

Optimization of Glass Plate Structures with Additive Manufacturing

Bachelor thesis by Emanuel Galileo Nowak
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Bei einer Thesis des Fachbereichs Architektur entspricht die eingereichte elektronische Fassung dem vorgestellten Modell und den vorgelegten Plänen.

Darmstadt, 12. April 2024



E. Nowak

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List of Abbreviations

AM	Additive Manufacturing
BE	Built Environment
BESO	Bi-directional Evolutionary Structural Optimization
BMUV	German Federal Ministry for Environment, Nature Conservation and Nuclear Safety
CaCO₃	Calcium Carbonate
CaO	Calcium Oxide
CFAO	Continuous Fiber Angle Optimization
CO₂	Carbon Dioxide
DED	Direct Energy Deposition
DIW	Direct Ink Writing
DIN	The German Institute for Standardization
EN	European Norm
ESO	Evolutionary Structural Optimization
EVA	Ethylene-Vinyl Acetate
FEA	Finite Element Analysis
FLS	Fracture Limit State
FTG	Fully Tempered Glass
FDM	Fused Deposition Modeling
H	Horizontal Glazing
HSG	Heat-Strengthened Glass
IGU	Insulated Glazing Unit
LS	Level-Set method
LSG	Laminated Safety Glass
Low-E	Low-Emissivity
MMC	Moving Morphable Components

PFLS	Post Fracture Limit State
PVB	Polyvinyl Butyral
SGP	SentryGlas Plus
SIMP	Solid Isotropic Material with Penalization
SLA	Stereolithography
SLM	Selective Laser Melting
SLE	Selective Laser-Induced Etching
SLS	Serviceability Limit State
SPG	Spray Printing Glass - A novel technique in glass 3D printing
SSG	Structural Sealant Glazing
TO	Topology Optimization
ULS	Ultimate Limit State
U-value	Value for thermal transmittance
V	Vertical Glazing
VIG	Vacuum Insulated Glass

Abstract

This thesis explores innovative approaches to improving the efficiency and sustainability of glass plate structures through additive manufacturing (AM) technologies. This research is located within the broader context of advancing sustainable building practices and optimizing the use of glass materials in construction, a material integral to modern architecture, but associated with high CO₂ emissions due to its manufacturing processes.

This work addresses the critical need for reducing the environmental footprint of glass production by leveraging AM to selectively reinforce glass plate structures, thus minimizing material usage while maintaining or enhancing structural integrity. The thesis delves into the state of the art in AM technologies in the built environment (BE) and glass, assessing their potential applications of adopting such technologies in glass and facade engineering.

A significant contribution of this thesis is the detailed examination of the mechanical, optical, and economic requirements for glass in building structures, including facades, barriers, horizontal and interior glazing, alongside the legal framework governing their use. Through a comprehensive review of existing glass types and their applications, this thesis sets the stage for exploring how AM can revolutionize the design and construction of glass structures.

The core of the thesis is the experimental and theoretical optimization of glass plate structures. It presents a methodical approach to topology optimization, evaluating different algorithms, software tools and optimization methods. For this purpose, the physical properties, material model and fracture mechanical behavior of 3D-printed soda-lime glass were discussed, providing a foundation for the optimization process. By creating different optimized geometries for a defined load case, it demonstrates the potential to improve the structural efficiency of glass plates and shows potential material savings of up to 70%.

Mechanical tests on additively manufactured glass further underscore the practical aspects of this research, offering insights into the material properties and the performance of optimized glass structures. The thesis concludes with a critical assessment of the optimized plates, discussing their manufacturability, economic viability, ecological benefits, and compliance with safety standards. The thesis proposes avenues for future research and potential improvements in manufacturing processes, highlighting the role of mock-ups and visualizations for the entry of this technology into the BE.

This thesis not only contributes to the academic discourse on sustainable glass constructions but also presents a viable path forward for the glass manufacturing industry to reduce its environmental impact. The thesis' findings demonstrate the feasibility of using AM to create optimized glass structures that meet the stringent requirements of modern construction while advancing the goals of aesthetics, sustainability and innovation in architectural design, highlighted through various visualizations.

1. Motivation

1.1. General

The utilization of glass in the construction industry has become indispensable. In 2018, the average proportion of glass in facades reached 48%, with skyscrapers reaching up to 100% glass composition [15]. This translates into an annual installation of 675 km² of flat glass in Europe in 2022 [15] or, in the case of Germany, an equivalent of 1.2 million tons of flat glass utilized in the same year [102, 53]. The prevalent use of glass in construction is attributed to its unique (material) properties, including:

- High transparency
- High durability
- High heat resistance
- High strength, especially in compression
- Low maintenance

In combination with other materials, these properties expand to include:

- High thermal insulation
- High acoustic insulation
- High safety
- Good adaptive light control

However, the high production amount of glass comes with a consequential high carbon footprint. In particular, the glass manufacturing process contributes to a significant environmental impact due to the high melting temperatures and the emission of CO₂ during the chemical process. In 2022, the German flat glass production industry emitted 1.16 million tons of CO₂ eq. [61]. This accounts for 0.8% of the total CO₂ emissions from the German industry [125]. The high CO₂ emissions are mainly influenced by two factors: The high process temperatures required for the production and processing of glass, and the process-induced generation of CO₂ during glass production due to the chemical conversion of CaCO₃ to CaO.



Figure 1.1.: Glass melting furnace.
Photo by Glas Trösch GmbH

Predictions from the German Federal Statistics Office (Statistisches Bundesamt) indicate a 2.5% decline in sales for the German flat glass industry from 2022 to 2025 [103], primarily due to stagnation in new constructions and increased energy and material prices. While this decline may lead to a proportional reduction in CO₂ emissions, the German Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMUV) does not anticipate a substantial market-driven decrease in the foreseeable future [121].

Consequently, in the upcoming years, there will be an intensified focus on reducing the carbon footprint of the flat glass industry. This is particularly motivated by increasing political pressure emanating from German and European climate goals for 2030 [1].

To mitigate this challenge, the industry is exploring various approaches to reduce their CO₂ emissions. Promising approaches include the adoption of more efficient melting furnaces powered by non-fossil heating sources, glass recycling, and the use of thinner glass [130]. Furthermore, additive manufacturing (AM) of glass presents a promising avenue for reducing CO₂ emissions in flat glass production. Therefore, this thesis explores how the additive application of glass to predefined locations on flat glass panes can reduce both the material requirement and consequently the carbon footprint of flat glass.

1.2. History and state of the art of additive manufacturing glass

Glass in AM represents a relatively recent development that lags behind other materials in this technological domain. The origin of AM dates back approximately 40 years, marked by Charles W. Hull's invention in 1984. Hull introduced the first rapid prototyping technology, commonly known as 3-dimensional printing [71]. This first 3D printer utilized Stereolithography (SLA), depositing liquid polymer layer by layer to construct three-dimensional objects.

Upon initial examination, the delayed integration of glass into additive manufacturing may appear understandable, attributed to its elevated processing temperatures. However, Sachs et al. documented the appearance of the first inaugural ceramic 3D printers in the early 1990s [108]. This development preceded glass counterparts by 25 years, while maintaining comparable processing temperatures. The reason that glass founds his way to AM so late is according to Xin following: "AM Glass fabrication has exhibited slower growth than ceramics because of its brittleness, low tolerance in process and full density requirement" [17]

From its inception, the concept of utilizing AM for glass in the built environment (BE) first emerged in 2010 by Rammig [106]. Rammig's focal application involved point fixtures for flat glass panes, deemed particularly promising. However, due to the absence of technology for point fixture printing, Rammig resorted to manual fabrication. Although her efforts garnered attention [105], the lack of computer-guided implementation rendered it unremarkable for industrial applications.

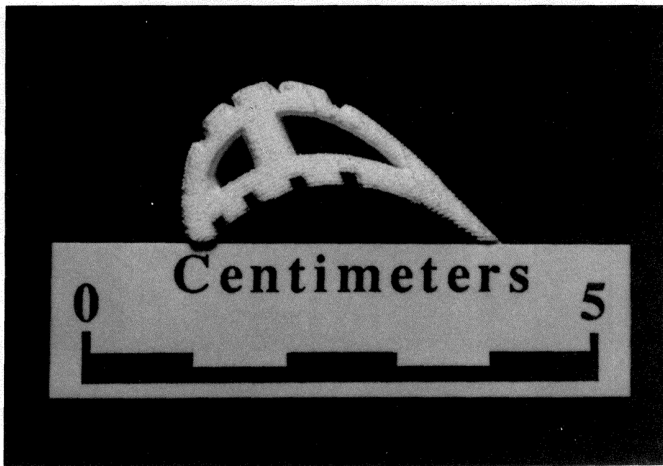


Figure 1.2.: Ceramic turbine blade - one of the first 3D-printed ceramic parts by Sachs et al. in 1990 [108]

a laser to fabricate three-dimensional objects. However, this technology garnered limited attention and failed to persist due to the nontransparency of the printed objects.

