IMPROVING MATERIAL PERFORMANCE THROUGH TOPOLOGICAL OPTIMISATION IN HIGH-RISE CONSTRUCTION

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Abstract. Material sustainability and wastage is becoming a core concern within the architectural practice, thus new approaches are being undertaken in design and construction. High-rise buildings are becoming more prevalent in today's cities, with the skylines of cities slowly rising. These high-rise buildings are constructed using a range of materials, primarily concrete, steel, and glass. The natural resources that are used to make these materials are slowly being depleted, thus there is a need to look towards a more sustainable material and method in which buildings are designed. This research project aims to develop a workflow in which the methodology of topological optimisation is applied to the design of a high-rise building to reduce material usage. Topological optimisation is the method which explores an alternate way in which structures are shaped and formed to reduce the volume of material while maintaining its structural integrity. The topological optimisation will be applied to specifically the columns, beams, and floorplates in this study. The results of this study will contribute to the research of sustainable design thinking through the method of topological optimisation.

Keywords. Sustainability; Topological Optimisation; Materiality; Material Waste

1. Introduction

Material sustainability and wastage is becoming a core concern within the architectural practice, thus new approaches are being undertaken in design and construction. High-rise buildings are constructed using a range of materials, primarily concrete, steel, and glass. The natural resources that are used to make these materials are slowly being depleted thus there is a need to look towards a more sustainable material and method in which buildings are designed (Crocker & Lehmann 2012).

In this research project, the methodology of topological optimisation is applied to the design of a high-rise building to improve material performance and reduce material consumption. Topological optimisation is the method which explores an alternate way in which structures are shaped and formed to reduce the volume of material while maintaining its structural integrity. This project will be following the overarching methodology of action research, wherein the researcher takes an iterative approach to plan, act, observe and reflect on a real-life problem (O'Brien 1998). The aim of the research project is to integrate topological optimisation within a design workflow of a high-rise building to generate structural data, aiding in the reduction of material usage in the building. Firstly, a mock-up high-rise building is generated with only the columns, beams, and floorplates. These structural systems are then topologically optimised through Ameba (topological optimisation plug-in). Different results can be generated through specifying different loads and specifying the ratio of material to be removed from the starting geometry. The new geometry generated from the optimisation will be structurally analysed and compared to the beginning geometry. Finally, the optimised geometry will be used to generate data such as the percentage of material remaining, which can then be used to calculate the weight and embodied carbons in that geometry. The data can be used to compare between the original geometry and other iterations of the optimisation to conclude the viability of implementing topological optimisation within the design of a high-rise building.

The results of this study will inform the architectural practice of the advantages of designing buildings using topological optimisation, emphasising the importance of reducing embodied carbons in the early stages of design through topological optimisation. This will consequently allow for the reduction of materials utilised within buildings, without sacrificing any structural performance. As sustainable design in architecture is becoming more of a priority, this project will contribute to the research of sustainable design thinking through the method of topological optimisation.

2. Research Aims

The primary aim of this project is to explore a methodology in which material usage in high-rise buildings can be reduced without compromising its structural integrity. This reduction in material usage will reduce material waste in buildings and allow for lightweight building designs. Through exploring these aims, the secondary aim of testing the viability of integrating the method of topological optimisation into the design workflow of a high-rise building is also explored.

3. Research Question

How can topological optimisation be applied in the architectural design process to reduce material waste, while maintaining structural integrity in high-rise buildings?

4. Methodology

Action research is the methodology in which researchers participate in both the practical and theory element of research. O'Brien (1998) states that action research is simply "learning by doing", where researchers take a holistic view of both real-life problems and implement theory to search for a result. Baskerville (1999) mentions that theory and social systems can only be understood as a whole, in which the action researcher takes a process, implements a change into that process and observes the results. This methodology of action research is seen as cyclical. Stephen Kemmis devised a diagram of action research with four steps: plan, act, observe, and reflect (O'Brien 1998). Gerald Susman has also developed a cyclical diagram of action research consisting of five steps: diagnosing, action planning, taking action, evaluating, and specifying learning (O'Brien 1998).

Through the methodology of action research, change is aimed to be achieved. Hearn and Foth (2005) mention "action research… is not only to understand the problem, but also provoke change". As stated before, action research investigates real-life problems. Azhar, Ahmad and Sein (2009) poses that the Construction Engineering and Management field is a "proactive" field, which in each new project is an "intervention into what exists and thus creates [a] new reality" (Azhar, Ahmad & Sein 2009), and state that a more proactive research method should be applied, such as action research.

In my project the methodology of action research will be implemented. Through taking a holistic approach of practical and theory, on a real-life problem, a change will be implemented, and the results will be observed and documented, and from that data future iterations can be improved upon. The methodology of this project will draw from Gerald Susman's diagram of action research. The problem will be identified, through theory and research data will be gathered about the problem, this will inform the researcher about possible solutions, a 'solution' will be implemented into practice, data is then collected and analysed, and this data will inform future iterations of the project.

