APPLICATION OF STRUCTURAL TOPOLOGY OPTIMIZATION TO THE DESIGN OF A UHPC STAIRCASE

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Abstract. *This paper presents an application of structural topology optimization to the shape finding of an ultra-high performance concrete (UHPC) staircase. In this project, the optimized geometry is used as an inspiration for a final parametric model, seeking minimization of different formwork and reduction of production costs. Therefore, the steps should have the same form, and the only different component should be the intermediate landing. Additional aims are the least amount of supports and the slenderest cross-section as possible. Selection of UHPC enables the definition of unusual geometries, that would be unfeasible with regular reinforced concrete. After the definition of the base geometry in the software, a first topology optimization is performed. Afterwards, the results are analyzed, the remaining parts are modeled with a smooth geometry, and the resulting geometry is simulated for stress analysis and adjusted until they meet design criteria.*

Keywords: *Structural analysis, Finite element method, Topology optimization, UHPC staircase design*

INTRODUCTION

There is a proposal for a new building for the “Centro de Inovação em Construção Sustentável da USP” (CICS). It will be a living lab, where innovative building technologies will be studied and tested (Poli USP, 2017). Here we present a case study of a staircase located at the entrance of this building. As required by the building configuration, this staircase will be a route of escape in case of fire and its top part cannot be modified.

The main goal of this study is to minimize the use of material, while creating an organic, unconventional staircase form, transmitting a sense of lightness of the structure. The proposed material is ultra-high performance concrete (UHPC). This material’s properties allow creation of different shapes, after all, it has no need for conventional concrete reinforcement. However, it can be expensive, and this study is important to achieve a cost-effective project. Having this in mind, the technique proposed to achieve the main goal was topology optimization. This technique withdraws material from the parts of the structure that are less needed, taking into regard a chosen fitness function. With the results of the topology optimization a smoothed form is proposed.

The software used for the structural analysis and topology optimization of this study is Fusion 360 (Autodesk). The final form is generated with Rhinoceros (McNeel) and its plug-in Grasshopper, which allows parametric design of free-form surfaces with visual programming.

1 THE MATERIAL

The Ultra-High Performance Concrete (UHPC) is made from very thin mineral aggregates. This results in a material with low porosity, minimizing capillarity pores, which improves durability (Schmidt, Fehling, Fröhlich, & Thiemicke, 2014). This type of concrete shows less or no need for conventional reinforcement with metal bars, depending on the design, because of its higher tensile strength. This enables creation of unconventional shapes, otherwise non-constructible with ordinary reinforced concrete. This material can be reinforced with organic, metallic, or polypropylene fibers, allowing for higher tension resistance without limiting the different shapes it might take. The UHPC reinforced with metallic and polypropylene fibers is used for fire resistant structures, making it suitable for fire escape route stairs. The UHPC may be also prestressed in high-tension areas, making it possible to overcome larger spans with slenderer cross sections. Nevertheless, it does present a high production cost, which may be compensated by saving high volumes of material by reducing cross sections. This way, it can be a more sustainable material in comparison with conventional reinforced concrete. In addition, if the complete lifetime is taken into regard, structures with UHPC can be considerably more cost-effective. Some common values of mechanical properties of Ductal UHPC, by Lafarge, are: compressive strength ranging from 100 MPa to 200 MPa; tensile strength ranging from 7 MPa to 9 MPa; and Young’s Modulus ranging from 35 MPa to 55 MPa.

2 TOPOLOGY OPTIMIZATION

Topology optimization is a technique that consists in removing material from the least solicited parts of the structure, aiming to optimize material usage. In the optimization study, each modeling specification may lead to a different result. Key specifications are the chosen support locations, forces applied, material, optimization objectives and the domain. The mesh, for example, has an important impact on the results: the algorithm works with material removal, and it can only remove a volume as small as the finite elements (FE) defined in the mesh. Thus, if the mesh has smaller elements, the more elaborate the result can be. (Bendsøe & Sigmund, 2003)

This type of optimization generates forms that are, in its raw results, quite difficult to build. For this reason, post processing is required of the designers. In the present case, the optimization is to be used as inspiration and as a guide to the creation of the stair's organic form; the results from the optimization may not be strictly followed.

