A Designing Methodology for Bicycle Frames Using the Topology Optimization Method

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Abstract. This work aims to present a methodology to design bicycle frames using the topology optimization method. The goal is to find an optimized layout of a structure within a specified fixed domain, applying known quantities (loads, support conditions and design restrictions) as boundary conditions. The optimization problem is written to obtain the minimum structural compliance with a given final mass and it was solved using the Sequential Convex Programming method (SCP). To simplify the process, the problem was divided into two steps. The first step consisted of performing a topology optimization analysis on a two-dimensional model. The result was then adapted into a three-dimensional domain on which the last optimization was performed to achieve the final geometry. Several combinations of load conditions were applied, and the obtained design was post-processed through a finite element analysis to check the structure's response. Results show that the proposed methodology can produce stiff and lightweight frames with reduced mass and unusual designs.

Keywords: Bicycle Frame, Topology Optimization, Finite Element Analysis.

1 Introduction

Cycling is a topic that always brings a lot of interest with it, and a large number of works related to bicycle technology exists in the literature. The development of technologies such as finite element analysis, design optimization, Aurora [1], and different solving methods for optimization problems, such as SCP – Sequential convex programming method Zillober [2], associated with the commercialization of FEA and optimization softwares resulted in works utilizing those methodologies becoming more common every day. These are often utilized as tools to enhance existing components and sometimes used as a means for designing, Bendsøe and Sigmund [3]. However, as stated by Covill et al. [4] "the development and fabrication of steel bicycle frames remains as much rooted in craftsmanship, art, and marketing as technical considerations". The aim of this study is to present a designing methodology for bicycle frames using the topology optimization method that simplifies the process and decreases computational requirements. In this paper, the methodology will be used to achieve a low mass optimized geometry that minimizes vertical compliance.

2 Application and Methodology Validation

The proposed methodology consists of defining a two-dimensional profile utilizing topology optimization that will be adapted into a three-dimensional domain, in which a final optimization will take place to achieve the optimized frame.

2.1 Boundary Conditions

A viable option for boundary conditions definition would be utilizing load cases found in the literature. However, for this study a simplified bicycle model under the weight of a cyclist following a path with two obstacles representing curbs was developed, and the reaction forces on four key nodes were recorded. According to a commonly used distribution found in the literature proposed by Soden and Adeyefa [5], 70% of the load was applied on the seat tube and the remaining 30% was applied on the bracket/handlebar. For the two-dimensional domain definition, geometry key points of a commercial bicycle frame were utilized.

2.2 Two-dimensional Profile

As previously stated, the optimizations performed on this study aim to minimize compliance of the frame. The results of maximum reaction force on each node were isolated and utilized to create four cases, presented on Figure 1, in order to better understand the response of each load on the resulting geometry.

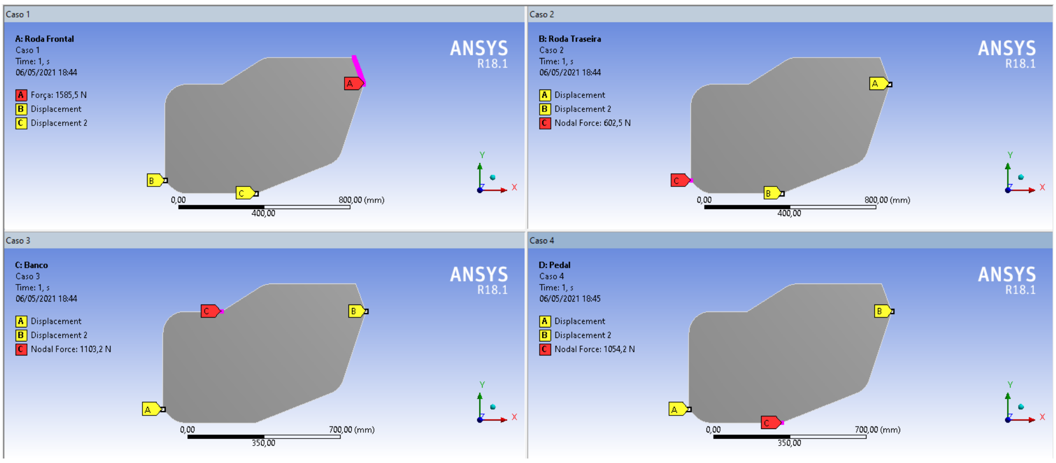

Figure 1. Load Cases 1 to 4, named form right to left starting on top left corner