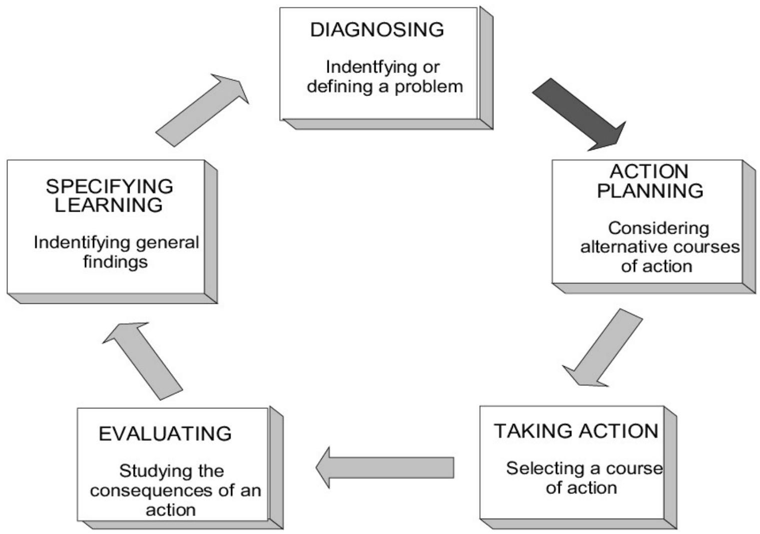


Figure 1. Gerald Susman's Diagram of Action Research

5. Literature review

With the population of our cities steadily growing there is a need to develop more buildings to keep up with the increasing population. However, the development of buildings should always respond to its context, including the functionality of a building and environmental surroundings of a building (Ibrahim 2007, p. 4). And as population increases more buildings are required, thus designers and developers turn to taller high-rise buildings "out of necessity… to achieve high density development" (Ibrahim 2007, p. 3).

With the recent increase of high-rise building development there has been research conducted into the structural systems of these high-rise buildings. A study conducted by Panchal and Patel (2014) analysed the system of a diagrid structure versus a conventional frame structure to compare the effectiveness of each structures capability of withstanding both lateral and vertical loads. This research demonstrated that a high-rise building using a diagrid structure displaced less from lateral and vertical loads compared to the conventional frame structure. Although the structural stability of a high-rise building is the first major priority, with the increasing amount of high-rise buildings, material usage is also becoming a major consideration. In the same study conducted by Panchal and Patel (2014), it was discovered that the diagrid structure consumed 13.01% less concrete and 57.9% less steel.

This interrelationship between the structural systems and, the materiality and material usage of a building is recently becoming considered more. In a study by Kim.D, Kim. J, and Chang (2014), the material properties of 800 MPa high strength steel (HSA800), was compared with the material properties of normal strength steel (SM570) and their applicability in a high-rise building. Both materials were tested in the same building model. From this study it was discovered that through the implementation of a stronger material (HSA800), 27% of SM570 steel could be replaced with the stronger HSA800 steel, resulting in the reduction of steel consumption by 9%. By being able to reduce material usage in buildings as shown through the studies conveyed by Panchal and Patel (2014), and Kim.D, Kim. J, and Chang (2014), design is moving towards a more environment friendly path.

Recently cross-laminated timber (CLT) construction has been making its way into the market. CLT consists of timber boards glued together in a crosswise pattern. "Layering crosswise brings advantages in terms of load bearing capacity in two directions, increased shear capacity… [and eliminates] shrinkage and swelling" (Van De Kuilen et al. 2011, p. 2). CLT is also well suited for high-rise buildings due to its light-weight properties along with its capacity to withstand loads in two directions and its shear capacity and that it can be engineered for fire resistance. In the study by Van De Kuilen et al (2011), a simple rectangular building was designed with more than forty levels, to test the feasibility of CLT in high-rise buildings. Through this study it was concluded that the use of CLT in high-rise buildings is feasible, however steel bars would be required to aid the CLT in taking up the tensile forces.

Furthermore, CLT is not only structurally sound, but is also renewable, due to the characteristics of timber (Ahmed and Arocho, 2019), consumes less energy during manufacturing, and consumes less energy during construction (Van De Kuilen et al. 2011, p. 7). Additionally, as CLT is comprised of primarily timber, CLT is carbon friendly, due to timber being a material with a negative C02 balance (Van De Kuilen et al. 2011, p. 7). These studies into the possibility of utilising a material that is not only structurally strong, but also renewable and carbon friendly, reinforce the viability and purpose of designing environment friendly structures through the means of researching materiality.

Other methods of decreasing material usage in buildings include the design and construction of lightweight structural forms such as the tree-like structures designed by German architect Frei Otto (Ahmeti 2007, p. 15). In the case study conducted by Ahmeti (2007), Frei Otto's design of tree-like columns was analysed through the case study of existing buildings that implement his design, such as Stuttgart Airport, Beaverton Library, and Therme Bad Oeynhausen. This case study concluded that through 'lightening' a structure, material is removed where it is not needed and in turn material can be reinforced where needed. Through these lightweight tree-like structures, both structural stability and material consumption is considered to reach a balanced outcome of structural strength and less material consumption.

