THE AM ENVELOPE

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ABSTRACT

Growing concern about resource consumption in the construction industry has brought new challenges to the design of façades. Compared to traditional techniques, AM stands out for the possibility of fabricating complex geometries embedding multiple functions. This study explored how the potentials of Fused Deposition Modelling can be used to create a multi-functional façade element for thermal insulation and structural stiffness. Physical testing and software simulations have been performed to assess the properties of complex geometries and retrieve design guidelines. A digital workflow was developed, encompassing performance-driven design, performance assessment and geometry generation for fabrication. The study highlights how, by manipulating porosity and material distribution, it is possible to design stiff, insulating envelope components which are suitable for manufacturing with FDM using polymers.

KEYWORDS

Additive Manufacturing - Thermal Insulation - Topology Optimisation - Façade - Digital design

REFLECTION

Graduation theme

My research aimed at exploring the potentials of additive manufacturing techniques to produce façade components which can serve multiple functions at the same time, making optimal use of material. The research topic itself was targeted at the integration of different disciplines, something which is somehow inherent to the design of the building envelope. In particular, thermal and structural performance are the two aspects that were investigated along with the definition of a façade concept. Computational design and use of digital tools helped in bringing all these aspects together, taking also into account the production technique. Therefore, this project is positioned between the different tracks that configure the BT master's programme. However, a prominent part of the research focused on the relation of geometry with thermal performance and additive manufacturing. This feature is also reflected in the choice of the mentors for my project, who belong to the Chairs of Design Informatics and Building Physics.

Graduation process

Background

The background for this study is a research line which already exists in the TU Delft AE+T department. It aims at investigating the potentials of additive manufacturing for the production of integrated components for climate control and optimised structural elements for load transfer. To a certain extent, this research aimed at combining this two lines and deal with both aspects at the same time, considering that climate control and load transfer are main requirements for a façade component and that additive manufacturing allows for integration of different performance through complex geometries. Being the topic relatively new to architecture, the literature research covered studies from different fields, mainly aerospace and mechanical engineering where additive manufacturing is already a well-established area of research and application. A major difficulty was the lack of studies about functional integration of thermal and structural performance. The additional step of combining these different aspects and retrieve guidelines for the research had to be taken.

Methodology

At the beginning, the approach for integration of structural thermal performance was not fully defined. Considering the outcomes of the literature research, it appeared clear that the two aspects could be tackled together but the geometry optimisation had to be done at two different levels: at the component level and at the material meso-scale. While at component level geometry optimisation relatively to structural performance is more significant, the relation between geometry and thermal performance is the main factor to be explored at meso-scale. The two geometry optimisations were done simultaneously and alternatives were evaluated having the integration of both performances in mind. An alternative approach for this problem would have been trying to explore both performances at meso-scale.

According to the initial graduation plan, extensive exploration and assessment of different geometry alternatives was proposed using analytical models, numerical methods and tests. However, physical tests for thermal performance could not be run on each geometry. The production of samples by additive manufacturing resulted to be time-consuming and very much dependent on the availability of facilities at the university. For this reason, production of lattice geometry could not be achieved and production of other geometry samples was limited to few alternatives. Therefore, evaluation of thermal performance for lattice geometries only relied on the simulation performed in COMSOL Multiphysics.

Thermal performance simulations covered a significant part of the research. Establishing a reliable model for assessing thermal resistance of different design alternatives was needed to retrieve guidelines for the final design. Although the physics of the problem being simulated was straight-forward, being limited to steady-state heat transfer, the complexity of the geometries resulted in considerable computation time and power. Simulation including all three heat transfer modes proved to be excessively expensive and impossible to use for quick evaluation of alternatives in the design process. Therefore, a significant amount of time was dedicated to elaborating and validating a simplified model to study the same problem. This required different steps in the simulations and comparison with the test results. The final model used for the thermal performance assessment is a simplified model which simulates heat transfer by conduction and takes into account convection and radiation indirectly. The assessment of structural performance through simulations was more direct, with the advantage of being performed within the parametric environment. Reliability of results could have been verified by performing physical tests on 3D-printed samples. This, however, was not possible in the available time frame.

