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INFLUENCE OF GEOMETRY RECOVERY ON STRESS STATE OF OPTIMIZED PARTS

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This paper discusses the influence of geometry recovery on actual stress fields within load-carrying parts that have to be reconstructed from the resulting surfaces obtained by topology optimization procedures. A typical result of a topology optimization process is a triangulated surface which represents the boundary of the optimized part. In a production environment, this triangulated surface is mostly used to reconstruct a proper CAD model of the optimized part. This process is by far not automated and may require significant skills and efforts. Unfortunately, it also unavoidably introduces variations in the geometry of the optimized part. Although visually these variations might seem to be rather minor, they may very quickly introduce significant stress field variations. These variations may result in harmful locally increased stress levels and even significant stress concentrations. To get more insight into these phenomena, the topology of a quasi-two-dimensional example part is optimized. The resulting geometry is then reconstructed with various levels of precision. For the obtained geometries, the stress fields are studied numerically. It is shown that stress field variations are indeed such that they may influence significantly the probability of fatigue crack initiation and consequently the service life of the part. Obviously, the geometry recovery after topology optimization should be done very carefully, especially if the part will be subject to cyclic loading during operation.

Keywords: Structural optimization, Topology optimization, Stress field, CAD model.

1 INTRODUCTION

Structural topology optimization is gradually becoming an almost inevitable constituent of design processes of load-carrying structural parts. In this way, structural parts can be designed as to assure minimal attainable stress levels and absence of stress concentrations for some prescribed, typically light-weight, volume. Such a part typically exhibits high resistance against fatigue crack initiation at cyclic loading conditions and a generally prolonged service life-time.

The result of a topology optimization process is a triangulated three-dimensional surface which represents the outer boundary of the optimized part. On one hand, this triangulated surface can be used directly in the production process, for example, if it is used to produce the part by engaging additive manufacturing technologies. On the other hand, in a production environment, a more common situation is to use this surface in order to obtain a conventional parametric CAD model of the part. In this paper, this procedure will be termed *geometry recovery* or *geometry reconstruction* for the sake of convenience.

Geometry recovery is by far not an easy process, Figure 1. To address this problem, various approaches can be taken, for example, by engaging reverse engineering procedures. It should be noted, however, that whatever path we choose, an acceptable final result will always require a substantial amount of tedious manual modeling. This will inevitably introduce geometrical errors since the recovered geometry will always more or less deviate from the actual optimal geometry. From the visual and intuitive point of view, these deviations will often not look very dramatic. However, relying on the assumption that the result is good just because it looks nicely curved and similar to the optimized surface, can be very wrong. Namely, there are well-known and rather simple examples that clearly show that (visually) rather minor geometry variations can result in a significant increase in stress concentrations.

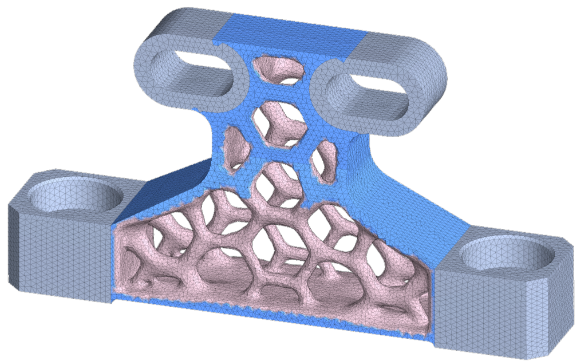

Figure 1. The geometry of an optimized part can be rather complicated and quite difficult to reconstruct.

A nice example of such a situation is a plane-stress plate with a central opening (Kegl 2000), Figure 2. The plate is loaded along its outer edges with two uniform but different distributed loads. For an infinite plate, the optimal shape of the opening can be derived analytically – it is an elliptical one. For a finite plate, the elliptical shape is a very good approximation to the actual optimal shape. Now, from the engineering point of view, a replacement of an elliptical opening by a circular one might not look very dramatic. Note, however, that such a change results in an increase of local stresses by about 55 % and this substantial deterioration of the situation is also well reflected in a huge variation of configurational forces (Fischer *et al*. 2012). Anyhow, it is obvious that such a change can dramatically reduce the service-life of a part under cyclic loading.

In order to gain some more insight into these phenomena, an adequate example problem was formulated and numerically studied. It is expected that this numerical study will show what approximately we can expect when minor or larger geometry deviations are introduced during geometry reconstruction.