While the previous study analysed column structures, a 2019 study by Aghdasi et al. (2019) explored the possibility of creating lightweight octet-truss systems for facades and floorings in a building. The study explored the reduction of material in floor structures through designing an octet lattice like system for a floor rather than have a completely solid block of concrete. The design of the octet lattice-like system was then tested using different compositions of concrete. Once again, through this study, a balance between structural stability and materiality has been met to improve the performance of the structure whilst under different loads.

Although reducing material consumption through optimising a structure of a building is a step towards a more sustainable future, a study Naji et al (2016) takes a different approach into the reduction of material consumption within a building. Naji et al (2016) explores the thickening and thinning of different layers in a wall, reducing material, but primarily to optimise the insulation of a building to reduce energy consumption in buildings.

Finally, topological optimisation is another method in which material can be reduced from structure, striking a balance between form and function. Beghini et al (2014) states that topological optimisation can be used as a method to reduce material consumption in a structure, while also maintaining its structural integrity, and providing aesthetics. The study by Beghini et al (2014) explores the possibility of implementing topological optimisation in high-rise building façade structures, and bridges. This study concludes that topological optimisation can bridge the gap between engineering and design.

With the development of our cities more materials are being consumed, which in turn leads to the increase of material waste. Researchers are exploring different methods and have different takes on how materiality can be manipulated to lead to a more sustainable living. Researchers such as Kim.D, Kim. J, and Chang (2014), and Van De Kuilen et al (2011) explore the possibilities of utilising stronger and more sustainable materials to reach a sustainable living. Other researchers try to optimise load bearing structure systems to achieve this, such as Ahmeti (2007), Aghdasi et al (2019), and Beghini et al (2014). With all this research and studies conducted into the materiality and structure of a building, a balance between the two can be achieved, and should be explored further through future research.

6. Case Study

6.1. PROJECT WORKFLOW

This case study explores the possibility of integrating topological optimisation into a design workflow. By doing so the structural systems of a high-rise building will have material reduced while still maintaining their structural integrity. This case study will follow the five steps shown in *Figure 2* to investigate the feasibility of topological optimisation in high-rise buildings.

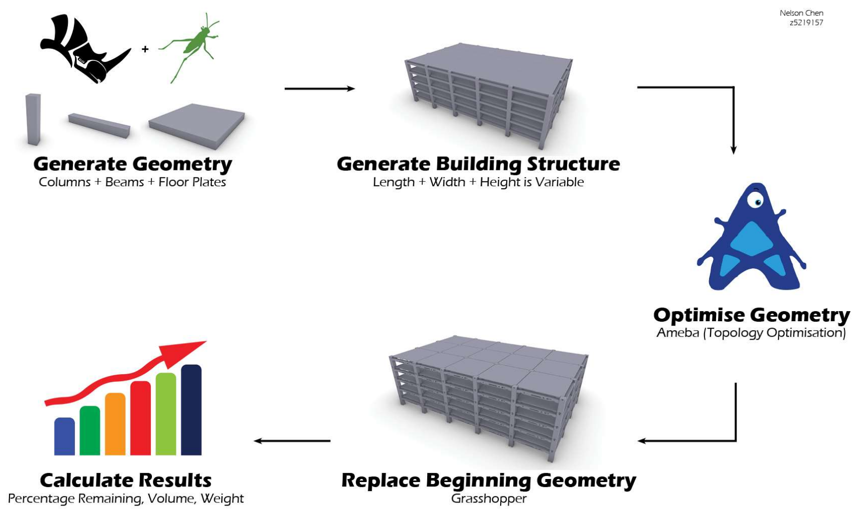


Figure 2. Project Workflow Diagram

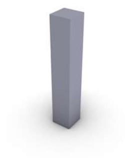
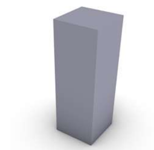
6.2. GENERATING GEOMETRY

Firstly, the structural systems of a building were modelled in Grasshopper, these included the columns, beams, and floorplates. From these models the initial volumes of each of the columns, beams, and floorplates can be calculated.

6.2.1. Columns

In this case study, the columns were generated as rectangular prisms. These columns had a variable height, width, and length. The variable height would allow for a higher variety of designs in which level height may vary (Table 1).

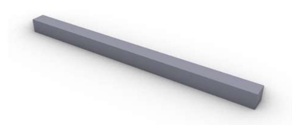
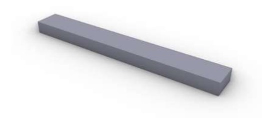
Table 1. Visual Representation of Column Variables

Thinner Column	**Thicker Column**
	

6.2.2. Beams

The beams were generated as rectangular prisms, with the height being variable. The beams are connected to the columns; thus, the length and width of the beam is dependent on the width and length of the columns (Table 2).