The cases shown in Figure 1 were used as objective functions and different weights (w_i) were assigned for them, creating 7 different Topology Optimizations (TO). This step allows a higher degree of influence on the results based on the project requirements. Based on Sigmund [6], the optimization problem can be written as:

$$min: c(x) = (w_1 * c_{case\ 1} + w_2 * c_{case\ 2} + w_3 * c_{case3} + w_4 * c_{case4}) = \sum_{i=1}^{N} U_i^T K_i U_i$$

$$subjected\ to: 0 < x_{min} \leq x \leq 1$$

$$: KU = F$$

where U and F are the global displacement and force vectors, respectively, K is the global stiffness matrix, x is the vector of design variables, x_{min} is a vector of minimum relative densities, N is the number of different cases used and c is the compliance. Table 1 illustrates the weights combinations for each TO.

Table 1. Cases weight combination for each TO

	$w_1\,(case1)$	$w_2\,(case2)$	$w_3\,(case3)$	$w_4\,(case4)$
TO1	0,25	0,25	0,25	0,25
TO2	0,40	0,40	0,10	0,10
TO3	0,10	0,40	0,40	0,10
TO4	0,10	0,10	0,40	0,40
TO5	0,40	0,10	0,40	0,10
TO6	0,40	0,10	0,10	0,40
TO7	0,10	0,40	0,10	0,40

Estimating an area from the lateral view of the commercial bicycle frame utilized to model the domain, it was found that its area was equivalent to 30% of the domain's area. Hence, mass retention was set at 25%. With all variables defined, the topology optimizations were performed. The profile chosen to develop the following steps of this study was the result from TO6, which is shown on Figure 3 alongside the optimization setup.

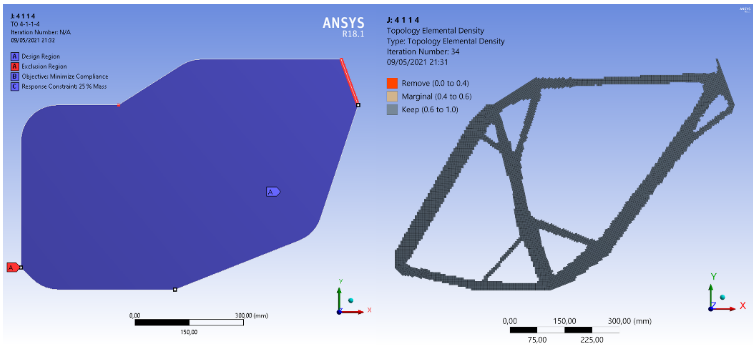

Figure 2. Optimization set up (left) and the resulting profile from TO6 (right)

Regions used for boundary conditions application are excluded from the optimization by default, these regions are shown in red. The tendency of NBR14714 [7] to associate a higher weight to frontal solicitations (Case 1) and the fact that in a critical scenario most of the load is applied on the bottom bracket (Case 4) supported selection of TO6. Additionally, associating the number of features composing the profile to its complexity and trying to keep it on the lower end, reassured the selection of TO6 to continue this study.

2.3 Final Design

In order to obtain the final geometry it was needed to adapt the two-dimensional profile into a three-dimensional domain and then perform a final topology optimization. A viable and commonly used option to perform a topology optimization would be to utilize a solid structure as the domain. However, it was noted that the results for the most part are solid structures, which was judged as not ideal for a bicycle frame. Also, to directly obtain a geometry composed of optimized cross-section tubes it would be needed to simultaneously perform a topological optimization and a shape optimization, which is not possible yet.