The structure of the paper is as follows: section 2 describes the engaged numerical test problem; sections 3 and 4 present the optimal and recovered geometries, respectively; the analysis results and discussion are given in section 5.

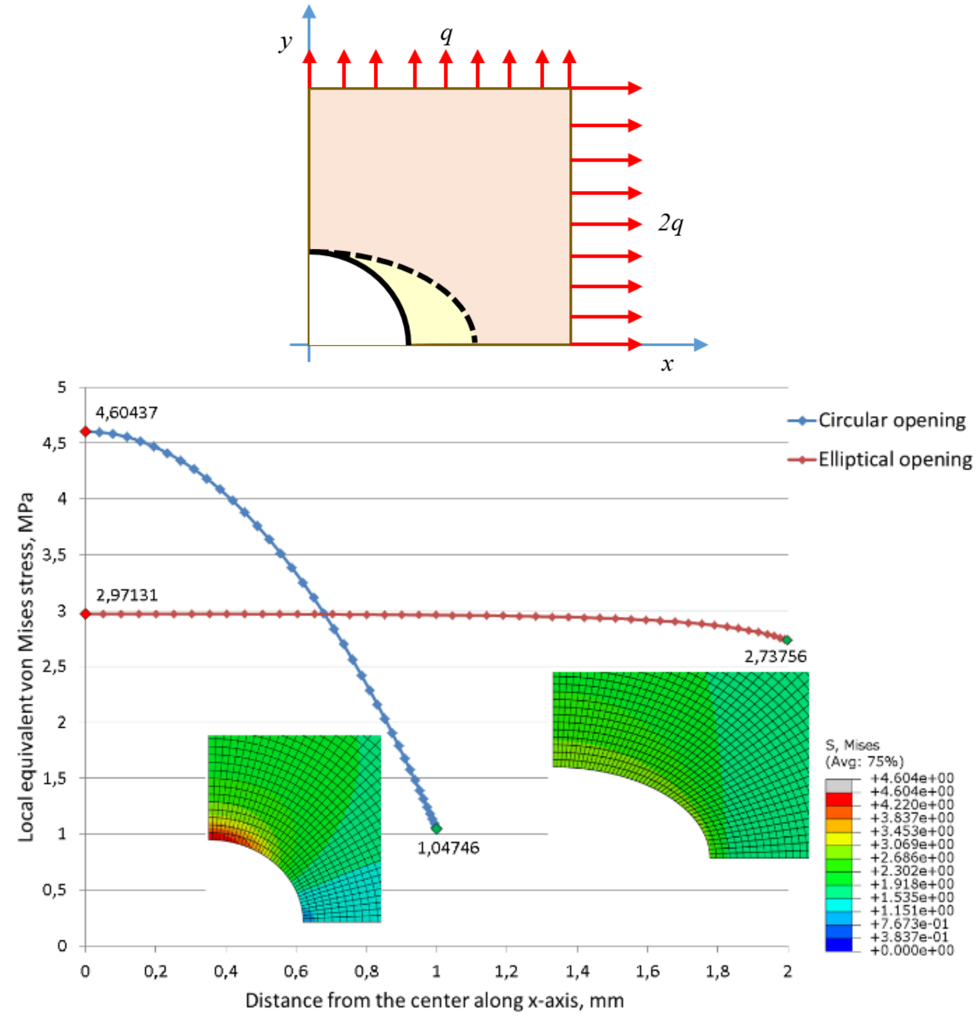

Figure 2. One-quarter of a plate with a central opening (above) and a stress diagram (below) showing the stress levels along the edges of both, the circular and the elliptical opening.

2 TEST EXAMPLE

The test example is a bracket consisting of a straight and curved flanges and a web, which has to carry most of the vertical load, Figure 3. The flanges are fixed regions that will not be touched by the optimizer, while the web region represents the free domain to be optimized.

The test bracket is centrally supported on the upper (curved) flange while the lower flange is loaded with a uniform pressure; the magnitude of loading is irrelevant for this study. The CAD model of this bracket was prepared with PTC® Creo® (2018) and the FEA model contains about one million of finite elements (linear tetrahedrons).

According to this setup, the optimization region is only the web of the bracket, which is a quasi-two-dimensional domain. One can, therefore, expect that the results will be easily observable. Furthermore, this will simplify the geometry recovery process and determination of stress levels on surfaces cut by the optimizer. Under the bottom line, one can expect that the influence of geometry variations on the stress field will be estimated relatively easily and with reasonable accuracy.