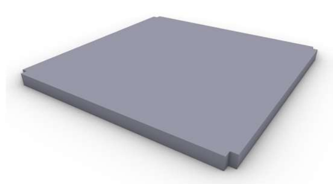
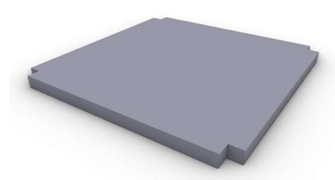
Table 2. Visual Representation of Beam Variables

Thinner Beam	**Thicker Beam**
	

6.2.3. Floorplates

The floorplates were generated as a rectangular prism, with the thickness being variable. The floorplate is attached to the columns on the corners thus the cutout of each of the corners is dependent on the column's length and width (Table 3).

Table 3. Visual Representation of Floorplate Variables

Smaller Cutout on Corners (Dependent on Column)	**Bigger Cutout on Corners (Dependent on Column)**
	

6.3. GENERATING BUILDING STRUCTURE

With the geometries of the column, beam, and floorplate modelled, a script is produced using Grasshopper to piece each component together to form a structure of a building. The grid size of the columns was set to 9x9 meters, meaning that every 9 meters a column would be placed. The length and width of the building could also be adjusted, keeping to a number divisible by 9 (i.e. 81x45 meters). The number of levels in the building is also variable. The variability of the script allows for the overall workflow to be able to be integrated into many projects. In this case study the length and width of the building is 27x45 meters, with 7 levels.

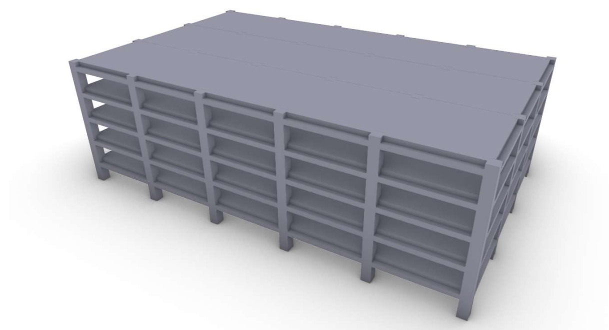


Figure 3. Visual Representation of the Building Structure

6.4. TOPOLOGICALLY OPTIMISE GEOMETRY

To topologically optimise the columns, beams, and floorplates, a plug-in called Ameba was utilised. Ameba is a plug-in developed by XIE Technologies, which allows users to specify different loading points, support points and volume fraction remaining, to an initial geometry. Ameba operates through cloud computing, meaning that the geometry, along with the specifications allocated to it through Ameba gets sent to an external server where the topological optimisation is calculated. The resulting geometry is returned to the user along with the iterations Ameba goes through to reach the result (Table 4). In this project Ameba will be applied to the columns, beams, and floorplates separately.

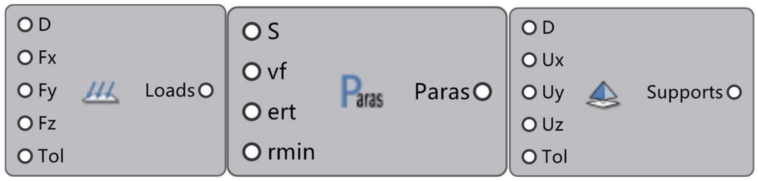
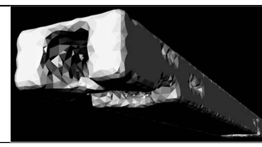
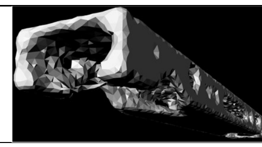


Figure 4. Nodes Provided through Ameba for varied Optimisation

Table 4. Examples of Iterations Ameba Provides

Iteration 1	**Iteration 6**	**Final Iteration**
		

6.4.1. Columns

The column was topologically optimised through Ameba by initially specifying the position of the loads and the supports. Due to the nature of columns being stacked one on top of each other the position of the loads applied on the column should be in the same position as the supports specified on the column. In this case the loads were applied on the four top corners of the column (Figure 5), consequently meaning that the supports of the column were on the four bottom corners (Figure 6).

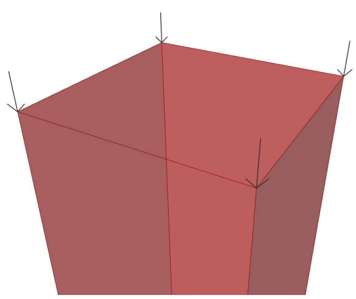


Figure 5. Position of Loads Applied on Column

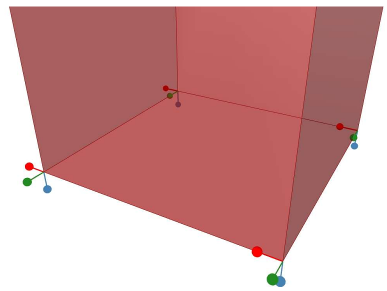


Figure 6. Position of Supports on Column

In this case, 50 per cent of the material was specified to be removed in Ameba.