Performance-based design

This thesis was a combination of research through design and performance-based design where the design was driven by the results of research and, in turn, the research focus and fields of exploration were highly dependent on the specific design objectives. To this purpose the use of parametric design tools was essential as it allowed quick generation of design alternatives that could be tested and assessed, retrieving guidelines for further exploration. The impossibility of performing FE analysis for heat transfer within the parametric environment was a limitation to the design process which prevented a more thorough exploration of the relation between performance and geometry.

Societal Impact

AM in the building industry

This research promotes the use of additive manufacturing techniques in the building industry. While these techniques are well-established in more advanced industries, their potentials are only now being explored for the built environment. Over the last decades, research from the academic world and the industry has made significant headway towards the implementation of AM proposing different solutions for a variety of materials and for the different scales of buildings. Examples already exist in which a whole building is produced by large-scale 3D printing, demonstrating how advancements in technology can now lead to a complete re-thinking of the building construction.

Nevertheless, the building industry is far from implementing AM techniques in the same way as it is done for traditional production processes. Additive manufacturing is still not cost-effective but this is already rapidly changing with advancements in the technology and the required tools. Another important aspect to take into account is the lack of building codes and regulations which specifically deal with 3D printed materials and components so that the use of these techniques is limited to exceptional conditions. Additive manufacturing may never really take the place of traditional manufacturing techniques but its potentials are such that new ways of designing and regarding buildings are arising. My research aimed at exploring how these potentials can be used and suggesting new scenarios for the design and production of building envelope components.

Sustainability

Sustainability is the underlying thrust for this research. The focus on the design of a mono-material multifunctional façade element arises from two main concerns: reducing material use and wastage in the building industry and improving the quality of the end of life options for the component. In principle, for a mono-material façade element, there would be no need for disassembly and cost related to the recycling process would be reduced. For polymer additive manufacturing 100% recycled plastic filaments already exist in the market along with systems that allow for shredding of scrap materials and extrusion as a new filament are being developed. If this was applied to large scale additive manufacturing, the quality of end of life options for recyclable polymer-based components would greatly improve. Additionally, the aim to optimise the geometry to achieve high thermal insulation in the component responds to the need for reducing use of active systems to control indoor climate. Therefore, enhancing the thermal performance of the building envelope using passive strategies would result in a reduction of CO_2 emissions.

A new language for architecture

Promoting the use of additive manufacturing techniques means moving from mass production to mass customisation. This is a really innovative concept for the building industry where standardization and modularity of the components play a major role. The starting point of my thesis was challenging the traditional way of regarding façade components as arrays of functional layers to be mass-produced in standard elements. If geometrical and assembly limitations derived from the production techniques are no longer there, the building envelope can be conceived as an integrated object in which shape responds to specific performances and design requirements, locally and in the most efficient way. This opens up a set of new possibilities for designers, also in terms of aesthetic quality. Performance can be the driving force for the establishment of a new architectural language where engineering and design are inherently related and shape is an informed geometry embedding material properties, performance, and functionality.

Conclusion

This study aimed at investigating how structural and thermal performances can be addressed using complex geometries and integrated in a mono-material façade panel created by additive manufacturing. The research focused on the exploration of the relation between geometry and performance at different design scales, taking advantage of the capabilities of additive manufacturing in order to design non-standard spatially varying geometries.

The results of the study showed that thermal and structural performance have divergent implications on geometry and that, in order to tackle both aspect together, compromises have to be made. To comply with the chosen target performances, the amount of material used in the final design is mainly driven by thermal principles. While the distribution of the material within the panel results from structural concerns, the use of topology optimisation related to material use would become more crucial if a smaller amount of material was involved and the component was to work closer to its material limits. Improving thermal resistance is a point to be further explored not only in relation to geometry but also to material properties.

Although it was not possible to produce a full-scale prototype as envisioned in the methodology, the feasibility of the production was demonstrated through different tests. These showed that the designed geometry is suitable for additive manufacturing. Production time is a major limitation of the processes which, however, is greatly dependent on the available facilities. Improving production efficiency is still required to scale up from prototype to building component.

Nevertheless, this study has explored different strategies for the integration of thermal and structural aspects using complex geometries to distribute material according to the required performance. The final design shows how such strategies can be implemented to create a mono-material component where the same element serves multiple functions without the need for additional elements, complying with current regulations for façade components.

Innovation in this project lies in the proposed design approach which combines existing principles and tools and applies them to the design of a building envelope component, suggesting further explorations in this direction.