In 2015, Klein et al. introduced the inaugural fused deposition modeling (FDM) printer for glass additive manufacturing [77]. Developed at the Massachusetts Institute of Technology (MIT), this printer liquefies glass within a small kiln and employs gravity flow to extrude three-dimensional glass objects through a nozzle. To mitigate thermal stress during fabrication, an annealer was constructed to encapsulate the printed object, facilitating controlled cooling. This study yielded the creation of significant-sized 3D printed objects, comparable in scale to clinker bricks. Over the next two years, refinements were made to this process. In 2017, the research team unveiled their investigative findings [13] along with the second version of their printer, the G3DP2. Additionally, prototypes featuring 3D printed columns made of soda lime glass were showcased at Milan Design Week in 2017 [73]. With individual element dimensions of 300 mm x 300 mm x 300 mm (l x w x h) and an assembled column height of 3 m, this development introduced a new era of glass 3D printing, garnering considerable media attention [94]. For completeness, it should be noted that Micron3DP developed a comparable process in parallel during 2016, although limited details were published. The first and last official publication follows in 2019[60].

The work conducted at MIT by Klein, Brun, Inamura, et al. represents a breakthrough in glass 3D printing, resulting in a substantial volume of publications in 2017. During this period, numerous universities and

In 2013, quasi-glass-3D printing technologies emerged, introduced by two independent companies, FEMTOprint and Lightfab [55, 21]. These companies pioneered the application of selective laser-induced etching (SLE) for the computer-guided glass manufacturing. Employing a subtractive manufacturing approach through etching, this technological innovation proved revolutionary for medical and optical applications. FEMTOprint and Lightfab demonstrated the capability to produce intricate, non-heritable complex glass shapes with high resolution, particularly beneficial in the mentioned domains. An example is given in Figure 1.3.

The subsequent year witnessed the emergence of Selective Laser Melting (SLM) approaches with glass, invented by Luo et al. and Fateri et al. [90, 54]. Although known for metal 3D printing, the SLM process involves layer-by-layer melting of powder with



Figure 1.3.: A reindeer made of silica glass using SLE, as big as a pinhead. Moveable legs and head. Produced by the company lightfab GmbH [21]

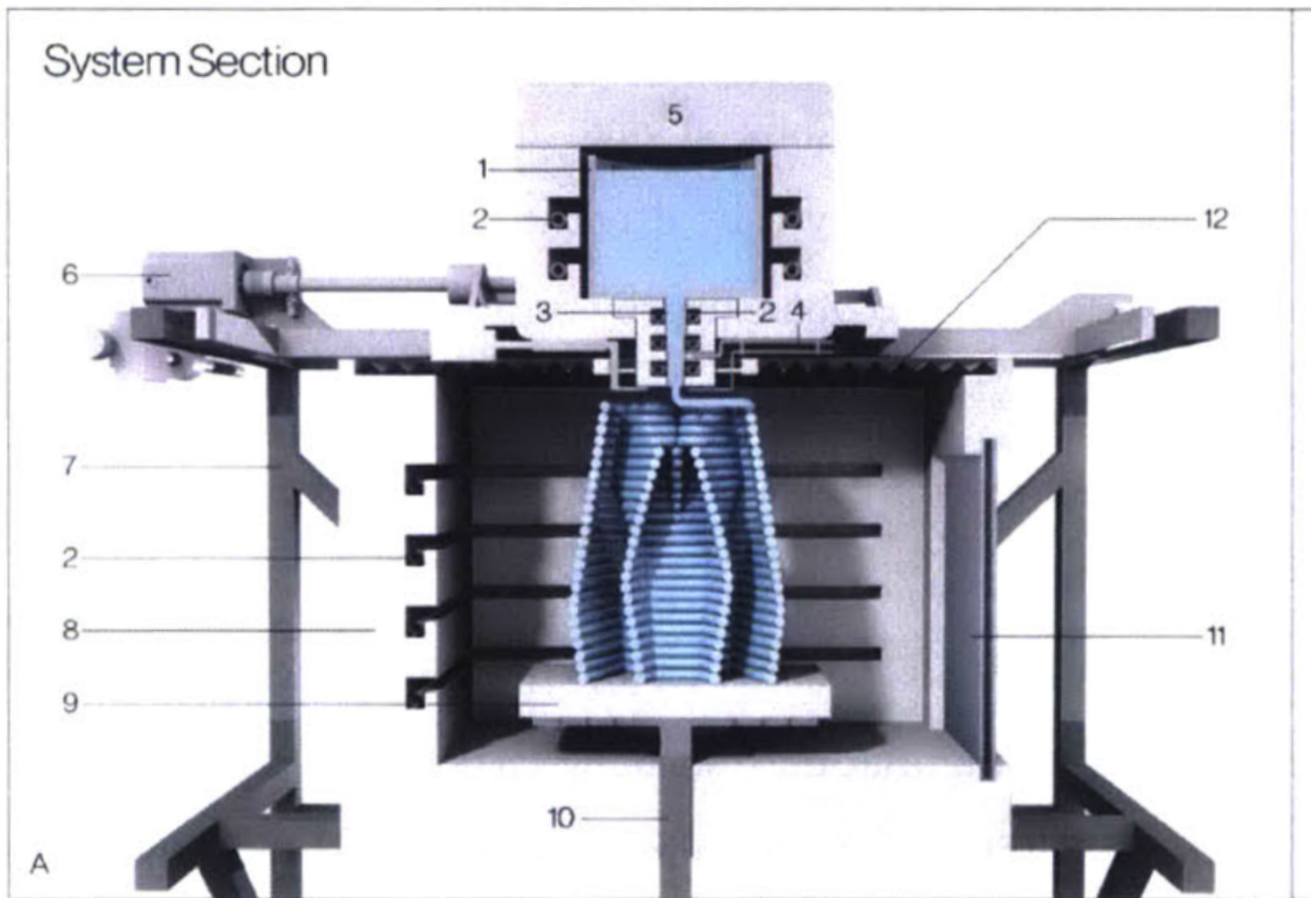


Figure 1.4.: Rendering of FDM glass printer by Klein et al. from MIT [77]. Detail elements are as follows: (1) crucible, (2) heating element, (3) nozzle, (4) thermocouple, (5) removable feed access lid, (6) stepper motors, (7) frame, (8) print annealer, (9) ceramic print plate, (10) z-drive train, (11) ceramic viewing window, (12) insulating skirt.

companies turned their attention to this process and its potential applications.

In the realm of civil engineering, Schneider identified it as a promising technology for the future of glass in buildings [110].

The Missouri Science and Technology University develops a Direct Energy Deposition (DED) process for glass printing. The approach by Luo et al. [91][89], involving laser-heating of glass filament, showed promise, but the investigation was limited to small, two-axis parts without thermal control over the printed objects.

At the Karlsruhe Institute of Technology in 2017 Kotz et al. developed a stereolithography process (SLA) for glass printing using an ultraviolet curable monomer[80]. This allows printing green bodies with the very high precision of stereolithography and sintering them afterwards with minimal energy usage (cf. Figure 1.5). The success of this approach led to the establishment of the startup Glassomer in 2018 [5], specializing in the production of components for optics, solar technology, medical technology, etc., with a maximum wall thickness of 5mm.

Additionally, in 2017, Nguyen et al. [98] introduced a Direct Ink Writing (DIW) process for glass. While similar to the approach by Kotz et al., the DIW process involves the deposition of a glass-monomer mixture. After sintering, the process results in clean silica glass objects, albeit with lower resolution compared to the

SLA process and constraints on maximal wall thickness. This limitation arises due to the necessity for the monomer to dissipate from the body, which is feasible only up to a specific thickness.



Figure 1.5.: Miniature model of the Eiffel tower made of silica glass printed with Glassomer's SLA process [79]

plementation, showcasing scalability to larger volumes. Concurrently, the Fused Deposition Modeling (FDM) process developed by Klein et al. found industrial interest, notably by QSIL SE, aiming to extend its application to print on flat glass panes [82]. A parallel approach involving material deposition on a building plate gained traction with the establishment of Maple Glass Ltd in Australia in 2020. By 2023, with their third commercial glass FDM printer, the company emerged as a market leader [2].

Among these commercial approaches, certain artists experimented with the DIW glass printing technology using a printer named VERO2. The outcome yielded non-transparent objects that, after a few vernissages, ceased to attract further attention [85].

