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INFLUENCE OF BOUNDARY CONDITIONS VARIATION ON TOPOLOGY OPTIMIZATION OF LOAD-CARRYING PARTS

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The paper discusses the problem of boundary conditions formulation in FEA-based design procedures of load-carrying parts driven by topology optimization. The emphasis is on the correct formulation of boundary conditions and the definition of corresponding load cases so that topology optimization will deliver a usable design. It demonstrates that inadequate preparation of load cases may lead to a result that seems to be reasonable, but may behave badly in practical application due to possible lack of robustness and reliability. To illustrate this, an example study is performed for a load-carrying bracket that is fastened by four screws. Namely, in such situations it may quickly happen that one or more screws become at least slightly loose. This changes the stress fields in the part dramatically. If this is not captured correctly in the applied load cases, this means that the topology optimizer will deliver some design that might be extremely sensitive to a loose-screw situation. Such a design may fail very quickly during normal operation.

Keywords: FEA, Lightweight design, Optimal design, Support conditions.

1 INTRODUCTION

Design of load-carrying parts is becoming a more and more challenging task for an engineer. Reasons for that are higher requirements related to longer lifespan, reduced material consumption, and specific demands of manufacturing technologies. Fortunately, the development of structural design and optimization procedures is 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. Unfortunately, proper engagement of all these tools may be quite tricky in real-life applications, which may lead to disappointing optimal designs. In many cases, the reason for a bad result is insufficient knowledge in the modeling of boundary conditions and poor understanding of their actual role within the optimization process.

In the field of development of structural optimization methods, one of the most important challenges is topology optimization of load-carrying lightweight parts (Rozvany 2009). Topology optimization can result in substantial benefits, compared to other optimization procedures (Bendsøe and Kikuchi 1988, Huang and Xie 2010). Nevertheless, its development was rather slow in the past, because topology optimization often generates shapes, 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. The latter ones seem to be especially well suited for topology optimized parts.

By engaging AM processes, almost every custom shape can be produced and excellent new materials have been emerging regularly in the past few years. This specific circumstance created new potentials for employing the 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 remove stress concentrations.

Design of a load-carrying part with prescribed material volume and without stress concentrations (and with relative low stress levels) is an extremely demanding task, which requires the employment of adequate numerical procedures, typically FEA combined with topology optimization (e.g., Harl *et al.* 2017). What is often underestimated in these procedures is the importance of accurate modeling of boundary conditions 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 summarized as follows:

- Misuse of standard FEA modelling practices. Namely, 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 supported. 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.
- Misunderstanding of the considered mechanical problem and 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 eventually (maybe accidentally) appear during the life time of a part. All such situations have to be added to the originally prescribed set of loading conditions.

The paper is intended to improve the understanding of the topology optimization process of load-carrying parts. More specifically, it addresses the problem of identifying properly all possible loading conditions in case of a screw fastening of a part. The outline of the paper is as follows. Section 2 describes briefly the considered example and the optimization task. In Section 3 all applicable load cases are formulated. In Section 4 the results of running various optimization tasks are presented and analysed.

2 DESCRIPTION OF THE EXAMPLE BRACKET AND OPTIMIZATION TASK

To illustrate the influence of boundary conditions on the computed optimal design, an example bracket, fastened with four screws, is selected. The bracket is mounted to a frame of a construction machine vehicle and carries a hydraulic motor and a wheel of the vehicle. This means that is has to carry all loads transmitted from the wheel to the frame. In this example, special attention will be given to consequences of changed boundary conditions caused by a screw becoming loose.

For the purpose of optimization, the wheel bracket is partitioned into two domains as follows: the subdomain that is free for optimization (Figure 1; light blue color), and the rest of the total domain that has to remain fixed and is thus not optimized (Figure 1; gray color).

The bracket is fastened by four screws and at the top additionally supported by the frame along a banded contact area. Thus, the supported surfaces are the upper frame contact area and the screw bores (Figure 1; dark blue color).