6.4.1.1. Analysing Results

The resulting geometry from the topological optimisation of the column can be seen in *Figure 7.* The 50 percent of the material removed resulted in the column being hollowed out and creating cavities on the exterior of the column.

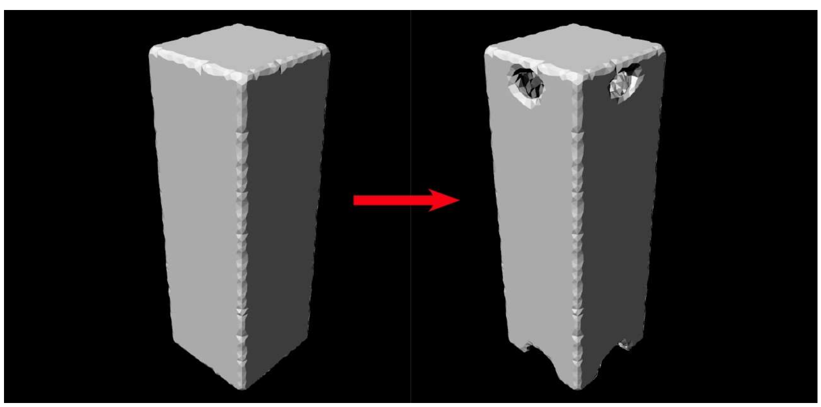


Figure 7. Before and After of Topological Optimisation on Column

Although the method of topological optimisation takes away material where it is not needed, the results from Ameba occasionally do not keep to that rule. This is where there is the need to analyse the structural integrity of the resulting geometry from Ameba.

Ameba provides a stress analysis of the resulting geometry, which can be used to compare with a stress analysis of the initial geometry.

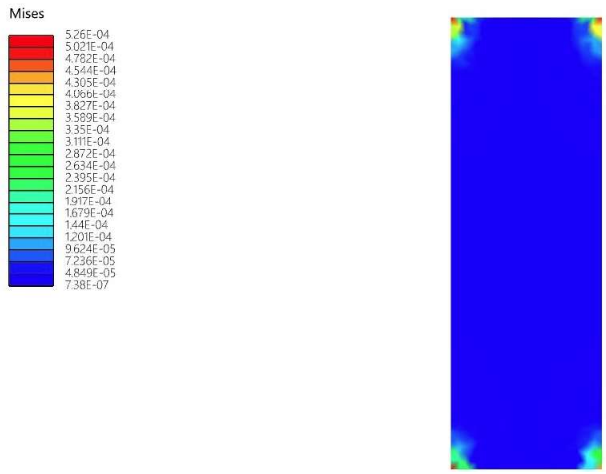


Figure 8. Stress Analysis of Column Before Topological Optimisation

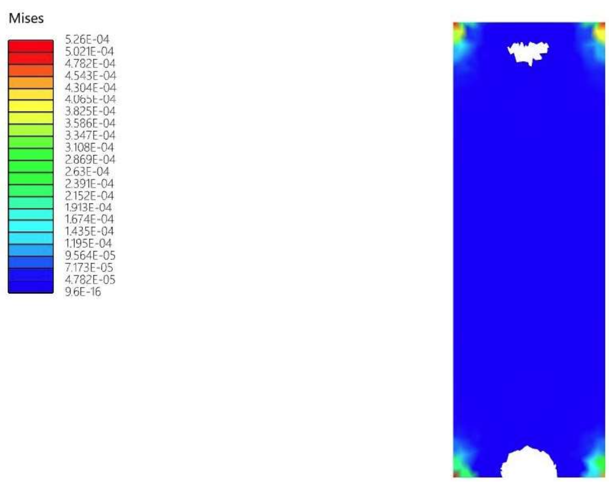


Figure 9. Stress Analysis of Column After Topological Optimisation

From *Figure 8* the maximum stresses of the initial geometry are located on the corners of the column, with maximum stress value of 5.26E-04. Compared to the stresses of the resulting geometry, the maximum stress value remained the same at 5.26E-04 (Figure 9). This ultimately means that the topological optimisation carried through Ameba was successful, and that even with 50 per cent of the material reduced the column's structural integrity was not compromised. This result implies that more material can still be removed from the column until the stress values begin to increase significantly.

6.4.2. Beams

The beam, although different from the column, the process of topologically optimising it through Ameba remains the same. The beams generated in this case study were modelled to aid in the supporting of the floorplate. Resultingly, the load applied onto the beam would be the entire top face of the initial geometry (Figure 10). The beam is connected to the columns on each end; thus, the supports were positioned on the four corners on each side of the initial geometry (Figure 11).