Following numerous publications and inventions in 2017, three predominant techniques emerged. A comparison of these techniques can be found in figure 1.6. The first, Direct Energy Deposition (DED), gained prominence. In 2018, von Witz et al. from the Laser Zentrum Hannover (LZH) [126] and Hostetler et al. from Missouri S&T [69] published investigations involving glass plate printing using a CO₂ laser. The second technique is Stereolithography (SLA). In tandem with Glassomer's success and new published results [79], analogous processes were introduced in 2018 by Liu et al. [87][16] and Cooperstein et al. [22]. These processes exhibit substantial similarity with distinctions limited to specific aspects.

The last technique is Fused Deposition Modeling (FDM), akin to the approach employed by MIT. In the same year this FDM process is also picked up for applications in building industry by Seel et al. [111, 112] with concepts and renderings for stiffening glass panes or creating point fixtures for flat glass panes on facades.

Following the surge in publications and innovations during 2017/2018, there was a subsequent decline in article output as attention shifted towards refining these three technologies for industrial application. In 2020, Glassomer, as elucidated by Moore et al. [96] and Kotz et al. [78], explored the potential to 3D print multicomponent glasses with distinct chemical compositions for novel applications.

In 2021, Fröhlich et al. [59] introduced advancements in their Direct Energy Deposition (DED) im-

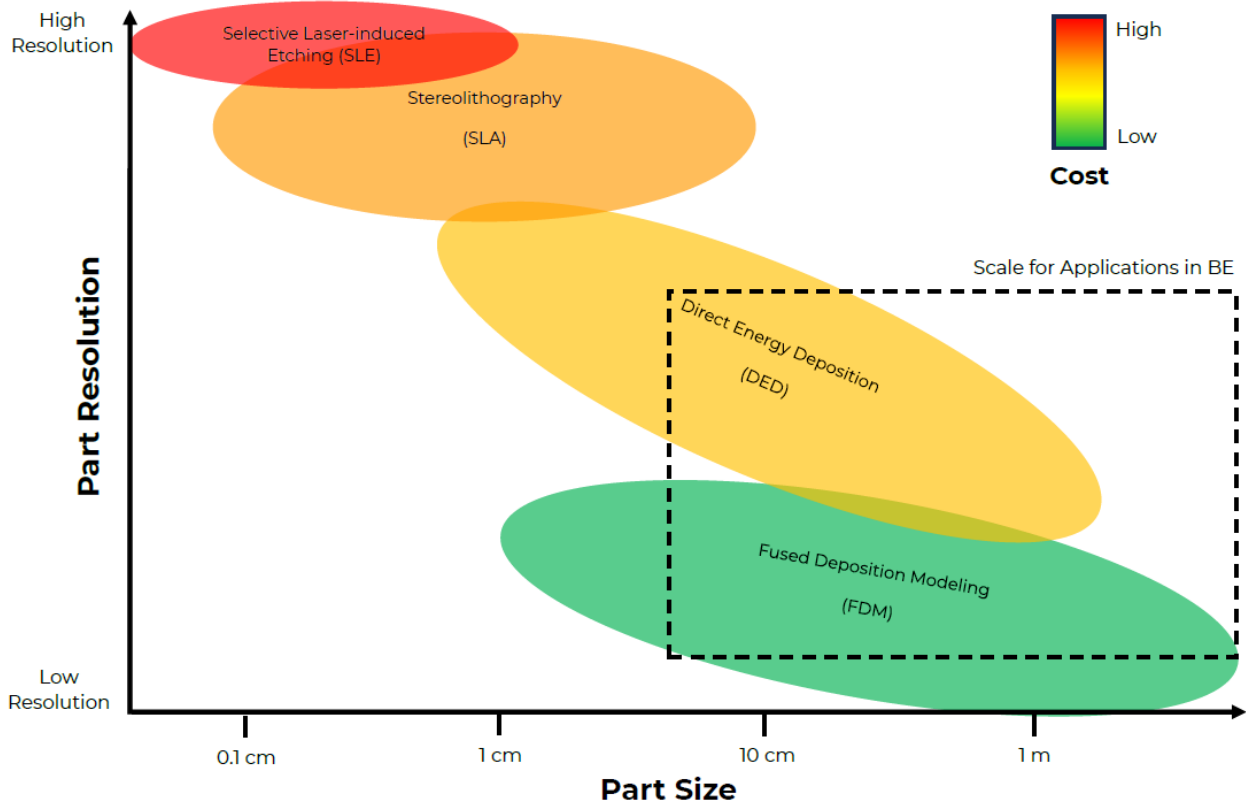


Figure 1.6.: Comparison of AM Glass manufacturing processes in terms of resolution, size, and cost per volume.

In 2022, the establishment of new companies marked a notable development. Nobula 3D AB emerged as a startup resulting from investigations conducted at the KTH Royal Institute of Technology in the field of Direct Energy Deposition (DED) [20]. The researchers at Nobula/KTH became the second group to publish mechanical investigations on the layer bonding of 3D printed glass processes, following MIT's work with Brun et al [13]. Simultaneously, Evenline, founded in 2022 by Stern, aimed to bring MIT's investigations in Fused Deposition Modeling (FDM) into the industry [52].

Additionally, in 2022, Fröhlich et al. [58] presented their advancements in DED machines and processes, demonstrating the capability to produce large volume glass structures with smooth surfaces. This achievement allows to dream of high loaded structural glass 3d printed objects.

In parallel, a feasibility study at TU Darmstadt explored a novel glass printing technique. This method called Spray Printing Glass (SPG) involves the spraying of powder onto a glass plate, subsequently melted between the nozzle and the glass plate. While still in its early stages, this approach should be kept in mind as soon as glass 3D printing matures in the industry due to its potential for faster deposition rates.



Figure 1.7.: 3d-printed cone made of silica glass with DED from the LZH.

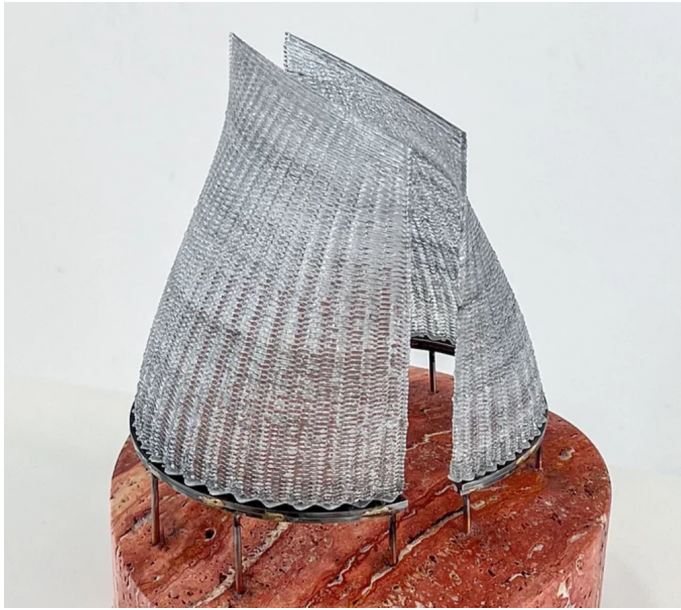


Figure 1.8.: Scaled model of the Qaammat Pavilion designed by architect Konstantin Arkitekter and printed by Maple Glass Printing Ltd. [2]

An overview of all companies and technologies is displayed in Figure 1.11.

In the realm of mechanical investigations pertaining to the performance of 3D printed glass objects, limited studies have been undertaken. Specifically, only two investigations, conducted by Chunxin Liu [20] and Brun et al. [13], focused on understanding layer bonding. Chhaded et al. [18] conducted a study to assess the stability and load-carrying capacity of the interface between layers and flat glass panes. These investigations are crucial for the integration of this process into the building industry and need to be focused on in future.