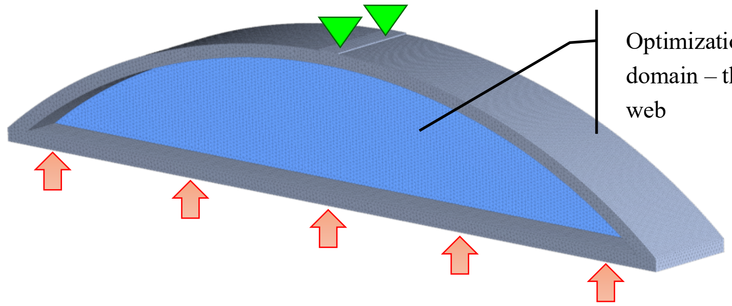

Figure 3. Test bracket; vertically loaded; the web is the optimization domain.

3 OPTIMAL GEOMETRIES OF THE TEST BRACKET

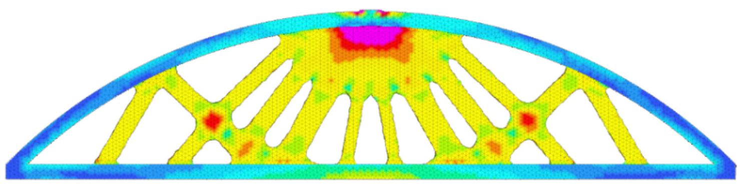

Figure 4. Optimal topology for 50 % volume part of the web; the stress legend ranges from 0 to 500 MPa.

One of the computed designs, namely for the 50 % web volume part, is shown in Figure 4. The stress legend ranges from 0 to 500 MPa and the violet color indicates stress levels above 500 MPa.

4 RECOVERED GEOMETRIES OF THE TEST BRACKET

Based on optimization results, the geometry of the bracket was recovered in four different ways with various grades of precision. In this way four more or less accurately recovered design variants, here denoted as A, B, C, and D, were obtained, Figure 5. For each of these designs, a full-material CAD model was taken as a starting point. The material was then removed from the web region by using various approaches as follows:

- Design A: Material was removed by inserting circular holes into the web region. The radii and positions of the holes were determined in a way to match visually as much as possible with one of the optimized designs.
- Design B: Material was removed by inserting elliptic holes into the web region. The radii, positions, and orientations of the holes were determined in a way to match visually as much as possible with one of the optimized designs.
- Design C: Material was removed by cutting the material of the web region along curves reflecting one of the actual optimal designs. This is geometrically the most accurate design recovery.
- Design D: Material was removed by cutting the material of the web region along some curves deviating to some extent from one of the actual optimal designs. The geometrical

deviations from the optimal design curves are such that they reflect typical consequences of excessive use of smoothing procedures.

Note that design D simulates a quite common situation that may result either from actually applying various smoothing procedures too aggressively or during a reverse engineering process. Namely, in the latter case, the number of triangles is often heavily reduced in the first step. After that, the resulting triangles are used as control points of new generated B-spline or similar surfaces. In this process material connections typically swallow at both ends and become thinner in the middle.