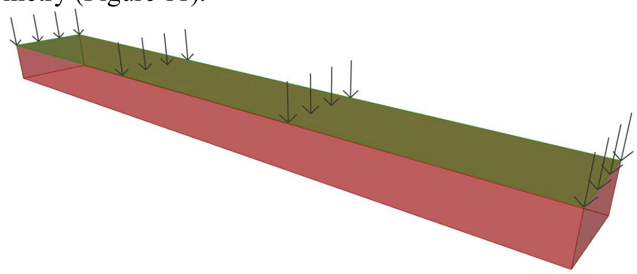


Figure 10. Position of Loads on Beam

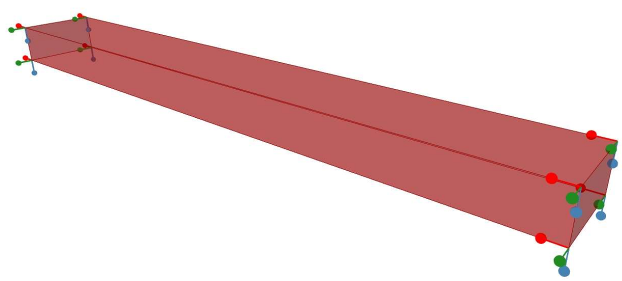


Figure 11. Position of Supports on Beam

In this case, 50 per cent of the material was specified to be removed in Ameba.

6.4.2.1. Analysing Results

The resulting geometry of the topological optimisation can be seen in *Figure 12*. 50 per cent of the material removed resulted in the beam being hollowed out, leaving the exterior sides to form truss-like structures.

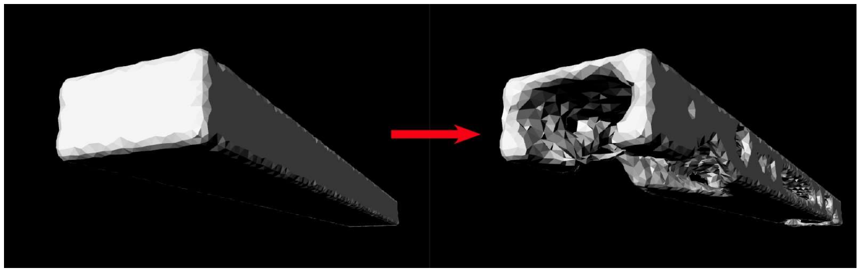


Figure 12. Before and After of Topological Optimisation on Beam

To ensure that the topological optimisation did not remove material where necessary, the stress analysis results were compared.

Figure 13. Stress Analysis of Beam Before Topological Optimisation

Figure 14. Stress Analysis of Beam After Topological Optimisation

From *Figure 13* the maximum stresses of the initial geometry are located on the corners on either side of the beam, with a maximum stress value of 2.14E+03. Comparing to the stresses of the resulting geometry, the maximum stress value increased very slightly at a value of 2.22E+03 (Figure 14). This means that although material was removed where it was not needed, the structural integrity of the beam was very slightly affected. To resolve this decreasing the percentage of material removed will decrease the maximum stress difference between the initial and resulting geometry.

6.4.3. Floorplates

The model of the floorplate was generated to be attached to the columns. Thus, the supports of the floorplate are located on the cutouts of the floorplate (Figure 15). As the floorplate is where there are live loads, the load specified on the floorplate was a uniform load, positioned on the entire top surface of the geometry.

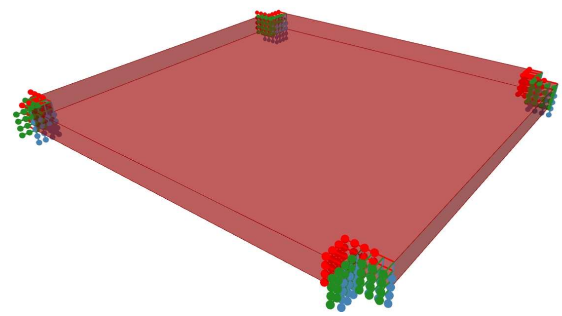


Figure 15. Position of Supports on Floorplate

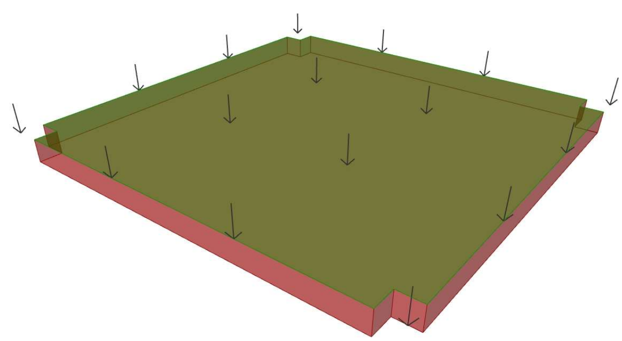


Figure 16. Position of Loads on Floorplate

In this case 50 per cent of the material was specified to be removed in Ameba.

6.4.3.1. Analysing Results

The resulting geometry of the topological optimisation can be seen in *Figure 17.* The specified 50 per cent of the material was removed from the under side of the floor plate, leaving only material around the cutouts where the floorplate meets the column.

