Additively manufactured 3D connection elements

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Abstract

The construction and operation of buildings are considered as the biggest influencing factors contributing to the world's global energy consumption. Therefore, the construction industry is a key industry to efficiently reduce the global energy demand for a more sustainable future. Representing the interface between the interior and the exterior of a building, the façade as a thermal barrier is one of the most influencing factors to the building's energy balance. Using additive manufacturing, advanced lightweight connection elements for façades can be manufactured, potentially combining reduced thermal bridges, material savings and improved assembly/disassembly enabling an efficient re-use of the parts.

Building Industry and Energy Consumption

The building sector is considered as the biggest contributor when it comes to the worlds global energy consumption and greenhouse gas emissions (Allouhi et al. 2015). In 2019 the construction and operation of buildings contributed to 35 % of the total energy consumption and to 38 % of the energy-related CO_2 emissions (United Nations Environment Programme 2020). Keeping this in mind, the building sector is one of the key industries regarding an efficient approach to reduce the global energy demand and greenhouse gases for a more sustainable future.

The development of improved building components with a minimized material consumption and optimized structural and thermal characteristics has the potential to lead to significant less energy demands during the manufacturing process of the components as well as to a reduced energy consumption during the operation of buildings. The building envelope represents the interface between the interior and the exterior of a building, hence being important for thermal insulation. The heat gained and dissipated through the façade as well as the performance of sun protection mechanisms contribute to the dimensioning of the necessary heating and cooling infrastructure, eventually making the façade one of the most impacting factors when it comes to the building's energy balance during service life (Knaack et al. 2007). Improvements to façade systems therefore appear to be a useful approach to achieve more sustainable buildings.

Further functions, the façade needs to fulfil, are resistance to and load transfer of wind loads, the weight of snow, live load (persons inside the building leaning against the façade), and stress loads caused by temperature or humidity changes resulting in deflections of components. Moreover, the load bearing capability for its self-weight and that of other building components as well as the protection from rainwater. Since the façade is also a highly impacting factor when it comes to the parameters that determine a comfortable environment for the user, these aspects must not be neglected when improving the façade's energy efficiency. Comfort parameters can only be measured subjectively, but include air movement, temperature, light intensity and humidity. Additional requirements, façades have to fulfil are of visual, hygienic and acoustic nature. Visual requirements consist of sufficient and, if available, natural light for the building's inside and the prevention of strong contrasts between light and dark areas as well as reflections. Hygienic requirements involve appropriate air circulation and acoustic requirements taking into account the handling of sounds from outside and inside that can be differentiated into air-borne and structure-borne sounds (Knaack et al. 2007). Furthermore, assembly efforts need to be considered. As buildings shape today's environment, aesthetic aspects should also be incorporated in the development of future façades, despite the importance for improving sustainability (Strauß 2013).

State of the Art in Façade Construction

Nowadays, systemized façades are predominantly used in the building industry, comprising a number of standardized components. Systemized solutions facilitate to meet the technical requirements for façades, which have increased significantly in the past and can only be accomplished using sophisticated methods. Besides to ease of design, they enable better process control due to a better predictability (Knaack et al. 2007).

Widely used façade systems include post-and-beam constructions consisting of a loadbearing base structure composed of sections made of timber, steel or

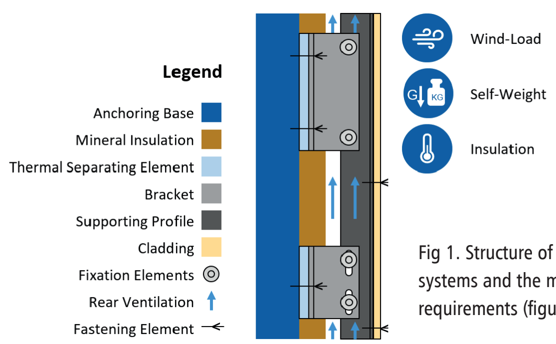

Fig 1. Structure of rear-ventilated façade systems and the most relevant loads and requirements (figure based on FVHF (2018))

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aluminium. Posts are typically mounted to the building's shell using 3-dimensional brackets, followed by the mounting of the beams. Subsequently, infill elements, such as glass panes, windows or doors, can be mounted onto the post and beam structure using mouldings. Load transfer from the infill elements into the beams is realized by support blocks (Knaack et al. 2007).

Rear-ventilated systems, shown in **fig 1**, represent another common type of façades. These consist of visible claddings mounted to supporting profiles using fastening elements. The supporting profiles are connected to brackets via fixation elements using fixed as well as sliding points. Using anchoring elements, the brackets are again fixed to the anchoring base usually represented by the outer wall of a building. Thermal separating elements need to be added in between the brackets and the anchoring base to prevent or to minimize thermal bridges. A mineral insulation layer is installed onto the anchoring base leaving the rear ventilation space between this and the cladding layer (FVHF 2018).

