetry of the optimized design, symmetrical support situations, here denoted as *S*3 and *S*5, were also added to the total set of all considered situations.

4.4 Optimization Tasks

In order to illustrate clearly the influence of variable support conditions on final design, two topology optimization tasks were formulated as follows:

- **Optimization task T1**: assumes only ideal support conditions. The bracket is loaded by 6 combined load sets *C*1-*C*6 and supported by the *S*1 support conditions. In other words, we have $6\times 1=6$ load cases $L_{i1}=CiS1,\ i=1,...,6$.
- **Optimization task T2**: assumes both ideal and worst-case support conditions. The bracket is loaded by 6 combined load sets *C*1-*C*6 and supported by five *S*1-*S*5 support conditions. In other words, we have $6\times 5=30$ load cases $L_{ij}=CiSj,\ i=1,...,6,\ \ j=1,...,5$.

In both optimization tasks the objective was to minimize the strain energy of the structure. The prescribed volume part is 50% of the initial domain. One technological constraint was imposed, requiring plane symmetry with respect to the *X*-*Z* plane.

5 OPTIMIZATION RESULTS AND ANALYSIS

Both optimization tasks were solved by using CAESS ProTOp optimizer that is well suited to address very large numerical models. In our case the finest finite element mesh contained 0.75 million nodes and 4.3 million tetrahedral elements.

5.1 Optimal Designs

The solution of the first task T1 yielded the first design, here denoted by *D*1 and shown in Fig. 6. Similarly, by solving T2, the second design, here denoted by *D*2, was obtained, Fig. 7.

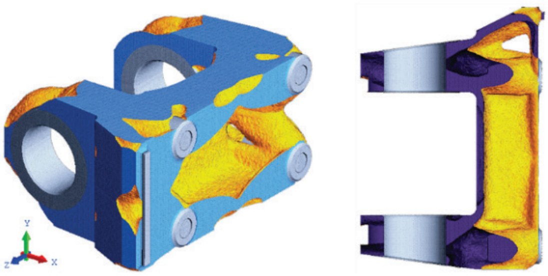

Figure 6 Optimal design *D*1 (idealized support conditions only): outer view (left) and cross-section view (right)

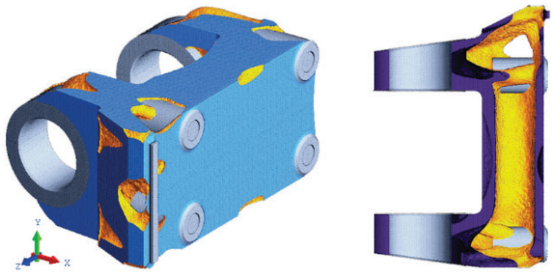

Figure 7 Optimal design *D*2 (idealized and worst-case support conditions): outer view (left) and cross-section view (right)

It is evident that both designs are quite different, although they have the same weight. Design *D*2 is hollow inside and it would surely be more difficult to manufacture than *D*1. Technological production aspects, however, are beyond the scope of this paper.

5.2 Design Performance Analysis

In order to evaluate the performance of optimized brackets under real operation conditions, both *D*1 and *D*2 designs have to be analysed with respect to all 30 possible load cases $L_{ij} = CiSj,\ i = 1,\dots,6,\ \ j = 1,\dots,5$. The structural response was then analysed with respect to stress levels and overall stiffness.

To enable a meaningful and simple comparison, the stress state of the bracket is here estimated by a single quantity σ_{R} termed the reference stress. In simple words, the reference stress represents the stress state on the so called cut surfaces, i.e., surfaces created by material removal during the topology optimization process (yellow surfaces shown in Figs. 6 to 7).

Two variants of σ_{R} are addressed here, as follows:

- $\sigma_{\mathrm{R}}^{\mathrm{AVE}}$ which is the average Mises stress, evaluated at cut surfaces, and
- $\sigma_{\mathrm{R}}^{\mathrm{MAX}}$ which is the maximum Mises stress, evaluated at cut surfaces.