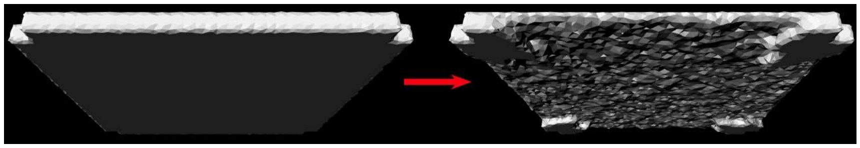


Figure 17. Before and After of Topological Optimsation on Floorplate

The structural integrity of the floorplate is analysed through the stress analysis Ameba provides.

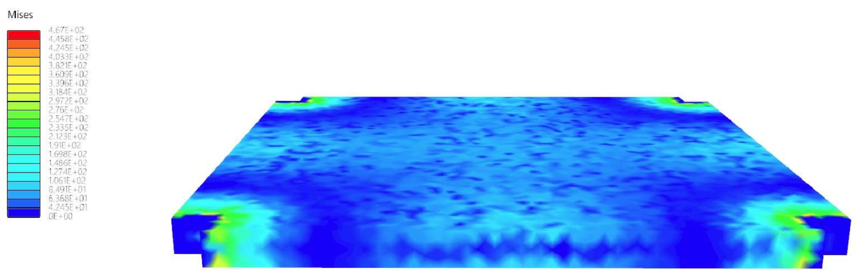


Figure 18. Stress Analysis of Floorplate Before Topological Optimisation

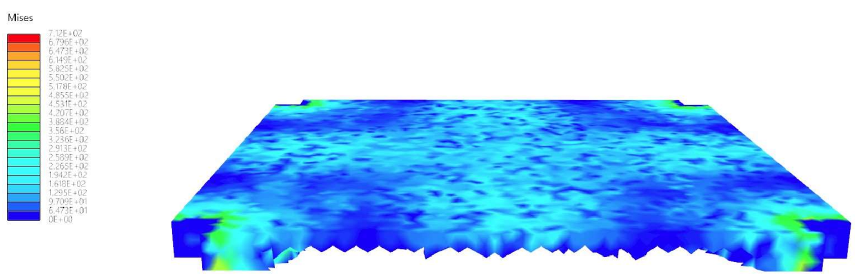


Figure 19. Stress Analysis of Floorplate After Topological Analysis

From *Figure 18* the maximum stresses the floorplate experiences are located around the connections to the columns, with a maximum stress value of 4.67E+02. Comparing to the stress values the floorplate experiences after the topological optimisation, the stress value increased significantly, with a maximum stress value of 7.12E+02. This result means that Ameba has taken away material away where it was needed to maintain the floorplate's structural integrity.

To resolve this problem the percentage of material removed was decreased from 50 per cent to 22 per cent. With this decrease in material reduced the structural integrity of the floorplate was not compromised by the topological analysis. The maximum stress value of the floorplate with 22 per cent of the material removed is 5.29E+02 (Figure 20).

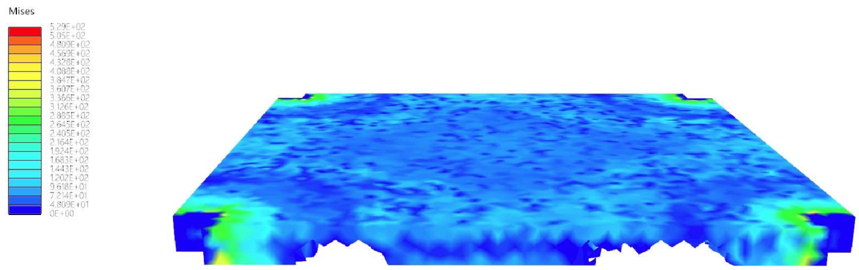


Figure 20. Stress Analysis of Floorplate with 22 Per Cent of Material Removed

6.5. REPLACE BEGINNING GEOMETRY

With the column, beam, and floorplate topologically optimised, the initial geometry of the building is replaced with the resulting geometries. From this optimised building the number of columns, beams, and floorplates can be tallied up to calculate final volume and weight.

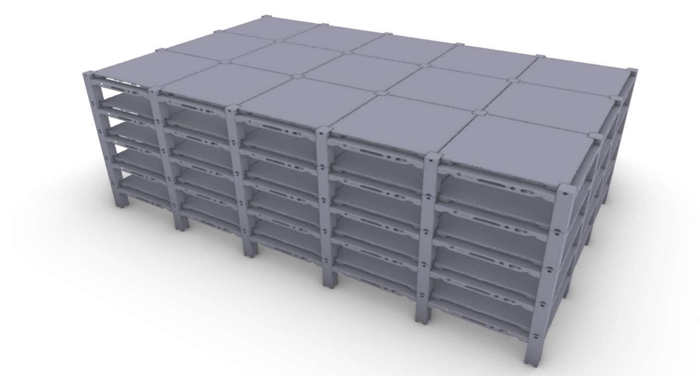


Figure 21. Building Script Populated with Topologically Optimised Columns, Beams, and Floorplates