Seeking to better align this study's goal with the possibilities allowed by the software, the three-dimensional domain was drawn utilizing pipe cross-section tubes with high thickness following the central lines of the profile resultant of TO6 with the assistance of a CAD software. Figure 3 shows the profile utilized and the domain.

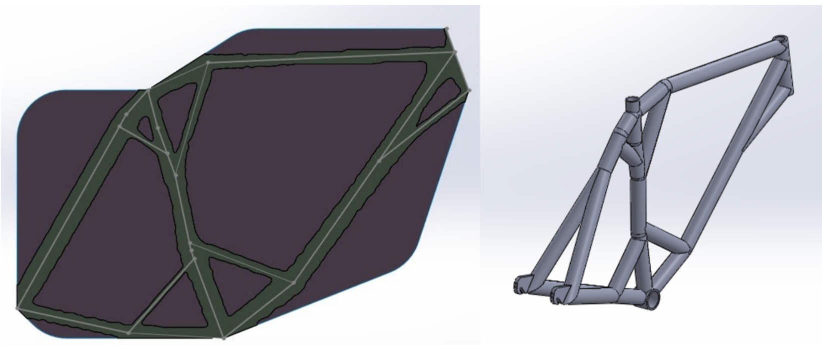

Figure 3. Two-dimensional profile (left) and three-dimensional domain (right)

The points for load application of the three-dimensional domain were modeled based on commercial components and their geometrical positions were not altered. Due to the high thickness of the tube utilized, the three-dimensional domain had a mass of 11,88 kilograms. Considering the reality of bicycle frames, a realistic range would be from 2,5 to 1,5 kilograms. In that sense, for the final topology optimization, the mass retention was set to achieve a result belonging to the specified range. Furthermore, the final topology optimization was subjected to the same conditions applied to TO6. The result is shown in Figure 4.

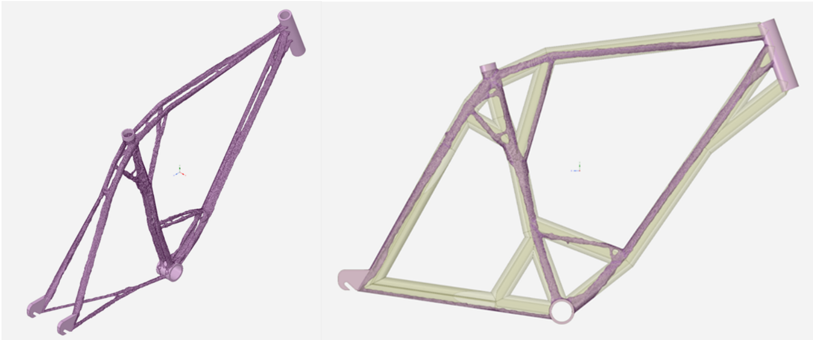

Figure 4. Final geometry (left) and superposition over three-dimensional domain (right)

The final mass obtained was 2,18 kilograms, which is in the acceptable range defined earlier. It is possible to identify a tendency to form trussed components on some zones of the geometry. Even though the result was not composed of tubes with optimized sections, the final geometry presents many interesting characteristics.

Looking at the superposition shown in Figure 4, it is noticeable that some components were completely removed from the geometry, while some others were slightly changed in shape and angle. When taking into consideration the two-dimensional profile shown in Figure 3, it is easily seen that the lower thickness bars were entirely removed from the final design. Furthermore, the response to some bars' removal was a change in the shape that resembles the initial distribution shown previously and suggests that utilizing a better starting point, the two-dimensional profile, still allows adjustments while lowering the computational resources usage.