The diagram in Fig. 8 shows $\sigma_{\mathrm{R}}^{\mathrm{AVE}}$ for both designs and all 30 load cases. The load case ID-s, shown in the diagram, is defined as $1 = C_1S_1,\ 2 = C_2S_1,\ \dots,\ 30 = C_6S_5$. Note that *D*1 was obtained by considering load cases 1-6 only, while *D*2 was obtained by taking into account all load cases 1-30.

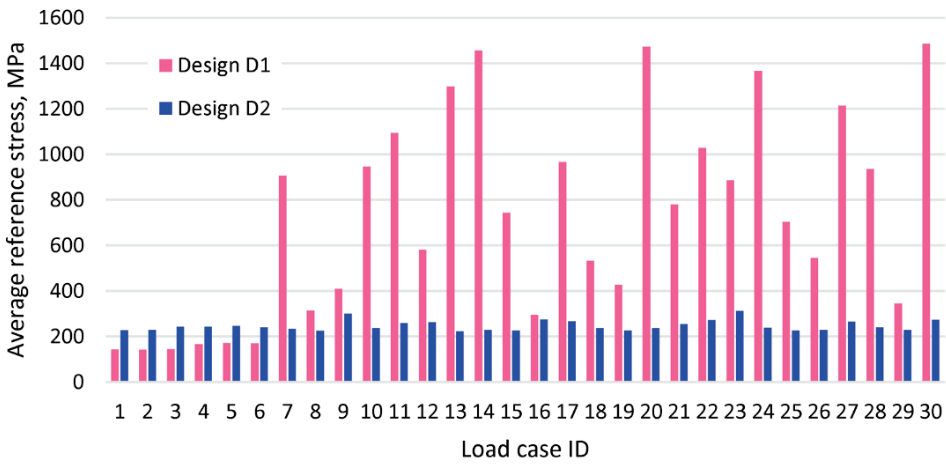

Figure 8 Average reference stresses $\sigma_{\mathrm{R}}^{\mathrm{AVE}}$ for both designs and all load cases

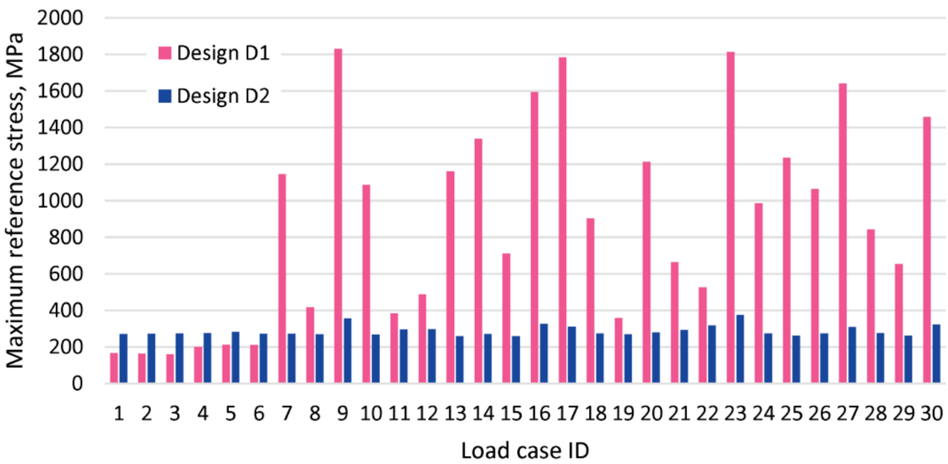

Figure 9 Maximum reference stresses $\sigma_{\mathrm{R}}^{\mathrm{MAX}}$ for both designs and all load cases

As expected, one can see from Fig. 8 that *D*1 performs excellent for load cases 1-6, while completely unacceptable stress levels are obtained for many of the load cases 7-30. On the contrary, the *D*2 design performs well under all load cases, although the stresses in load cases 1-6 are somewhat higher than those of design *D*1. The ratio of the highest *D*1 stresses to the highest *D*2 stresses is about 4.9. Under ideal support conditions only (load cases 1-6) the stresses of *D*2 are on average about 51% higher than those of *D*1.