3 FE MODEL

To carry on the FE analyses, we chose Fusion 360 (Autodesk). Its academic version does not limit the number of elements for analysis, and it has cloud based analysis, which speeds up the analysis process which would otherwise count on personal computer processing capacities. The program has static stress, modal, and topology optimization simulations, which are the three types of analysis required to design the staircase. The software also allows appropriate mesh visualization and modification.

3.1 Supports

The supports are top and bottom surfaces that are in contact with upper and lower floors as shown in Figure 1. Both surfaces are specified with fixed translation in all directions.

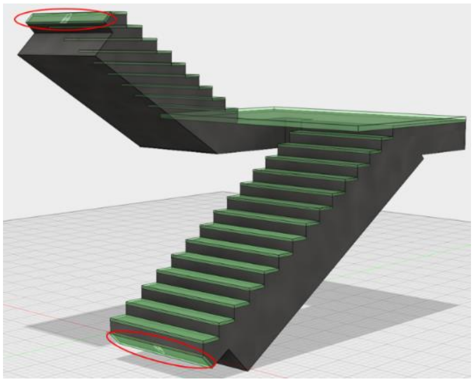

Figure 1. Staircase model; red circles show surfaces with fixed support conditions

3.2 Material

The material property values inserted in the program are shown in Table 1, and were defined taking into consideration Ductal UHPC specifications. They provide upper and lower

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boundary values, and the lowest or median values were chosen for the model, but never the highest ones.

Table 1. Material properties inserted in the model

Property	Value
Young's Modulus	$45 * 10^9$ Pa
Poisson Ratio	0.20
Density	$2500\ \mathrm{kg/m^3}$
Compression Strength	$140 * 10^6$ Pa
Tensile Strength	$8 * 10^6$ Pa

3.3 Domain

In this staircase, areas where people will walk on cannot be changed. Thus, the domain for application of the optimization algorithm was defined as everywhere but the steps and intermediate landing surfaces. In addition, support surfaces are not part of the domain. These areas are highlighted in Figure 1.

Another domain setting that has great impact on the optimization results is the initial volume of material and where it is located on space. For instance, if there is a large volume of concrete underneath the walking surfaces, then there is a lot of space where material could be removed. The possibilities of material distribution on space is different from an initial form where the sections are already slender. The initial volume of material is highly influential on the result. The first model has a large volume of concrete, and the last model has a thinner profile; this way, various forms can be studied.

3.4 Loads

The loads considered for this staircase are listed in Table 2 following the Brazilian design code (ABNT, 1980) and the values referenced by Cobb (2004).

Two loading scenarios were studied: the first was only self-weight, service load and finishes; the second was with all the loads applied.

Table 2. Load types applied in the model

Loading type	Value
Self-weight (program calculated)	$\text{volume} * \text{density}$
Service load	$3000\ N/m^2$
Finishes load	$1000\ N/m^2$
Railing line load	$740\ N/m$
Railing accidental vertical line load	$2000\ N/m$
Railing accidental horizontal line load	$800\ N/m$

3.5 Mesh

Another modeling specification that has great impact on the optimization results is the size of the mesh. When the mesh has large sized elements, the algorithm cannot make too many modifications on the structure; while the processing time is relatively fast, the resulting structure is not very elaborate. However, if the mesh is refined, then there are much more structure layout possibilities, many elements can be defined as voids. The mesh refinement increases a lot the processing time, but the results get more elaborate, showing different layouts than what might have been initially thought. The mesh sizing also needs to take into consideration how intricate the formwork can be. Refining it beyond a certain level might not be interesting: computational costs increases considerably and resulting forms increase in its complexity.