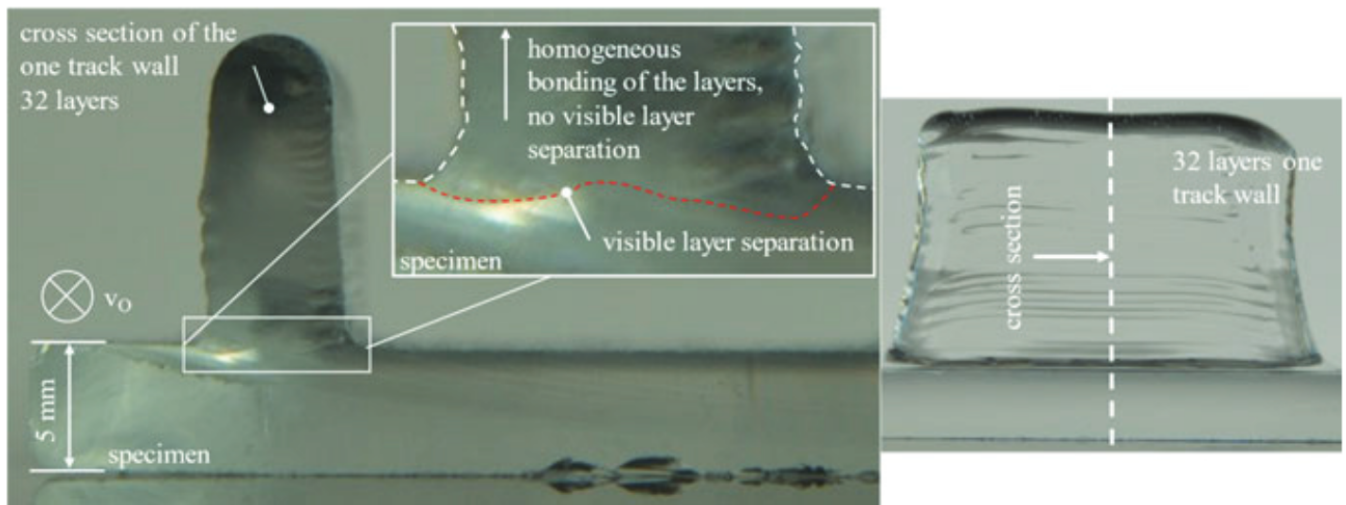
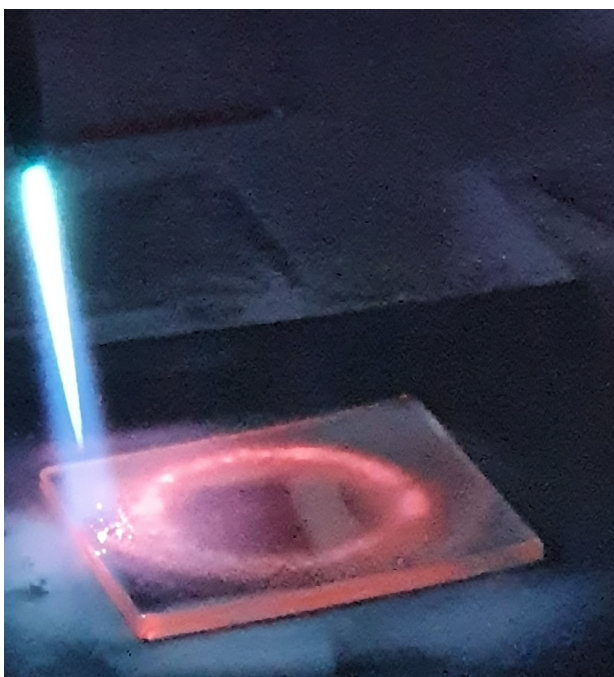


Figure 1.9.: Borosilicate glass wall printed using the DED process by Fröhlich et al. [58]



(a)



(b)

Figure 1.10.: Spray-printing glass (SPG) at TU Darmstadt (a) during spray process and (b) the final test specimen.

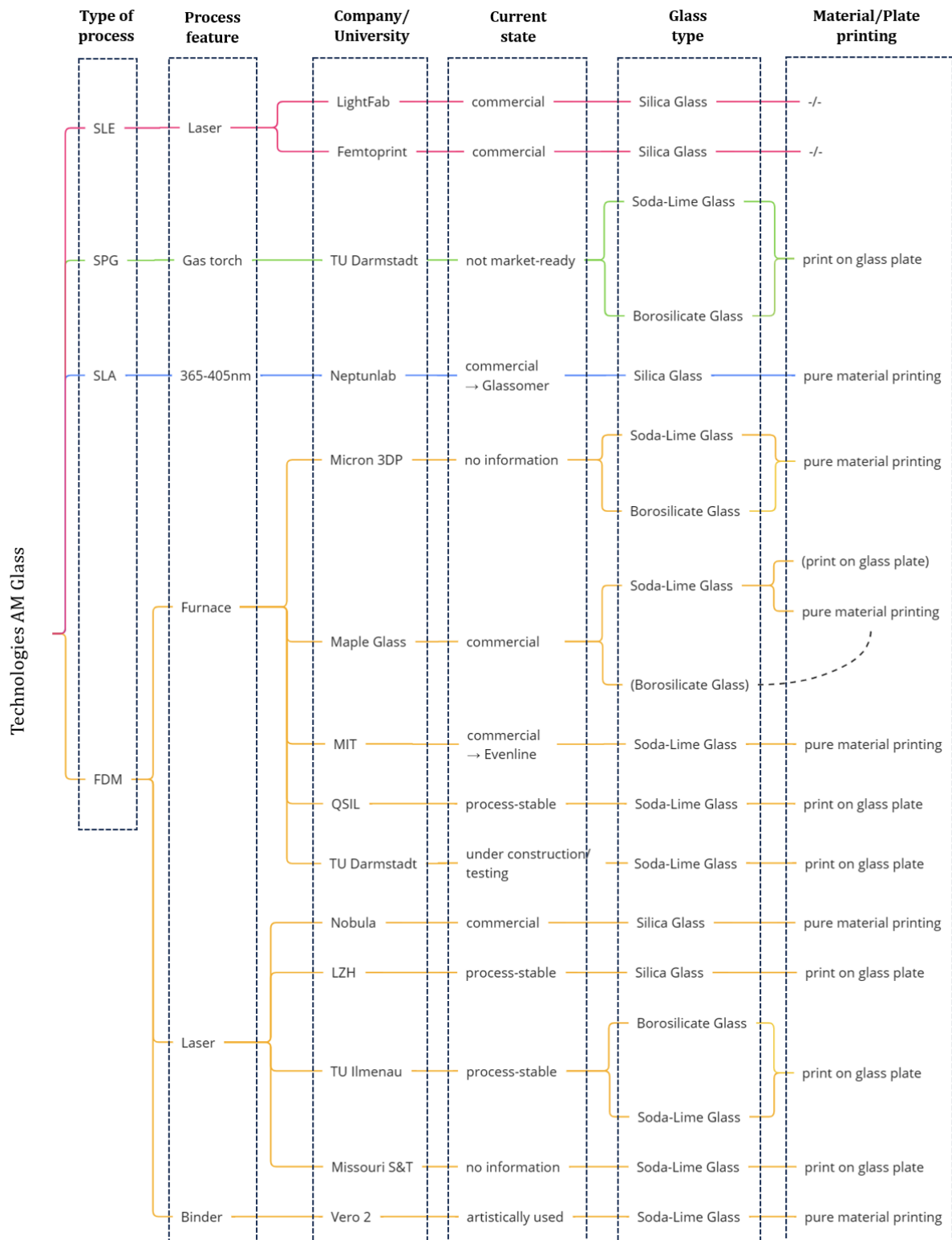


Figure 1.11.: Overview of companies and technologies in 3D printing glass. As at December 2023.

1.3. State of the art of additive manufacturing in the built environment

AM, commonly known as 3D-printing, has gained significance in the BE in recent years. This technology enables the production of complex structures and forms that were previously unattainable through conventional methods.

In the nascent stages of any technology, comprehensive investigations are imperative. Among the pioneering studies was Concrete Contour Crafting, initiated by Khoshnevis at the University of Southern California in the 1990s [75]. These investigations have evolved over the years to encompass a diverse range of materials, including metals, plastics, cements, sand, fiber materials, gypsum, paper, wood, etc. The scope of application also expanded to include the printing of entire structures as well as structural components of buildings, high-efficiency facades, restoration projects, prototypes, interior fittings etc.

In recent years, the potential of AM, particularly in the Built Environment (BE), has become evident. The advantages include:

- Flexible and generative design
- Rapid production
- Minimization of material usage
- Reduction of waste
- Utilization of recycled materials
- Long-term cost effectiveness of machines
- Reduction of human error

Despite these advantages, AM in BE is not without drawbacks like:

- High investment costs
- Challenges in quality control
- Issues related to standardization
- Labor shortages

Over time, many of the disadvantages associated with this technology have diminished, marking a shift from investigation to widespread industrial application. This transition is fueled by factors such as declining investment costs in machines, rising costs of energy and materials, and a growing emphasis on AM in the BE by engineers [12]. This progress is exemplified by formnext®, the world's largest 3D-printing fair. In 2019, with the exception of the special exhibition "Built Environment Additive Manufacturing" (BE-AM), no company showcased 3D printed objects or concepts suitable for the BE [56]. However, by 2023, more than 40 companies were actively involved in developing concepts or products tailored for the built environment [6].



Figure 1.12.: 3D-printed facade in Regensburg, Germany produced and designed by additive tectonics GmbH [68].