A rather similar observations can be made by taking a look at the maximum reference stresses, Fig. 9. One can see again unacceptable performance of design *D*1 for the higher load cases and a good overall performance of *D*2. The ratio of the highest *D*1 stresses to the highest *D*2 stresses is about 4.8. Under ideal support conditions only (load cases 1-6) the stresses of *D*2 are on average about 48% higher than those of *D*1.

The overall structural stiffness can be estimated from the maximum displacements data, Fig. 10. The stiffness ratios *D*1/*D*2 are about 1.09 for load cases 1-6 and about 0.69 for load cases 1-30. In other words, *D*1 is on average about 9% stiffer than *D*2 with respect to load cases 1-6. With respect to load cases 1-30, however, *D*1 is on average about 31% less stiff than *D*2.

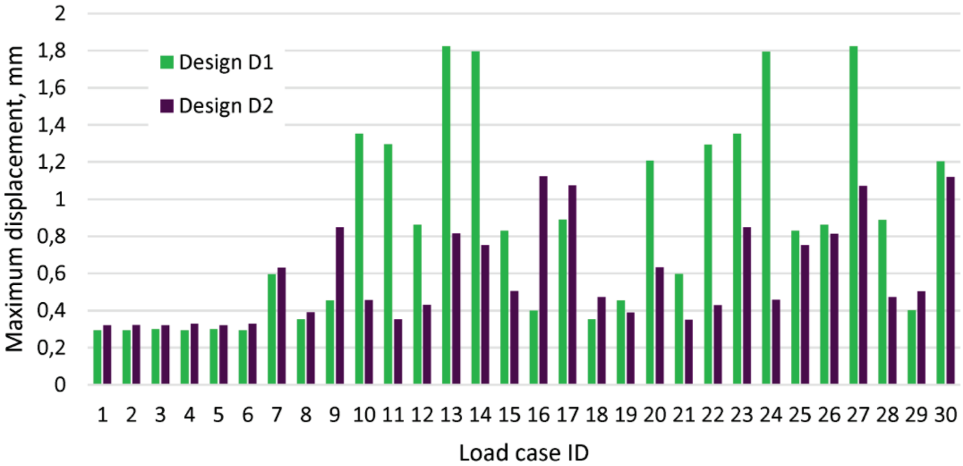

Figure 10 Maximum displacements for both designs and all load cases

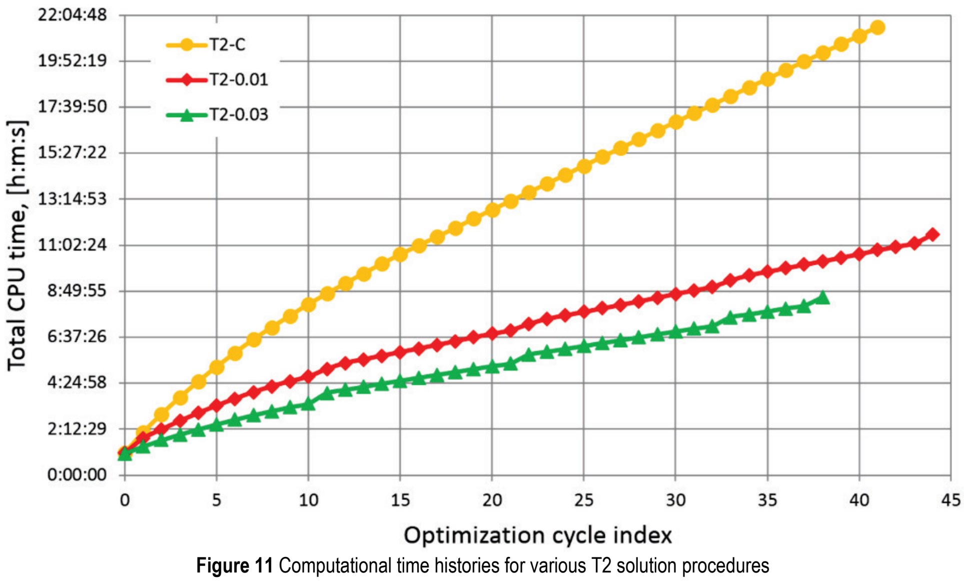

Figure 11 Computational time histories for various T2 solution procedures

The fact that design *D*1 does not perform well under load cases 7-30 is of course an expected result. What is here interesting, however, is the extent of poor performance of *D*1 under these load cases. A stress increase by a factor of 5 highlights the immense importance of, firstly, identifying properly, and secondly, imposing additionally all possible variations of boundary conditions. Only in this case one can expect to get a robust and reliable final design. On the contrary, failing to identify and add some boundary condition variation, may lead to a very quick structural failure.