3.6 Optimization objective

The optimization objective in the model is set to minimize volume while maximizing structure stiffness. For the first couple of models the volume fraction was set to 50%, and on the last two it was set to 80%. The program shows results with a ruled legend that allows for visualization of values different than the targeted percentage of volume, making it possible to see less or more material distribution.

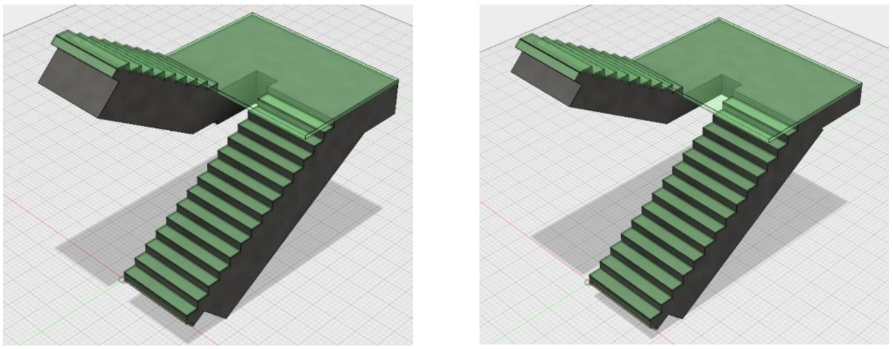
4 FE MODEL RESULTS

Initially it was thought that, once a step design was defined, a set of iterations would occur between parametric and FE models to define the sizing of the steps and intermediate landing. Afterwards, however, it was chosen to carry out the topology optimization of thinner volumes of concrete until it was not possible to withdraw anymore material from the structure because of lack of compliance with design codes. The parametric design would be detailed with the volume obtained from the last FE model. This way, program switching could be reduced to a minimum.

A sequence of different initial volumetric configurations, or, in short, "volumetries" were analyzed. For each volumetry there was a sequence of mesh refinements. The last models were studied for both load cases described.

4.1 First and Second Volumetries

First Volumetry. The first volumetry analyzed has an average thickness of 85 centimeters (Figure 2a). It was analyzed using the default mesh size of the program: elements with a model-based average size ranging from 1% to 8% of the total volume. The first results were of less material on the external sides of the staircase, and concentrated material on the internal part. The intermediate landing also presented the same configuration, with less materials on its borders, and concentrated material on the areas closer to the steps. This landing configuration would be reducing weight on the furthest areas from the supports, and increasing stiffness on the inner part of the landing, where it has higher stresses.



(a) **(b)**

Figure 2. First (a) and second (b) volumetries with highlighted restricted areas for optimization.

The second mesh was defined with model-based size elements ranging from 1% to 2% of the total volume. The results from this mesh configuration started showing some differences from the first. The same concentration of material on the internal part of the staircase was found; however, a small concentration of material was set on the outer parts of the steps, and on the bottom part of the domain as well. The appearance was of a hollow beam which the cross-section was the same width as the step's width. This hollow beam extends from the bottom step, up to the intermediate landing, and then, again, from the intermediate landing up to the top step. The intermediate landing showed similar configuration as the first one. The hollow cross-section would resist torsional stresses very well and balance different accidental loads on the railings. However, the structure would be quite bulky, which is not the intended outcome.

A third mesh, more refined, was generated, and the results were very similar to the second analysis. The hollow beam cross-section had a smoother outline, and still showed more material concentrated on the internal part of the steps. The intermediate landing showed similar results as well, but some of the material were extended to support the landing's borders. These results are all illustrated in Figure 3, every mesh refinement is presented in a column: (a), (b), and (c).