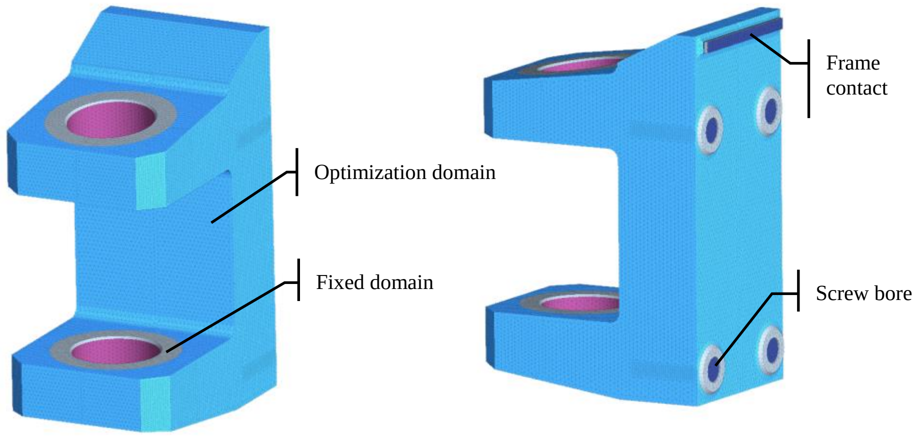

Figure 1. Domains and supported surfaces of the example wheel bracket.

The bracket is loaded by 5 basic load sets A-E (Figure 2), as follows:

(a) vertical load (A; 7.5 kN),

(b) loads due to vehicle acceleration (B; 2x40 kN) or deceleration (C; 2x40 kN),

(c) loads due to vehicle driving through the left (D; 2x40 kN) or right (E; 2x40 kN) bend.

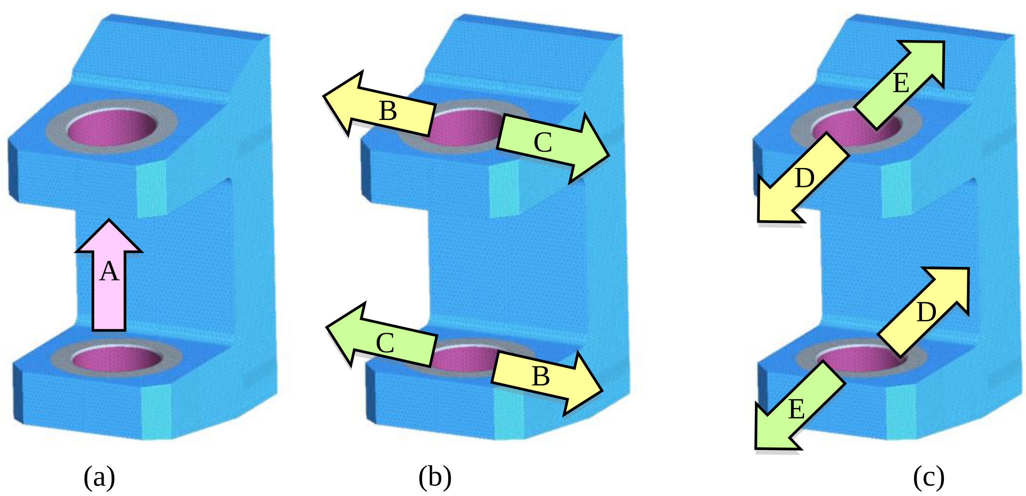

Figure 2. Basic load sets A-E acting on the wheel bracket.

The optimization task is approximately defined as follows: find the optimal topology of the bracket if the volume of the free domain has to be reduced by 50%. By the term optimal, we mean maximal structural stiffness and minimal attainable stress levels. This is a classical topology optimization problem that can be solved by minimizing the structural strain energy.

3 DEFINITION OF ALL POSSIBLE LOAD CASES

An important (desired, but potentially dangerous) effect of topology optimization is that the final design is fully and exclusively adapted to the specified boundary conditions. Therefore, it is of extreme importance that the set of all applicable boundary conditions is carefully analyzed, defined, and included into the definition of the optimization task. 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 (LC). In a typical optimization task, several different load cases are needed in order to describe all applicable situations. It should be noted that, in general, all load cases may differ in both, supports and applied loads.

The applied loads are described by 6 different situations; each of these situations is defined as a combination of basic load sets A-E as given in Table 1.