Illustrations of this technological progression include projects such as "the bridge" by MX3D [14], "freeform facades" by Jansen AG [118], and the burgeoning German company Additive Tectonics [68]. Additive Tectonics serves as a notable example, demonstrating the scalability of this technology by considering both economic and ecological aspects (cf. Figure 1.12). Taking a more significant leap, PERI 3D Construction has already achieved a series of successful house printings using concrete and is on the brink of standardization [100].



Figure 1.13.: First 3D-printed residential building in Germany located in Beckum, printed by PERI 3D Construction GmbH [100].

The recent integration of AM in the architectural landscape has redirected the focus of architects and clients towards intricate and high-performance AM components within the realm of building and construction projects. The interest has been growing even stronger since the technology became competitive and is increasingly used in construction projects. This trend offers a distinctive opportunity to address the under-explored role of glass in additive manufacturing and to finance further development and research through the industry.

1.4. State of the art of glass in facade

Glass is a predominant material in facades due to its unique and indispensable properties. It is challenging to envision a facade without the presence of glass. Consequently, glass features in nearly every facade. In modern high-rise buildings, the facades often consist almost entirely of glass, reaching up to 100% coverage.

Facades incorporate diverse glass products, typically untreated float glass, coated float glass, thermally toughened glass, laminated safety glass (LSG), and insulated glazing. Table 1.1 provides an overview of the sales quantity of flat glass in Germany for 2020 and 2021, offering insights into the prevalence of these glass products in facades. Besides, it is noteworthy that many of the sold untreated float glasses are further processed, and only a few are used unprocessed in the facade. The same applies to the other products. [62]

Table 1.1.: Sales quantity of flat glass in Germany for 2020 and 2021. Bundesverband Flachglas [62].

Glasstype:	Sales 2020 [1.000 m ²]	Sales 2021 [1.000 m ²]	Ratio 2020 [%]	Ratio 2021 [%]
Float glass untreated	140.827	143.537	56,78	56,23
Float glass coated	43.450	44.381	17,52	17,54
Thermally toughened glass	17.266	17.700	6,96	7,00
Laminated safety glass	18.363	18.823	7,40	7,44
Insulated glazing	28.116	28.557	11,34	11,29
Total	248.022	252.998	100	100

1.4.1. Float glass

Float glass, made of soda-lime silica glass, remains the architectural glass most used, as indicated in Table 1.1. The manufacturing process involves float glass systems where molten glass flows onto a liquid tin bath. The glass, due to its lower density, floats on the tin bath until it cools down to 600°C. Subsequently, it is carefully cooled in a separate section to below 100°C. This technique allows for the production of flat glass with dimensions of approximately 3.5 m in width, unlimited length, and thickness ranging from 2 mm to 35 mm. Figure 1.14 schematically illustrates the manufacturing process. Float glass serves as the fundamental product for nearly all types of flat glass. It exhibits a characteristic bending strength of $f_k = 45 \text{ N mm}^{-2}$. Since

their inception in 1960, these float glass lines have become indispensable and dominate the glass industry [110].

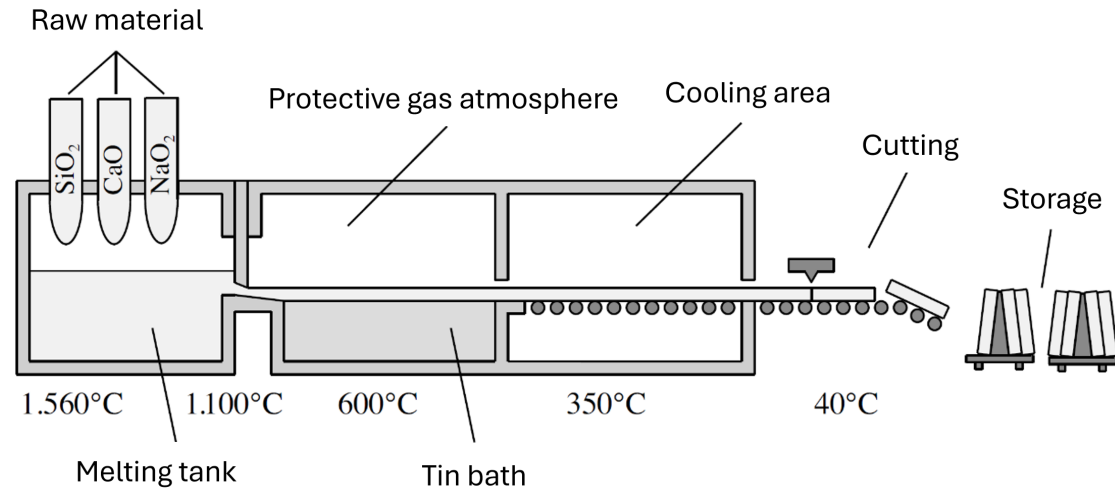


Figure 1.14.: Float glass manufacturing process. Schneider Glasbau [110].

1.4.2. Coated glass

To enhance the performance of glasses, a variety of coatings have been developed. The most prevalent coatings include:

- Heat-insulating coatings (Low-E coatings)
- Solar-heat-protection coatings
- UV-protection coatings
- Self-cleaning coatings
- Anti-condensation coatings
- Anti-reflective coatings
- Decorative coatings

These coatings specifically modify the float glass's emissivity, reflectivity, transmissivity, and surface properties, as illustrated by the examples. It is important to note that a glass cannot have all coatings simultaneously, and the selection of coatings should be carefully assessed based on the application area and costs [97].

1.4.3. Thermally toughened glass

Fully tempered glass (FTG) undergoes a process of being heated to approximately 100 K above its transformation point and is then rapidly cooled. This induces compressive stresses on the surface of the glass, reducing the impact of strength-reducing surface effects. As a result, the characteristic minimum bending strength increases to $f_k = 120 \text{ N mm}^{-2}$. The temperature resistance also improves due to the tempering process (approximately 200K). Additionally, thermally toughened glass breaks into small, cube-shaped fragments, reducing the risk of cutting injuries. Heat-strengthened glasses (HSG) are produced using a similar method but are cooled more slowly than thermally toughened glass. It achieves a characteristic minimum bending strength of $f_k = 70 \text{ N mm}^{-2}$.

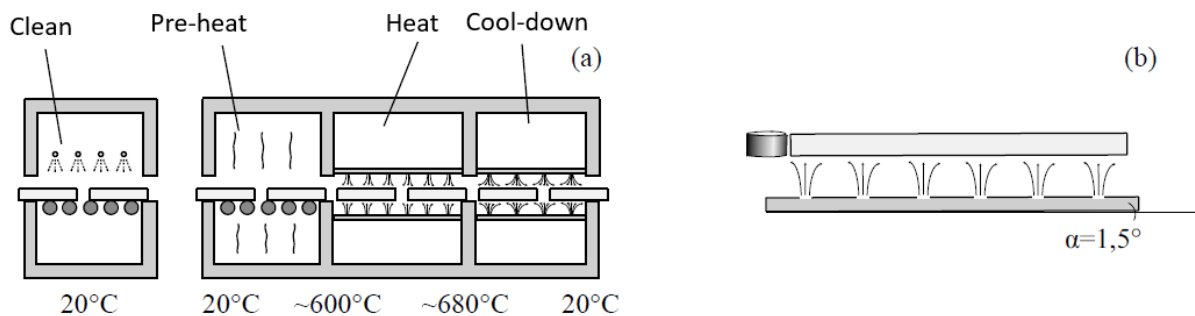


Figure 1.15.: FTG-Process according to Glaston. Process of thermal toughening on air cushions (a), position of the glass during toughening (b). Schneider Glasbau [110]

1.4.4. Laminated safety glass

Laminated safety glass (LSG) consists of a glass pane with one or more layers of glass, which are bonded together by one or more interlayers. These interlayers are typically made of a polymer material such as polyvinylbutyral (PVB), ionoplasts (SentryGlas Plus® (SGP)), and ethylene-vinyl acetate copolymer (EVA). Specific requirements for interlayers are outlined in standards for LSG. They must withstand environmental factors, provide sufficient residual load-bearing capacity, and establish a strong bond between the glass layers. This ensures that even in the event that one glass pane fails, the structural integrity of the component is maintained and the glass fragments remain in place. In various applications such as overhead glazing, laminated safety glass has become mandatory due to these reasons.[110]

1.4.5. Insulated glazing

The concept of insulated glass was initially presented in a patent by Stetson in 1865 [72]. Insulated glass units consist of 2 or more glass panes, where the space between the panes is filled with air, argon, krypton, or xenon. The filling significantly reduces heat transfer through both conduction and convection between the panes. However, two-thirds of the heat transfer is attributed to radiant heat transfer, which is minimally reflected by the gases in the gap. Therefore, insulated glasses are typically equipped with a Low-E coating to reflect thermal radiation. The edge seal in insulated glass plays a crucial role, as it must withstand static loads, absorb moisture, and prevent gas leakage or moisture diffusion into the space between the panes.