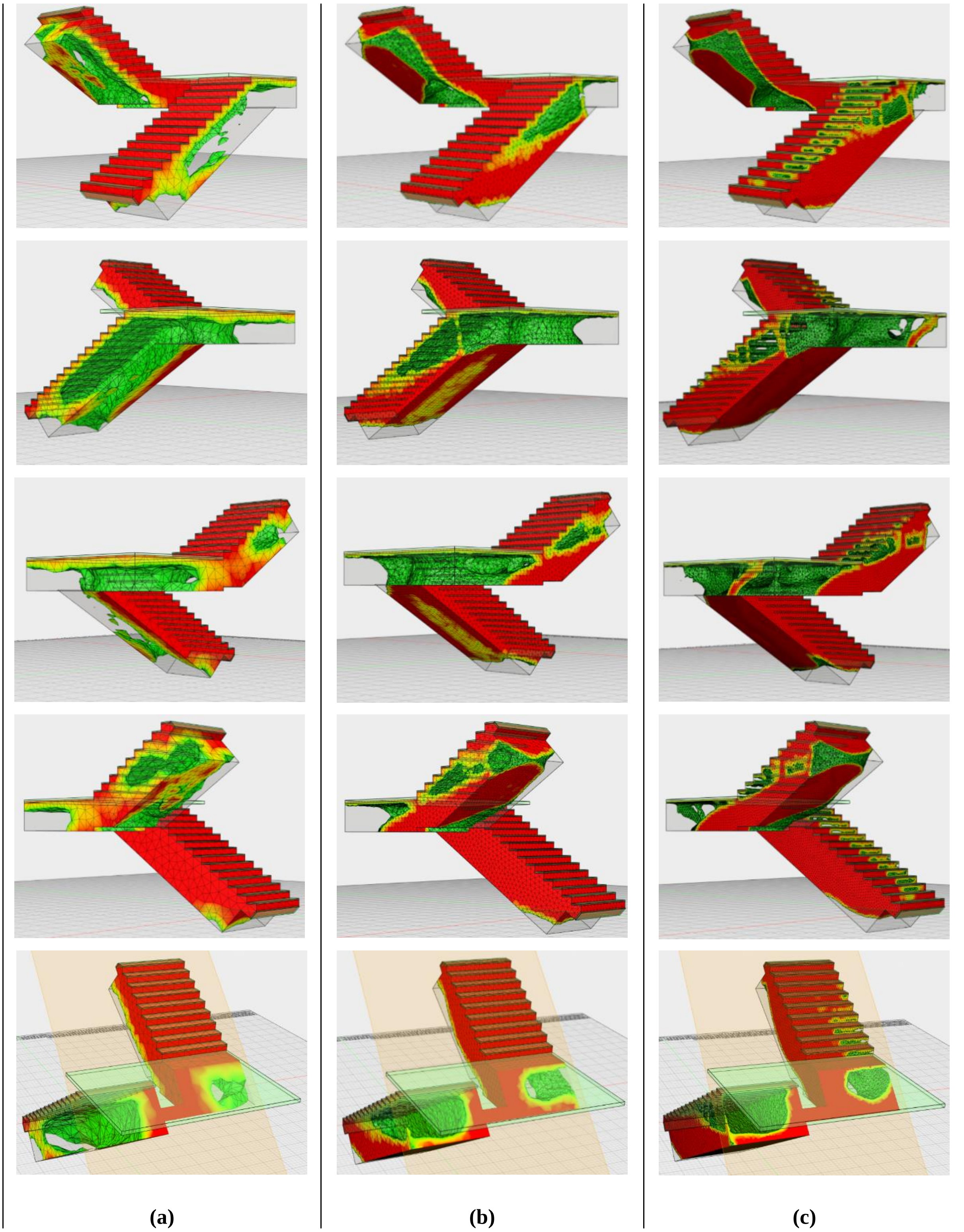
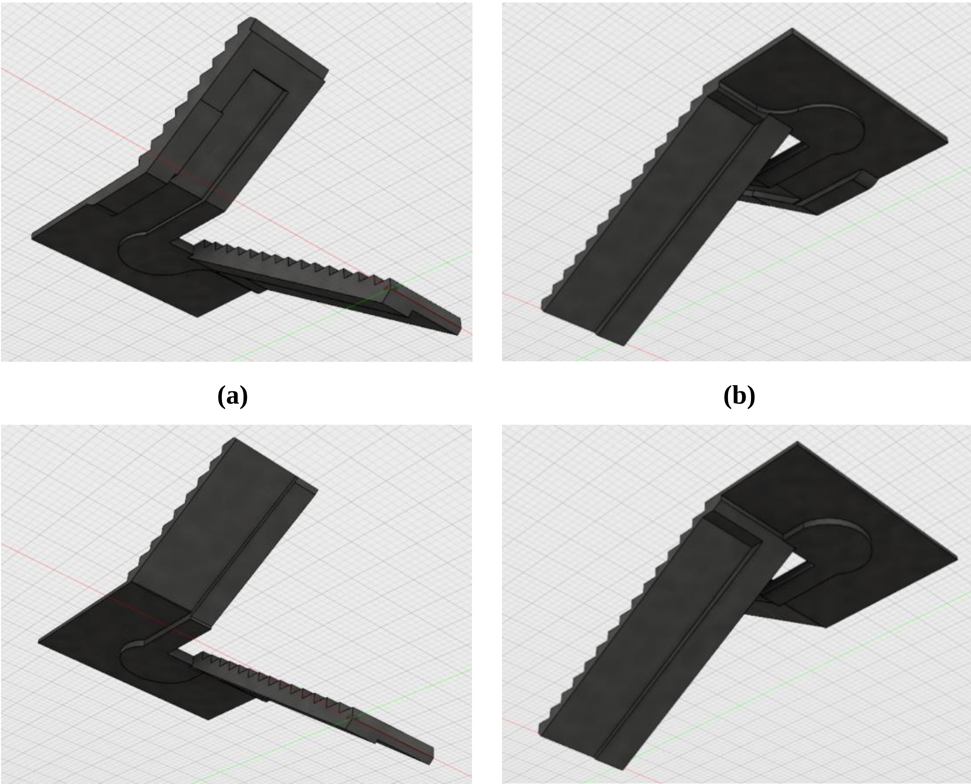