Connecting elements, such as brackets, connectors and fasteners, are crucial for both systems. Currently available connections lead to point-like and line-like thermal bridges by linking the different layers from outside to inside and affect the energetic quality of a building negatively. Established connecting technologies often involve bending resistant welded joints as well as screwed head plate joints which can either be flexible or bending resistant. Manufacturing and installation of these systems usually involves high efforts. Furthermore, non-reversible welded joints prevent an effective re-use and recycling. Reversible, plug-in mechanisms, like sigma knots (Grube und Landskröner 2001), can in contrast easily be assembled and disassembled to be efficiently re-used and recycled. However, such easy detachable solutions are not yet well established in the industry.

Improving Façades using AM

Novel, innovative connection elements should strive to be more sustainable by consisting of elaborate lightweight geometries that are able to reduce thermal bridges and hence increase the energy efficiency of the building as well as consider detachable joints to enable reusability. Besides finding the optimal structure regarding a minimum weight while making optimum use of the material properties, lightweight engineering in the construction industry is aiming for a maximum reduction of the cumulative energy demand for structures with even increasing importance in the future. This includes the primary energy deployed for the manufacturing, the energy used during the part's lifetime and the energy needed for recycling and reusing the material (Englhardt 2013).

When it comes to improving the building envelope, the application of additive manufacturing (AM) can contribute to enhanced functionalities of façades by enabling the production of geometrically complex parts, enabling enhanced functionalities including the optimization of structural aspects, the simplification of the manufacturing process and installation, complex shaped free form façades, and the room climate (Strauß 2013). These complex structures, combining structurally optimized parts, meaning less material consumption, as well as improved geometries to minimize thermal bridges, are hardly feasible to manufacture using well established technologies. AM rapidly evolved in the past years and consolidates manufacturing technologies that are based on a layer-wise application of material. Regarding the construction industry, AM attracted some attention by printing entire buildings from concrete using extrusion-based processes. However, other AM-processes gain in importance in this sector considering different materials and smaller building parts as they are needed in façade construction (Paolini et al. 2019). In the metal-based Laser Powder Bed Fusion (LPBF) metal powder is selectively melted by one or more lasers layer by layer resulting in the required part. Due to the layer-wise characteristic and the complete melting of the metal powder dense parts of almost arbitrary complexity can be produced that can withstand mechanical and thermal loads and therefore meet the requirements in façade construction (Gebhardt et al. 2019).

Even though printing complete façade systems will not be economically feasible with the currently established processes and available machines, LPBF is particularly advantageous for the realization of (structurally) advanced and individualized connecting elements. Thus, a hybrid approach combining relatively small additively manufactured connection elements and larger conventionally manufactured standardized parts of established and certified façade systems is promising (Strauß und Knaack 2015). Re-designing such connections allows the integration of additional functions as mentioned above yet using less material and requiring fewer parts, leading to a simplified assembly (and disassembly when required) as demonstrated by Strauß (2010). His developed façade node is customizable and optimizable regarding the respective loads, deformation, number of needed joints and their angles by a parametrized design. These tailored joints facilitate the use of only rectangular sawn posts and beams enhancing the elimination of defects like water leaks usually resulting from inaccuracy (Strauß 2013). The advantages of the application of optimized (structural) building elements produced by AM are further shown by Galjaard et al. (2015), who focused on the structural and lightweight aspects and Mrazovic et al. (2018), who compared additive and conventional manufacturing methods in the building industry regarding their environmental impact.

Redesigning an exemplary connecting node of a tensegrity structure exploiting the design freedom of LPBF Galjaard et al. (2015) obtained an optimized function integrated part that was 75% lighter than the conventionally manufactured original. Starting with a parametric generation of the design space of the node, followed by a topology optimization, the design process finished with a refinement of the geometry and a further step in which manufacturing constraints were considered. Even though they focused on a single node, their design procedure was developed to be easily transferrable to the development of other nodes with differing connection configurations and structural boundary conditions (Galjaard et al. 2015).

By means of two case studies regarding metallic building components (a large window frame and a bracket) Mrazovic et al. (2018) assessed measures such as applicability, environmental impact as well as cost comparing the production via AM and conventional manufacturing. They confirm the feasibility of AM in the building industry and claim a 87% reduction of the environmental impact but point out the higher costs and the slower production rate (Mrazovic et al. 2018).

So far, the efforts of applying metal LPBF in the building industry mainly aimed for material reduction, individualization for complex façade designs and improved assembly (simplifying the installation and eliminating the risk of leakages due to inaccuracies in the preparation of the individual components). Reducing thermal bridges and thus increasing the building's energy efficiency using the potentials of AM could not be perceived as a subject of research in the literature survey carried out, but is one main goal of ongoing research activities at the DAP and STB of the RWTH Aachen University. Further objectives include the efficient application of recycling material originating from the building industry, material efficiency using methods for lightweight engineering, e.g. topology optimization and biomimetic lightweight structures, as well as reusability enabled by easy detachable connection mechanisms. ■