Typical double-pane insulated glasses have a U-value of approximately $U_g = 1.1 \text{ W m}^{-2} \text{ K}^{-1}$, while triple-pane insulated glasses have a U-value of around $U_g = 0.5 \text{ W m}^{-2} \text{ K}^{-1}$.

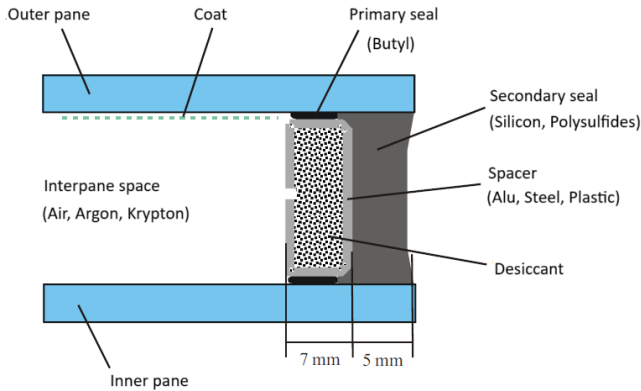


Figure 1.16.: Typical structure of a multi-pane insulating glass unit with two-stage edge seal system. Schneider Glasbau [110].

Since the 1980s, there has been increasing research on vacuum insulated glass (VIG). These share a structure similar to that of insulated glass, but the space between the panes is evacuated. To maintain the separation between the panes, small, nearly invisible spacers are arranged between them. With such vacuum insulated glass (VIG), a U-value of approximately $U_g = 0.5 \text{ W m}^{-2} \text{ K}^{-1}$ can be achieved, in contrast to triple-pane insulated glass, with lower glass and overall thickness. Research in this area has intensified significantly in recent years and initial products are establishing themselves on the European market [110]. A typical structure of a VIG is shown in Figure 1.17.

1.4.6. Special glazing

In the realm of facades sometimes profiled cast glasses encounters. These are elongated cast glasses with a U-shaped cross section, commonly used in industrial construction because of their cost-effectiveness and stability, enabling the glazing of long elements without vertical supports [110].

Another category of specialized glazing includes wire glasses. These cast glasses incorporate an internal wire mesh designed to retain fragments in place in case of failure. However, wire glass is no longer considered a safety glass by current standards [65].

In recent years, glass has evolved into high-tech-products. Glasses from companies such as Merck (eyrise™) [117] can alter their transparency with the touch of a button through piezoelectric crystals in the interlayer. Moreover, glasses can be manufactured so thin that they become flexible and serve as movable components in facades. The integration of photovoltaics within facade glasses and the production of freely shaped, double-curved glasses are now possible. However, these innovations remain niche products and are likely to stay so in the near future.

1.4.7. Development

Apart from the special glazings mentioned, the glass industry has seen limited innovation in the past decades. The glass products discussed in this section 1.4 have existed for a long time and have just undergone optimization in terms of both performance and cost. Many glass experts anticipate the market establishment of VIG as the next big innovation, although this is doubted by some [70].

Another innovative step would involve the development of glass as a structurally supportive element. The achievement of structural support with glass while adhering to safety standards presents a significant challenge due to its brittleness. However, structurally supportive glass could usher in a new era of glass architecture, enabling more efficient and highly transparent building envelopes. Current research explores various approaches to the structural use of glass, with additive manufacturing being one such approach.

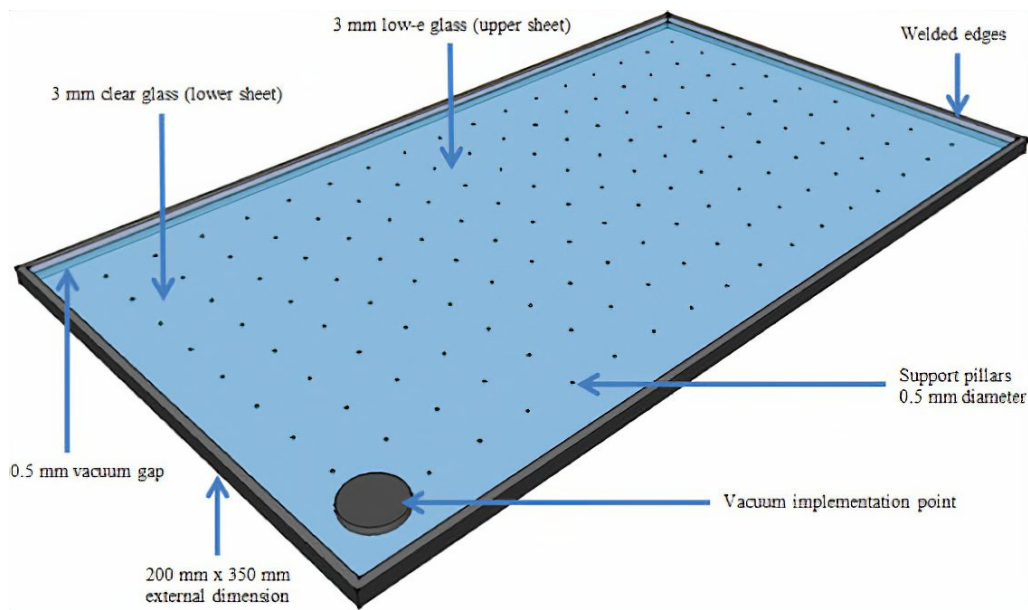


Figure 1.17.: Typical structure of a vacuum insulating glass unit. Grosvenor-Restoration [122].



Figure 1.18.: Glass as a structural element in the Steve Jobs Theater. Photo by Foster + Partners [57].

1.5. State of the art in topology optimization of plates

Historically, people have always strived to build efficiently and generate high performance structures by using a low amount of material. First evidence of highly efficient constructions dates back to ancient times. In the ancient Roman Empire, Vitruv wrote in his "De Architectura" [101] about vector-active structures, including a

variety of truss constructions and about arches, which are well-known as formative structural elements in aqueducts.

In contemporary times, engineers strive to optimize a variety of building structures for material efficiency. Bridges and trusses have been extensively researched, optimized, and implemented in projects, showcasing their ability to span large distances with minimal material usage. However, other structures also serve as highly efficient load-bearing systems, such as shell structures, membrane structures, cable net structures, folding structures, etc. [109].

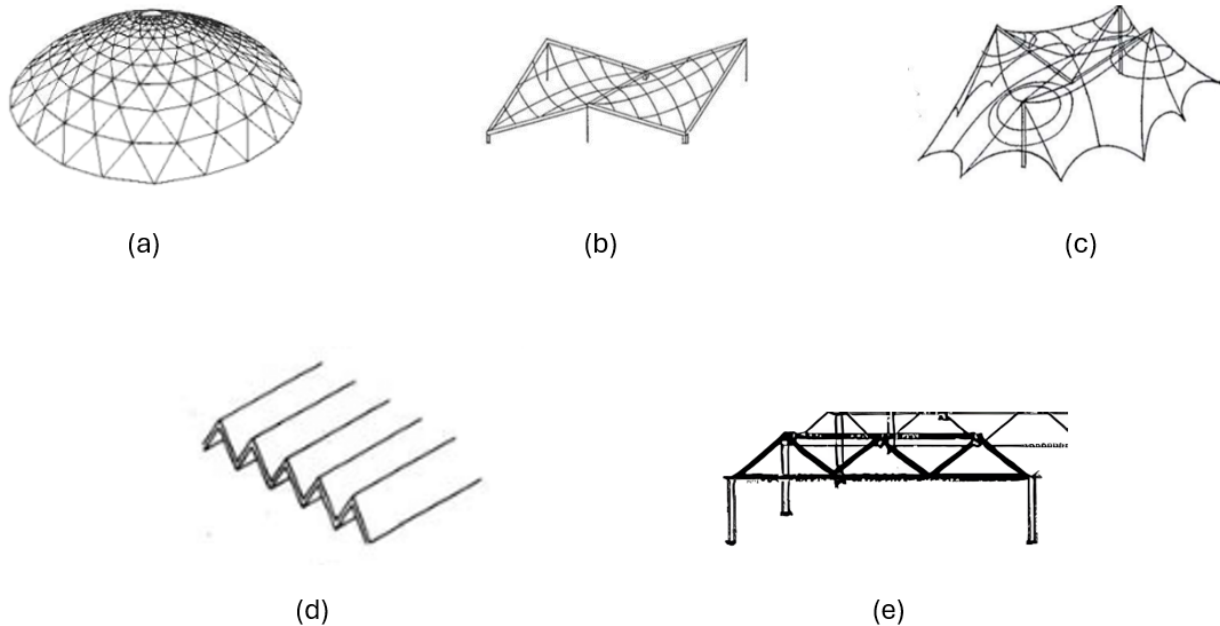


Figure 1.19.: Overview of different load bearing systems: (a) Shell structure, (b) membrane structure, (c) cable net structure, (d) folding structure, (e) vector-active structure. Stefan Schäfer [109].