Figure 3. Topology optimization results of first volumetry organized in columns: the first (a), second (b), and third (c) mesh refinements

Second Volumetry. The block was defined with an average thickness of 40 cm. The second set of analysis was analogous to the first one, but with a thinner outline (Figure 2b).

4.2 Third Volumetry

The third shape was created with previous results. Between the first step and the intermediate landing there was a thicker layout on the internal side of the steps (a “side beam” along the steps). The intermediate landing was modified to have more material on the internal part as well, and less material near the borders. Between the intermediate landing and the upper step there were two thickened parts on each side of the steps, while material from the middle area was withdrawn (two “side beams”). This can be observed in different views of the same model in Figure 4a and Figure 4b.



(a) **(b)**

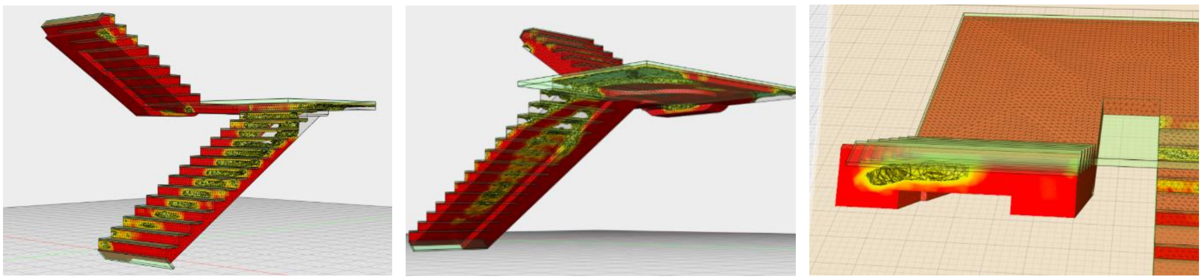
(c) **(d)**

Figure 4. Third (a, b) and fourth (c, d) volumetries

In the first mesh analyzed, the topology optimization results showed that the lower part of the steps needed less material on the “side beam”. The intermediate landing retained most of its material, and the upper part of the steps did not need as much material as specified, providing a thinner outline.