Table 1. Loading situations – combinations of basic load sets A-E.

Loading situation	Set A	Set B	Set C	Set D	Set E
1	x	x			
2	x		x		
3	x	x		x	
4	x	x			x
5	x		x	x	
6	x		x		x

Regarding the supports: the part is theoretically supported at four screw bore surfaces and at the frame contact area. Theoretically, these support conditions are the same for all loading situations, meaning that we basically have 6 load cases denoted as LC1 through LC6. Let us denote the corresponding optimization task as T1.

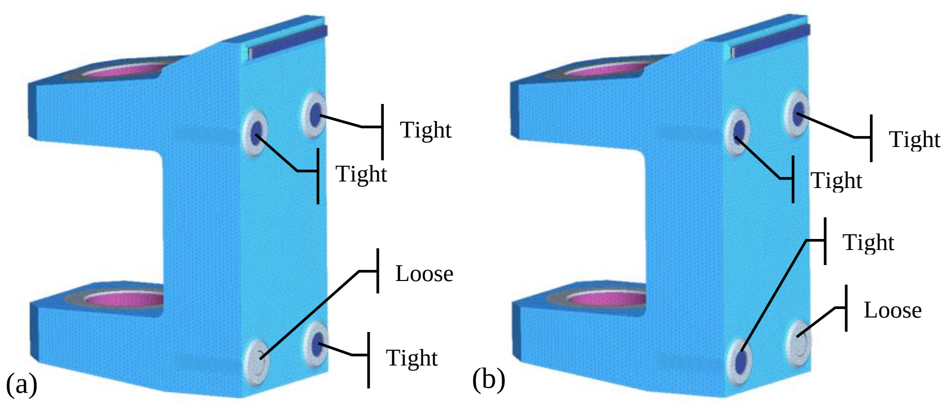

Figure 3. Boundary conditions of the hydraulic engine beam – one of the screws is loosened.

Let us now assume that one of the lower screws becomes loose (Figure 3). This changes the support conditions and to include this possibility into the optimization process, 6 additional load cases have to be defined: LC1A through LC6A (6 loading situations at changed support conditions). In a similar way, other screws may also be become loose. In this work, we will just add another set of load cases LC1B through LC6B covering the situation of another lower screw becoming loose (Figure 3b). So, we now have a total of 18 load cases LC1-LC6B which define another optimization task, here denoted as T2.

4 OPTIMIZATION RESULTS AND ANALYSIS

Both topology optimization tasks (T1 and T2) were solved by CAESS ProTOp. The results are analyzed briefly in the following.

4.1 Optimal Design T1 (All Screws Tight; 6 Load Cases)

Figure 4 illustrates the stress fields within the optimal design T1. Figure 4a shows the stresses computed within the optimization process, where all screws were tight. One can see that maximal stresses (excluding numerical peaks) are mainly around 200 MPa.

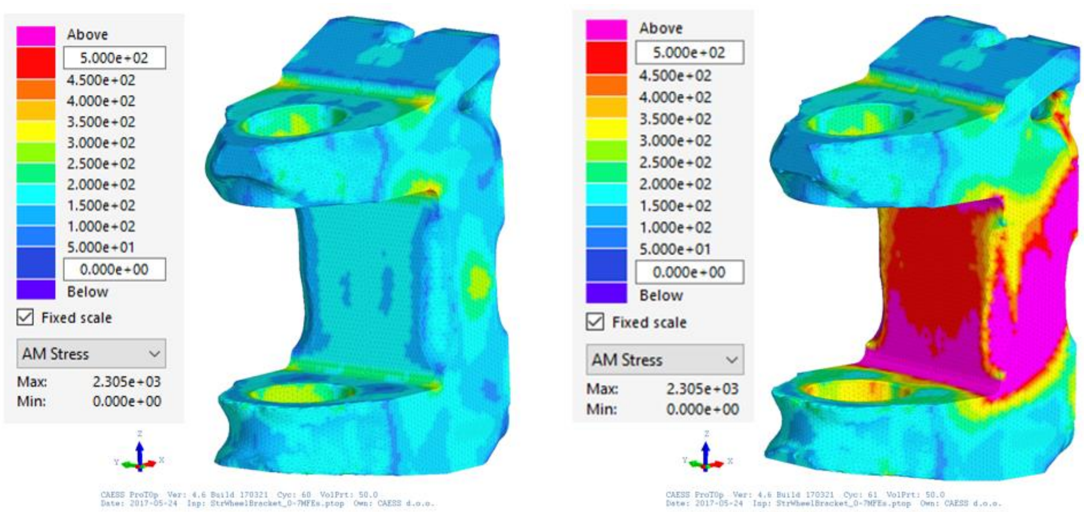

Figure 4. T1 optimal design stresses: (a) all screws tight and (b) one screw loose.