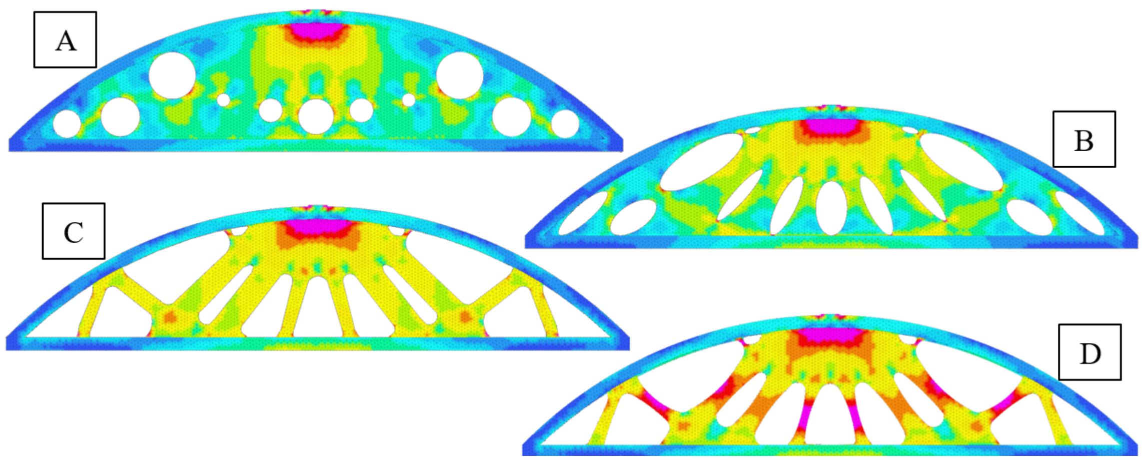

Figure 5. Recovered design variants A, B, C in D; the stress legend ranges from 0 to 500 MPa.

5 RESULTS AND DISCUSSION

All recovered design variants were analyzed for stress levels by using the same software as for optimization (CAESS ProTOp® 2018). Since we are interested in the influence of optimized geometry variations, only the stresses within the web part were observed. More precisely, for comparison purposes, a quantity here called the reference stress, σ_ref, was computed. It is defined as the maximal von Mises stress computed on cut surfaces (along with the edges of the holes cut into the web region of the bracket).

Let us take a look at the detail of design B, shown in Figure 6. The stress levels along the cut surfaces (web holes edges) illustrate very nice the problem related to 'just-approximate' geometry recovery. Namely, after optimization, the stress levels along cut surfaces should be more or less constant and at the lowest attainable levels. What we can see on design B, however, is that the average stresses are rather low while there are a few locations with relatively very high-stress concentrations. One can assume that this 'approximate' geometry recovery process swept away pretty much all gains delivered by the optimizer. Namely, for a cyclic loaded part, the restored stress concentration can dramatically increase the possibility of fatigue crack initiation and consequently structural failure.

Unfortunately, these restored stress concentrations can be relatively high. To illustrate this, let us take a look at Figure 7. The diagram shown presents reference stresses for various designs and corresponding volume parts. One can see that for any particular volume part, the original optimized design always exhibits the lowest stresses. So, one can assume that any geometry recovery process (that introduces design variations) will typically worsen the stress state.

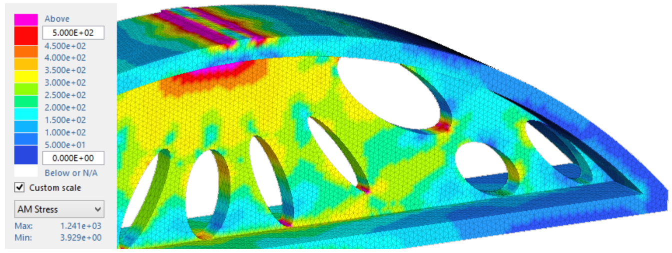

Figure 6. A detail of design B; on cut surfaces one can observe relatively low average stress levels and relatively high-stress concentrations.

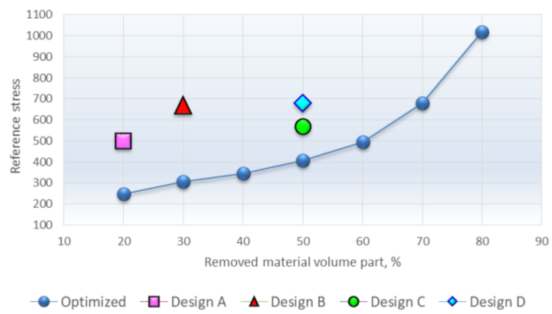

Figure 7. Reference stresses of all optimized designs (curve) and of the 4 recovered design variants (isolated points).

As expected, one can also see that the recovered geometry should be as close as possible to the optimized one in order to minimize the discussed negative effects. In our case, the best-recovered geometry exhibits a stress rise of about 40% (design C). With excessive smoothing, this reference stress rise is already about 70% (design D). The worst situation, however, is when predefined fixed geometries like circles or ellipses are used to cut the material. The reference stress rise here was more than 100%.

6 CONCLUSION

The result of topology optimization of load-carrying is typically given by a triangulated surface which represents the boundary of the optimized part. This surface is commonly used to restore a conventional CAD model of the optimized part. Practical experience shows that this procedure is typically not done carefully enough. What is often missed is that even visually harmless geometry variations may very quickly raise the stress levels significantly. The results presented in this paper clearly indicate that careless geometry reconstruction procedures may quickly annihilate pretty much all of the gains delivered by the optimization process.

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