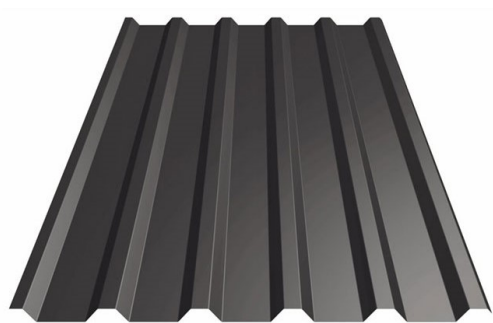


Figure 1.20.: A simple trapezoidal steel sheet whose stiffness has been increased by folding [93].

Apart from optimizing global structures, there is a frequent focus on optimizing local, individual components. An example of this is seen in stairs and walls designed as folding structures to enhance their stiffness [127]. Similarly well-recognized in BE is the optimization of the stiffness of steel sheets through processes such as bending, folding, and punching, or the use of simple gratings, which at the first glance are surprisingly highly material-efficient.

However, the most significant efforts in optimizing local components have been directed towards ceilings. This is primarily because these slabs need to span considerable distances with minimal thickness, as structural slabs in construction cannot have unlimited thickness. A lower weight translates also to reduced

self-load and, indirectly, lower costs. To maintain or increase the span without adding thickness, numerous

concepts have been developed, with the consistent goal of enhancing the stiffness of the ceiling element. Examples include vaulted ceilings and coffered ceilings, especially prevalent in older (monumental) buildings. In more modern structures, one often encounters mushroom slabs, ribbed or beam slabs, and hollow-core slabs.



(a)



(b)

Figure 1.21.: (a) Coffered concrete ceiling, (b) ripped concrete ceiling [93].

Due to factors such as costs, construction processes, materials, etc., these concepts do not fully exploit the material. They merely represent an approximation of the interpretation of Kirchhoff-Love plate theory by Czerny, Pieper/Martens, Stiglat/Wippel, or others [124].

Through computer-aided modeling and additive manufacturing, these approximations can be calculated and executed with increasing precision. An example of this is a reinforced concrete ceiling by Trummer et al. [119], where the void-forming elements of the ceiling are individually manufactured in advance using additive manufacturing according to the computer calculations.

However, these approaches to topological optimization are limited to two dimensions. In the example of the reinforced concrete ceiling shown here, it can be observed that the structure in the z -direction, i.e. normal to the plane of the plate, remains constant. The reason for this on the one hand lies in the fact that the underlying plate theory of Kirchhoff and Love [76] is only valid in two dimensions, on the other hand that 3 dimensional objects are more challenging to manufacture. Additionally the limited literature available on analytical topological optimization of plates focuses exclusively on the two-dimensional domain [10, 23].

The fact that much potential for material savings is still wasted due to the limitation of two-dimensional space is demonstrated by Kropiowska et al. [81] and the results of this thesis 5. Expanding the complex analytical concepts for topological optimization from the 2-dimensional to the 3-dimensional space would likely be impractical, if possible at all. Therefore, a suitable approach is to resort to numerical methods. Utilizing FEA and the corresponding topological optimization algorithms 3.2, highly efficient spatial structures can be created with minimal effort. An example of such an optimized plate is presented by Bernhard et al. [3]. The



Figure 1.22.: An optimized reinforced concrete ceiling from Trummer et al. [119], in which the cavities were prefabricated using 3D printing, reinforcement was placed between the 3D printed objects and then concreted.

plate has no design restrictions and, under the given load conditions, represents thereby a high-performant structure within its design space.

The realization of plate structures without design restrictions is extremely rare to date, as suitable manufacturing techniques are lacking. Additive manufacturing offers extensive possibilities, but, for example in the case of concrete, especially in conjunction with integrated reinforcement, it does not provide complete design freedom. Therefore, 2-dimensionally optimized slabs, as mentioned above (example Trummer et al. 1.5), currently represent the more economical option.

For completeness, it's crucial to note that the discussed optimizations here primarily apply to components made from a single isotropic material. Approaches to topological optimization of components made from multiple materials (multimaterials) and anisotropic materials (as is the case in additive manufacturing or with fiber-reinforced composites) are still in the early stages of development [115]. Further informations about isotropic and anisotropic optimization can be found in Section 3.1.

In the domain of plate-like facade elements (as opposed to ceilings vertically oriented plates), topology optimization has not yet been implemented. The reason for this lies in the fact that in non-transparent facades, struts and underlying structures provide quick, easy, and cost-effective bracing and attachment of the facade elements making an optimization simply redundant.

Topology optimization is therefore only meaningful for transparent facade elements, where reinforcement structures in the background are not desired due to optical requirements, and the plates should exhibit an extremely high degree of transparency over large spans. However, for small spans, as commonly found in house windows, such optimization is not worthwhile, as the load on the windowpane is extremely low.

In Chapter 3, the objective is to employ topology optimization algorithms and FEA to discover optimized structures for horizontal and vertical glazing, similar to the approach taken by Bernhard et al. (1.5) or Trummer et al. (1.5) for reinforcing concrete slabs. As of now, such an approach is not documented in the literature.

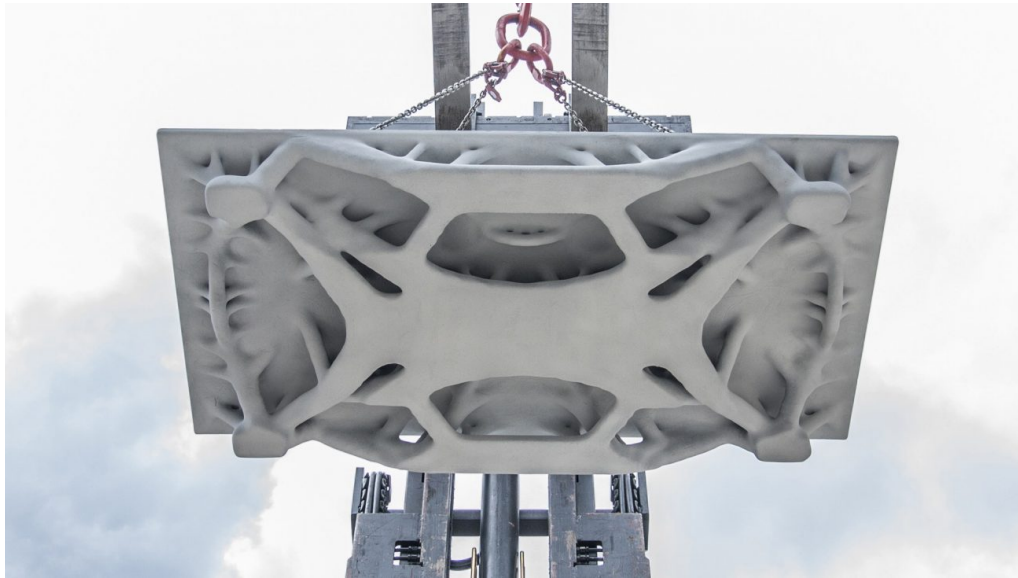


Figure 1.23.: Topology optimized concrete slab from Bernhard et al. [3]. The shape of the formwork was 3d-printed from polymer and filled with fiber-reinforced concrete.

1.6. Vision of additive manufacturing glass in the built environment



Figure 1.24.: Illustration of a glass 3D-printed faucet [93].

Visions for AM glass in the BE remain niche areas with limited exploration, as is also partly the case with AM glass. Beyond that, AM of glass is a recent domain, as indicated in Section 1.2. Especially, the fabrication of larger structures has only become feasible since 2015 [77], which makes it possible to think about possible applications in first place. In the academic realm, TU Darmstadt is a notable contributor, focusing on applications and publishing literature, exemplified by Seel et al.'s work [111]. On the corporate front, Maple Glass Ltd. is actively exploring applications in the BE. Their collaboration with Foster+Partners in 2022 resulted in several visions and showcasing a small display [2].

Current applications and future visions of AM Glass can be categorized into two operational domains: interior applications and facade-related applications.

In interior applications, a wide range of possibilities exists, particularly on a small scale, such as door handles, faucets, etc. Additionally, glass handrails affixed to glass railings present a potential application. Staircases entirely constructed from glass could also gain popularity. Currently, individual glass panes and steps are connected using metal components or adhesives. A fully glass staircase, as depicted in Figure 1.25, combines aesthetic appeal with structural innovation, aligning with the architectural demands of high-end buildings.



Figure 1.25.: Connection of glass stair treads to flat glass using AM.