Let us now take a look what would happen, if for this design one of the lower screws becomes loose. Figure 4b shows the corresponding stress field. One can see that now the maximum stresses are significantly higher and range around 600 MPa. In other words, one loose screw would worsen the stress field dramatically and eventually cause failure of the part.

4.2 Optimal Design T2 (One Screw Might Be Loose; 18 Load Cases)

Figure 4 illustrates the stress fields within the optimal design T2. Figure 5a shows the stresses computed within the optimization process, where one screws might be loose. One can see that maximal stresses (excluding numerical peaks) are mainly around 350 MPa.

Let us now take a look how this part would perform under normal conditions (all screws tight). Figure 5b shows the corresponding stress field. One can see that now the maximum stresses are somewhat above 200 MPa.

By comparing these stress fields with the stress fields obtained with optimal design T1, one can see the following: (i) under normal conditions, design T2 performs only slightly worse than design T1 and (ii) under the loose-screw conditions, design T2 performs ways better than design

T1. Obviously, design T2 can be seen as a much better alternative because of its much lower failure probability under non-ideal support conditions.

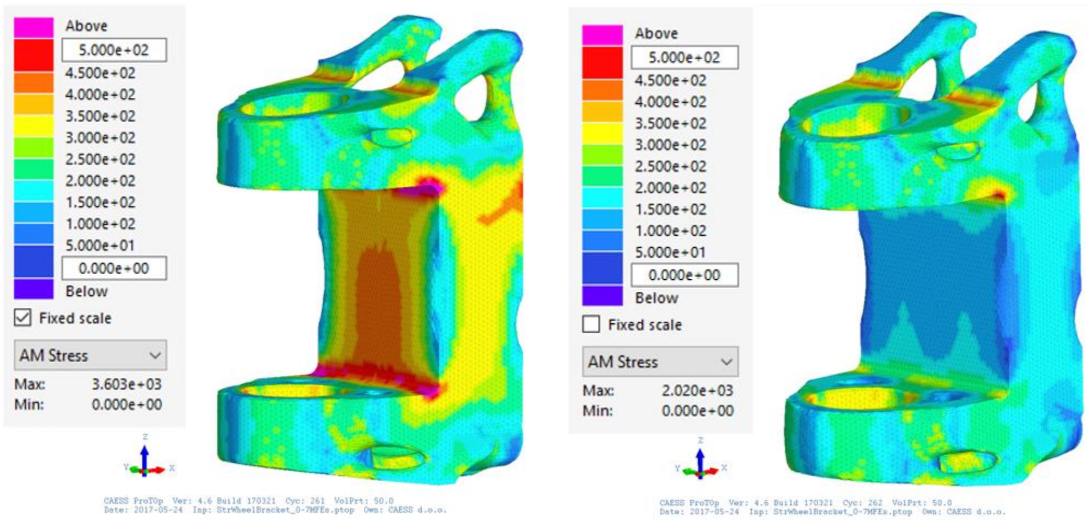

Figure 5. T2 optimal design stresses: (a) one screw loose and (b) all screws tight.

5 CONCLUSION

Topology optimization procedures are becoming indispensable in the design of light-weight and efficient load-carrying structural parts. Unfortunately, their engagement is more sophisticated as this might seem to be at a first glance. Perhaps the most exposed problem is the difficulty to describe and capture accurately enough all possible support/loading situations. Actually, one missed load case may deliver a design that may fail rather quickly under real-life operating conditions. Therefore, for any topology optimization task, careful analysis, formulation, and verification of all possible support /loading situations should be done with greatest care possible.

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