6.6. CALCULATE RESULTS

With the columns, beams, and floorplates topologically optimised, the percentage (P) of material of each of the geometries remaining can be calculated. In this case, the percentage of the columns remaining after the optimisation is 50 per cent; the percentage of the beams remaining after the optimisation is 50 per cent; and the percentage of the floorplate remaining after the optimisation is 78 per cent. From this the mass of the material remaining can be calculated. Through the initial geometry generated, the volume (V) of a single column is $3m^3$; the volume of a single beam is $4m^3$; the volume of a single floorplate is $40m^3$. In this project, the building was set to have the dimensions of 27x45 meters, with 7 levels. In this case there would be 168 columns (*n*), 266 beams (*n*), and 105 floorplates (*n*). To calculate the Total Volume (TV) of the entire building *equation 1* is used.

$$TV = n \times V \quad (1)$$

From *equation 1* the TV: of columns is $504m^3$; of beams is $1064m^3$; of floorplates is $4200m^3$.

Using the TV of the initial geometries in the entire building, *equation 2* can be used to calculate the Final Volume (FV) remaining in the building after the topological optimisation.

$$FV = TV \times P\% \quad (2)$$

From *equation 2* the FV of the optimised geometries is: $252m^3$ for the columns; $532m^3$ for the beams; and $3276m^3$ for the floorplates. Adding all these values together the volume of the final building is $4060m^3$, a decrease of $1708m^3$ from the original $5768m^3$.

Using this data the weight of a building and the embodied carbons can also be calculated by multiplying the weight of a material per meter cubed with the final building's volume, similarly calculating the embodied carbons can be done by multiplying the final building's volume with an embodied carbon per meter cubed.

7. Discussion

Through this case study, the methodology of topological optimisation was successfully integrated into a design workflow of a high-rise building using Grasshopper and Ameba. By being able to integrate topological optimisation into a design workflow of a high-rise building material usage was able to be reduced in each of the column, beam, and floorplate by up to 50 per cent. Thus, the project aim of reducing material usage in a high-rise building was successfully achieved.

Although the case study successfully met the aims set out, there were some constraints that hindered the quality of the results. One of the constraints include the 10-week time limit in which the project was restricted to. Given more time the project could have been expanded upon. The current project digitally proves the capability of integrating topological optimisation into a design workflow of a high-rise building. However, the project could be expanded upon through the exploration of machining technologies in which the resulting geometry outputted from Ameba could be manufactured in the physical world. This would require extensive research on a variety of materials and their properties, for example steel 3D printing or multiple-axis CNC milling for CLT.

Another constraint that was encountered during the project was Ameba's cloud computing. As the cloud computing requires files to be manually sent to the servers, the process of automating the workflow was not possible. The process would require human input to adjust different settings such as load and support positions on a geometry, then manually sending a new file to Ameba's servers each time. Although the automation process was not specified in the aims of this project, for future development trying to automate this workflow would be a challenge.

Regardless of the constraints, the case study undertaken produced positive results for the viability of integrating topological optimisation in a design workflow of a high-rise building, specifically using Grasshopper and Ameba. The results from the case study directly address the sustainable design in architecture, through reducing material usage, ultimately reducing material waste. The implications of the results from the case study is the capability for buildings to be constructed with higher storeys. Due to the reduction in material usage, the weight of the building and each of its storeys is reduced, this implies the ability for the building to be constructed higher disregarding building height limitations in different cities. Furthermore, through designing lighter-weight buildings, constructing on top of existing buildings, such as Bates Smart's Collins House project, will allow for more levels.

8. Conclusion

Sustainable design is nothing new, researchers have explored methods of reducing material usage in buildings through researching stronger materials, as well as researching shapes and designs which form a stronger structure using less material. This study explores the latter by generating new designs which form a stronger structure using topological optimisation. Topological optimisation allows material usage in high-rise buildings structures to be reduced, which in turn reduce material waste within the architectural and construction fields. Developing a workflow which integrates the methodology of topological optimisation allows for the generation of geometries with reduced material volumes, which allow for lightweight building components to be designed. This process has been explored through an iterative process using Grasshopper and Ameba. The reduction of material waste will not only satisfy the concerns of architects, clients and stakeholders alike, but will allow the previously wasted material to be implemented into more storeys in a building or a into a new building all together. This study contributes to the research others have conducted into sustainable design. Although the study was conducted using digital means, it was proven that building structures can have their material usage reduced by up to 50 per cent, meaning that the 50 per cent of material can be utilised elsewhere. It is without a doubt that buildings can be designed employing the method of topological optimisation, it is whether these complex designs can be translated to reality through machining methods and technologies.

Acknowledgements

Thank you to Aaron Coats, Stephen Green, and Peter Pittas from Bates Smart for the fresh perspectives, ideas, and guidance they provided during the period of this project. Thank you to Nicole Gardner and Matthias Hank Haeusler for providing insightful feedback on the writing and project conducted. And thank you to Nic Bao and Daniel Yu for providing me assistance with technical issues throughout my project.

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