Since some domain limiting components kept a semi-tubular profile, mainly on the rear section of the frame, it would be a viable and natural choice to replace them with circular or pipe cross-section tubes. Additionally, it is visible that the geometry has some undesirable details such as stress concentrators, unconnected components and other minor details that should be addressed through a model redrawing. Even though this post processing step is vital in topology optimization studies, it does not belong to the scope of this study. Hence, this procedure will be kept at a minimum with simple smoothing and simplifications. Nevertheless, it is important to notice that too many simplifications might take away distinguishable features of the geometry and lose the progress achieved with the optimization.

2.4 Design Validation

Two load cases from the literature, Covill et al. [8], were used for the final validation. The first one represents vertical solicitation aligned with the plan of symmetry, while the second one presents out of the plan of symmetry solicitations. They will be referred to as vertical load case and lateral load case respectively. The results for total deformation and equivalent stress are shown in an amplified scale for better visualization.

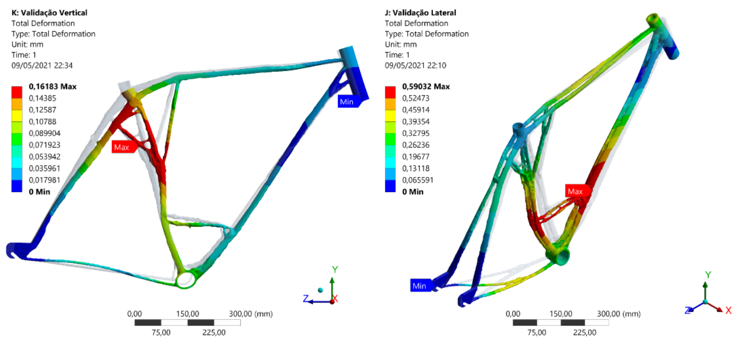

Figure 5. Total deformation results for Vertical load case (left) and Lateral load case (right)

The total deformation results for both cases present reasonable values, providing good stability for the geometry, although loads out of the plan of symmetry were not taken into consideration during the process of obtaining the optimized frame design. Figure 6 presents the equivalent von-Mises stress results.

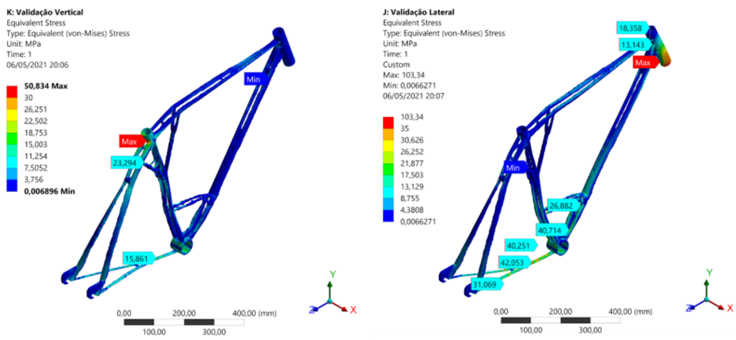

Figure 6. Equivalent stress results for Vertical load case (left) and Lateral load case (right)

As expected, the geometry shows better results for the vertical load case. Nonetheless, the resulting values are in an acceptable range for both cases, indicating that the geometry still has room for improvement. This can be checked by introducing a stress constraint in the problem, but it is beyond the scope of this investigation.

3 Conclusions

This paper presented a methodology for bicycle frame designing. The procedure consisted of defining boundary conditions, dividing them into different cases, associating weights according to project requirements, creating a two-dimensional profile utilizing topology optimization and adapting it into a three-dimensional domain modeled with pipe cross-section tubes in order to provide a better starting point for the final topology optimization. Thus obtaining the final geometry, a new perspective to material distribution for frames through new features addition was presented. The validation analysis resulted in low values for deformation and stress, proving the methodology's viability and also implying that the optimized frame can be further improved. The methodology presented can be adjusted to better suit the project's needs and requirements, such as the utilization of alternative materials, load cases, restraints and objective functions.

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