5.3 Analysis of Selective Load Cases Activity

The example FEA model considered in this paper is not a particularly large one; it contains about 2.3 million DOF. Although the presented optimization problem can be solved within reasonable time without resorting to selective load cases activity (SLCA), the employed FEA model is still large enough to offer some insight into how much benefits one can expect by engaging the SLCA procedure, proposed in this paper. For this reason the larger task T2 was solved not only by engaging the conventional procedure, but also by using selective load cases activity. The corresponding procedures are denoted as follows:

- T2-C - conventional procedure (no load cases deactivation)
- T2-0.01 - SLCA procedure; activity trash value ε = 0.01; inactivity number m = 10;
- T2-0.03 - SLCA procedure; activity trash value ε = 0.03; inactivity number m = 10.

All tasks have been run by using the same convergence criteria and the same optimization parameters. Fig. 11 illustrates the CPU time histories for individual tasks. One can see that T2-0.01 performs significantly better that T2-C. A further, but not so significant improvement in efficiency can be observed for T2-0.03.

A comparison of the results, Tab. 3, reveals that the obtained results are quite similar from the mathematical point of view; only the stresses are somewhat higher for T2-0.03, but this would be probably improved by subsequent surface smoothing via shape optimization. This indicates that the selected activity trash values were appropriate in the sense that the final design was not disrupted too much. At the same time, the savings in computational times seem to more than justify the engagement of the SLCA procedure. One can see that the average CPU time per cycle decreases from over half an hour down to about 13 minutes.

Table 3 Design and results comparison for various T2 solution procedures

Procedure	Strain energy / N·mm	Average reference stress / MPa	Max displacement / mm	Average FEA count per cycle	Average CPU time per cycle / h:m:s
T2-C	45470	291	1.143	30.0	0:30:44
T2-0.01	45480	268	1.144	14.7	0:15:25
T2-0.03	45410	309	1.141	12.6	0:13:08

6 CONCLUSIONS

An example structural part was optimized under various boundary conditions in order to illustrate the importance of proper identification of all possible load cases. From the obtained results, the following conclusions can be made.

Modern optimizers are obviously capable to fully adapt the optimized design to the specified boundary conditions. This means that a failure in identifying and applying a particular support/loading situation may result in dangerous designs prone to early failure.

If a load-carrying part is fixed by screws, a possibility of any screw becoming partially or fully loose should be carefully evaluated. Namely, according to the presented results it is obvious that a loose screw may increase the stress levels by an order of magnitude which would probably result in an imminent structural failure.

Proper identification and inclusion of all possible support situations can assure a much more robust design which is resistant to various accidental support variations. Such a design will perform slightly worse under the ideal support conditions which will be reflected in somewhat higher stress levels. However, in reality the ideal support conditions may very quickly turn into quite different ones. According to the results, a robust properly designed part should be able to perform well under such scenarios.

According to the results and numerical experience, one can say that inclusion of too many load cases into an optimization task is far better and safer than accidentally excluding even one, potentially critical, load case. According to the presented data, it seems that any missed variation of support conditions is probably even more critical than a missed variation of applied loads. This makes proper modeling of support conditions and their possible variations perhaps one of the most critical stages in preparing a topology optimization task.

Finally, the inclusion of various boundary condition variations increases the already demanding optimization task by an order of magnitude. As the results indicate, the proposed selective load cases activity procedure can be successfully engaged in order to mitigate the computational efficiency problem. As numerical experience shows, the activity trash values should be chosen in the range of a few percent while the inactivity number should be taken from the range between 5 and 10. This usually proves to deliver good results.

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