The second mesh configuration results only changed on the upper part of the steps: a hollow cross-section was formed, following the sequence of the previous volumetries.

The third mesh configuration resulted in more voids on the lower part of the steps. The voids were located along the middle part of the steps. The intermediate landing presented less material towards its boundaries. The upper part of the staircase kept the configuration from the previous mesh analysis. This result can be observed in Figure 5 (a), (b), and (c).

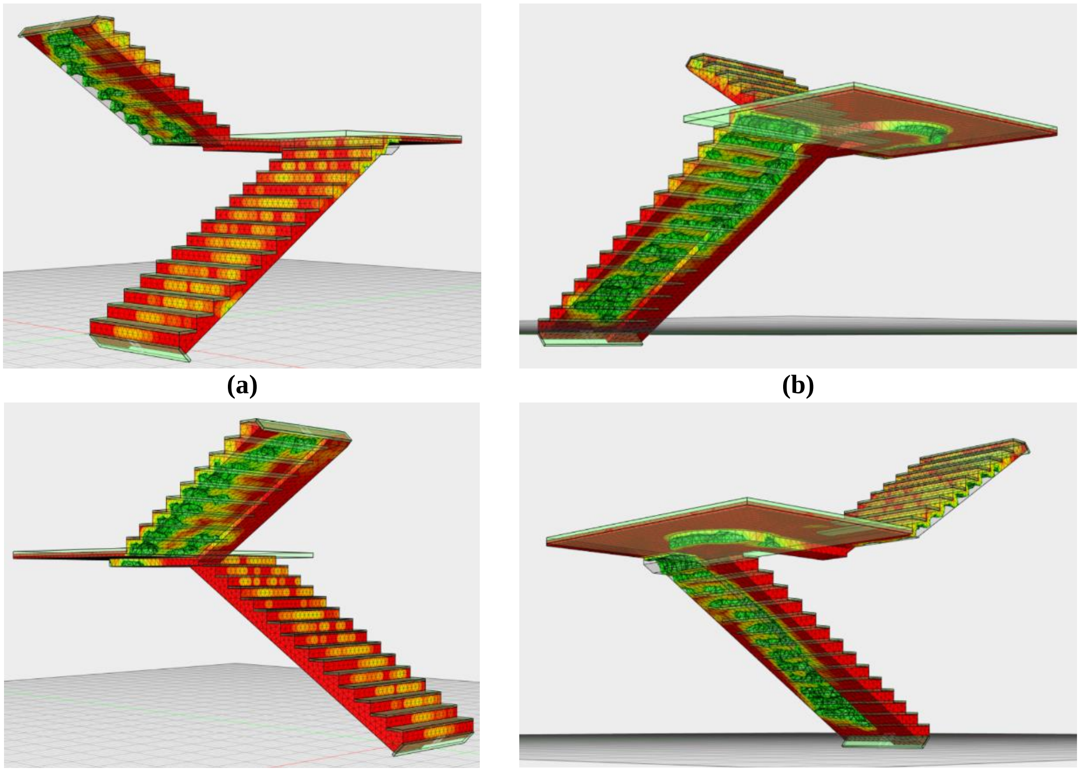


(a) (b) (c)

Figure 5. Topology optimization results for third volumetry, third mesh: two views (a), (b), and a cut (c)

4.3 Fourth Volumetry

The fourth volumetry (two views are shown in Figure 4c and Figure 4d) was generated taking into consideration the third set of analysis. A single "side beam" was formed along the internal side of the steps and the landing, leaving the outer borders of the staircase with a thinner outline. The mesh generated was as refined as the last mesh configuration on the third volumetry. More material was withdrawn from the outer borders of the staircase. This configuration was carefully analyzed for stresses and displacements, showing compliance with codes. The last topology optimization resulted in a volume of 3.25 m^3, and is shown in Figure 6 (a), (b), (c), and (d) (four different views of the same result).



(a) (b)

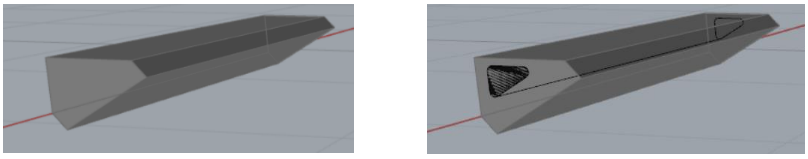
(c) (d)

Figure 6. Topology optimization results for fourth volumetry with four views: (a), (b), (c), and (d)

5 PARAMETRIC MODEL

The generation of the parametric model considers the total volume calculated on the final topology optimization. This way there can be less modifications due to insufficient stiffness on the parametric model created on the different software.

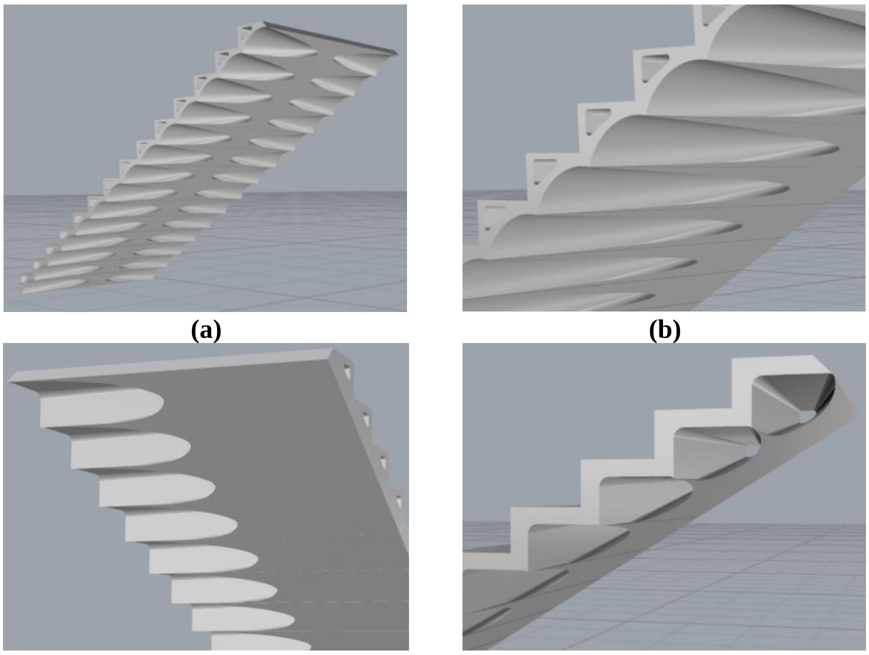
This model is built with a base solid that takes the form of the step and the riser (Figure 7a). Other solids are created to extract material from the base solid (Figure 7b). These other solids have many ways of being created in the software, depending on how the final shape is desired. They go from triangular extrusions to ellipsoids, or handmade curves extruded to points.



(a) **(b)**

Figure 7. Initial setting of one step in parametric model: base solid (a); and solid difference (b).

Once the final step geometry is created, it is copied in a linear array on the defined slope of the staircase. Various geometries were generated, a couple are shown in Figure 8a and Figure 8b, and the last one (Figure 8c and Figure 8d) was chosen to be analyzed. With the parametric model, the shape can be easily modified, the cutting geometries can be adjusted and changed, allowing for quick future changes it might need.



(a) **(b)**

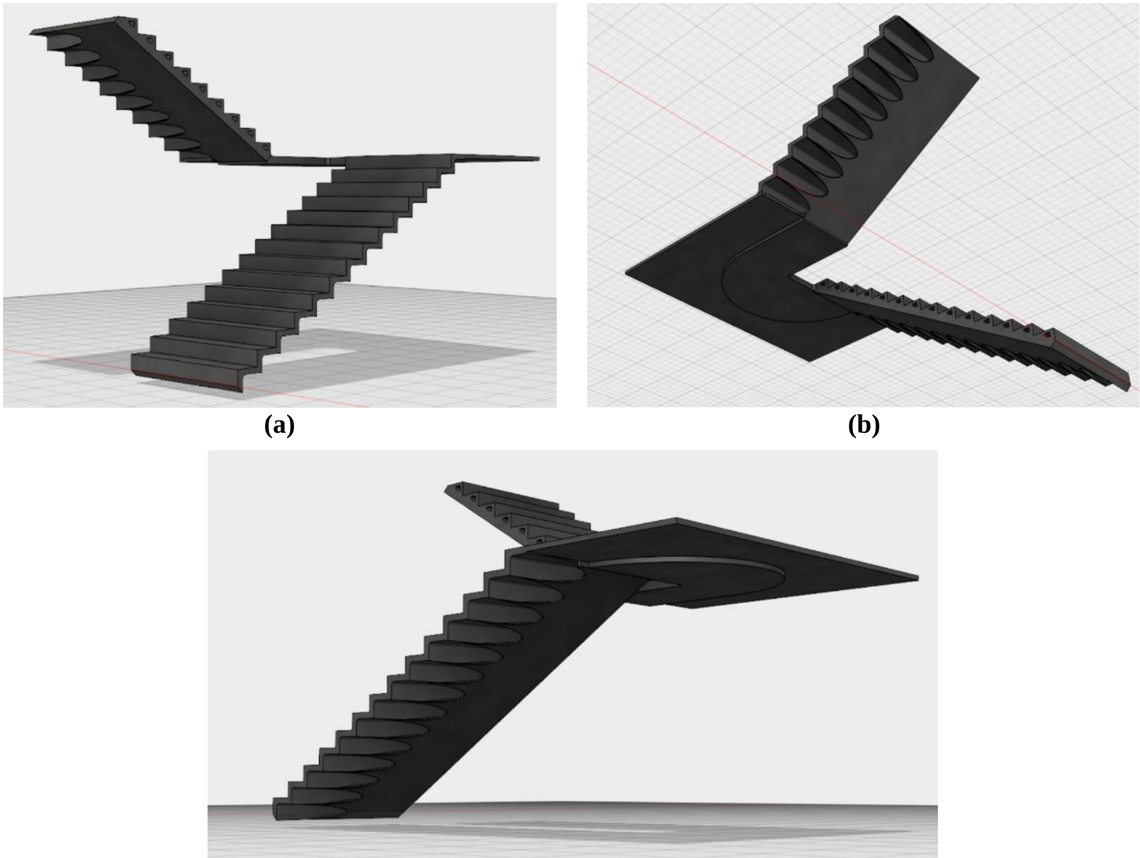
(c) **(d)**

Figure 8. Parametric model geometries: two initial models (a), and (b); and final model views (c) and (d).

6 FINAL RESULTS

After the parametric model is created there must be a verification of the shape on the FE analysis software. If the model meets design criteria then the form created can be constructed. However, if the model fails to meet design criteria, then there is a need to go back to the parametric model and adjust the design to be more robust wherever it needs the most.

The inserted model (Figure 9) shows compliance with design codes, with a maximum of 7mm deflection on the furthest point of the intermediate landing, which is 5.6m away from the supports. The internal areas of the intermediate landing present small areas of peak tensile stresses, indicating areas that might need local reinforcement. The natural frequency of this modeled staircase is 8.1Hz, which leaves a comfortable distance from the lowest desired frequency: 5Hz (Bachmann, 1995).



(a) **(b)**

(c)

Figure 9. Final model views (a), (b), and (c)

7 CONCLUSION

This paper provides an example on how topology optimization studies can be applied to generate organic forms and reduce material usage of structures. This optimization technique is not only valuable to minimize material usage, but it also reshapes how architects and engineers discuss different structural design approaches.

We show how different mesh sizes, with different initial volumetries provide the variety of results, and, finally, how parametric modeling allows for quick modification of shape for good visualization of the design. It is also important to know the interdependency of optimization technique, shape design and material choice. If it were not for UHPC this would have been a much more limited project.

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