On the facade front, two major applications stand out. Firstly, printed transparent glass joints on flat glass panes (see Figure 1.26). This introduces a novel method for mounting flat glass panes, ending the need for drilling or adhesives. Furthermore, it leads to a better structural integrity, providing longevity by avoiding aging due to UV radiation, etc. and removing thermal bridges.



Figure 1.26.: AM glass joints for mounting glass panels in the facade.

The other significant vision involves reinforcing flat glass panes, illustrated in Figure 1.27. Enhancing the stiffness of the panes enables the use of thinner glass or larger dimensions, thereby unlocking the potential for material savings and employing flat panes as structural elements. The feasibility of implementing this vision with AM will be explored in this thesis.



Figure 1.27.: VAKKO® headquarter in Istanbul, Turkey. The facade is fitted with glass panels that have gained stiffness through a deep-drawing process [123].

1.7. Goals and structure of the thesis

In Section 1.3, it is demonstrated that AM is currently gaining prominence in the BE, with an increasing prevalence of additively manufactured components in buildings and construction projects. Given the recent advancements in AM Glass, as discussed in Section 1.2, the question arises as to when AM Glass will make its mark in the construction industry.

Among the commonly used materials in construction (concrete, steel, wood, brick, plastic, glass), glass appears to be the furthest from entering the BE through AM processes. This is primarily due to the current limitations in the scaling of the AM Glass process, as described in Section 1.2, which currently does not exceed dimensions of 300 mm x 300 mm x 300 mm. Another factor is the inertia of the glass industry, as discussed in Section 1.4, which shows a reluctance to invest significantly in new innovations. Additionally, there is a lack of essential mechanical tests that demonstrate the robustness of this technology, which is essential for the building industry. Despite these challenges, the most crucial aspect is the need for well-defined use cases for this technology, substantiated by reliable calculations and, more importantly, feasibility demonstrated through mock-ups. A mock-up is vital because a technology can only gain acceptance in construction when architects, builders, engineers, and clients are convinced of its benefits.

An exceptionally interesting application involves stiffening flat glass panels, a task currently achieved only through opaque substructures (cf. Section 1.5). When attempting to span a certain distance without substructures, the only option is to significantly increase the thickness of the panel. However, to achieve high stiffness, this approach is mechanically inefficient, presenting an opportunity for substantial material savings. Given the high CO₂ emissions in the glass industry, as outlined in Section 1.1, such savings are mandatory.

To delve into this case study, Chapter 2 initially identifies fields of application, exposures, and requirements for glass panels under bending stress. Subsequently, in Chapter 3, topology optimizations are conducted based on various loading and support scenarios to reveal optimal structures for stiffening glass panels. It is assumed that the only viable manufacturing processes, FDM and DED, exhibit a best approximation of their mechanical performance through anisotropic material behavior. This assumption will be scrutinized in Chapter 4 through an experimental series. Additionally, the potential of stiffening glass plates through AM of Glass is to be demonstrated through experiments. Concluding with simple renderings of the optimized components in Chapter 5, the aim is to inspire the construction of a mock-up, facilitating the technology's entry into the built environment.

2. Requirements and criteria for glass in buildings

In this chapter, the mechanical, optical, economic, and legal requirements for glass plates under bending stress in construction are examined. Special attention is given to the fields of application, including the associated mechanical exposures, supports, and criteria, as these factors play a crucial role in both the optimization and the application of AM Glass.

2.1. Mechanical and static requirements

Glass under bending stress is categorized into two installation orientations according to DIN 18008-1 [24]:

- Vertical Glazing
- Horizontal Glazing

Vertical glazing refers to glass panels with an inclination not exceeding $\pm 10^\circ$ relative to the vertical. Glass panels inclined more than $\pm 10^\circ$ relative to the vertical are classified as horizontal glazing. In some instances, standards use for nonhorizontally oriented horizontal glazing the term "inclined glazing".

Vertical glazing systems (V) can be categorized according to DIN 18008-1 [24] into three fundamental application areas:

- Facades
- Barrier glazing
- Interior glazing

Horizontal glazing systems (H) can be classified according to DIN 18008-1 [24] into the following four categories:

- Horizontal glazing without specific fall-protection function
- Accessible glazing
- Fall-through protective glazing
- Walk-on glazing

For each of these application areas, the following sections will briefly describe the implementations, exposures, supports, and criteria.

2.1.1. Facades (V)

2.1.1.1. Fields of application



Figure 2.1.: Example image of a double-glazed window [93].

Window. The glass is held in the frame on all four sides using sealants in combination with spacer blocks, clamps, etc. Windows rarely exceed dimensions of 2 m x 2 m, as larger openings are typically not present in the building environment. When an entire wall or surface is replaced by glass, it is referred to as a full glass facade.

The most common type of full glass facades and part of the frame systems are post and beam systems. They consist of vertical and horizontal profiles, posts and beams, typically made of aluminum, steel, or wood. The requirements for these profiles are regulated by DIN 13830 [36] [9]. The primary load-bearing function is carried out by the posts, since glass, according to DIN 12488 [31], is generally not allowed to carry static structural loads of other components. This regulation applies to all standardized glass facade systems. Glass is attached in post and beam systems using horizontal and vertical pressure plates. It must be ensured that the glass only comes into contact with soft materials as described in DIN 12488 [31]. Metal-glass contact is to be avoided.

Frame systems are the most typical and widely used systems for vertically installed glass in construction.

Among these, and likely most familiar to the average user, is the common "window". Often, the term window is used synonymously for various objects. However, DIN 14351-1[38] defines the windows as follows:

A product with a frame and sash or a fixed sash that makes a transparent opening in a building envelope, which may be combined with fanlights or mullions.

In this context, the use of glass, or soda-lime glass specifically, is not strictly mandatory; however, alternative materials are seldom encountered within the built environment. A typical window mainly consists of two components: the glass and the frame. Almost any well-known glass product, such as annealed glass, HSG, FTG, LSG, IGU, VIG, can be used as the glass. However, FTG and LSG are less common, as windows often do not meet high safety requirements. The frame is usually made of aluminum or wood and often includes intricate mechanisms to open the window.



Figure 2.2.: A glass facade designed as a post and beam system made of wood [93].

Unlike windows, glass panes on post and beam facades are typically installed into their frames on-site. In theory, there are no strict limitations on the glass dimensions; however, they are often restricted in one direction by the manufacturing width of the float glass lines (maximum ca. 3200 mm) [50].

If the glass elements for the facade are delivered with a pre-assembled frame system, it is referred to as an element facade. These elements are typically floor-to-ceiling and are directly attached to the structural framework. Element facades have fewer design possibilities due to their connection to the structural framework but offer the advantage of quick and easy assembly and disassembly on-site.

Unlike frame systems, Structural Sealant Glazing (SSG) systems bond the glass to the edges instead of clamping it. This allows for an exceptionally high level of facade transparency and creates a flat appearance on the exterior. SSG is covered by DIN 130022 [35], and individual systems are approved through an ETA or a general construction approval (abZ) (cf. Section 2.5). According to the German List of Technical Building Regulations (LTB) - Part 2, mechanical support can be omitted up to a height of 8m but is mandatory beyond this limit in Germany.



Figure 2.3.: Example of an SSG system. The proportion of glass to sealing is increased compared to other systems [93].

Instead of securing glass through its edges, this can also be achieved through point-fixing devices at the perimeter. Glasses are in most cases provided with holes into which typically polymer-based sleeves are inserted and secured with a steel bolt. The positioning of these holes is strictly regulated in various product standards due to the high local loads at the drill holes (cf. DIN 12337 [30], DIN 12150 [29], DIN 1863 [43], DIN 18008-3 [32]). Glass panes can then be attached through the steel bolts to the underlying support, enabling transparent facades with minimal interruptions to the glass panes and the possibility for an extremely delicate design.

There are numerous additional applications for vertical glazing. However, all of these fall into the category of special constructions as they need to be verified through individual evidence (ZiE). Examples include spider fittings, bonded point fixings, glass composite systems, and corner glazing.

2.1.1.2. Exposures

For vertical glazing in facades without specific usage requirements, two main mechanical influences are

considered:

- **Dead load:** The dead load affects the glass pane parallel to the plane of the pane in vertical glazing. Although it has a lesser impact than in horizontal glazing, it remains significant and should not be overlooked.
- **Wind load:** Wind imposes additional mechanical impact normal to the plane of the pane and depicts the main impact on vertical glazing.

To determine the dead load, according to DIN EN 18008-1 [24], the geometric dimensions are assumed at their nominal values. The density of soda-lime glass is set to $\rho_g = 2500 \text{ kg/m}^3$ [27]. The assessment of the dead load is considered a permanent action, regardless of whether the glass pane is load-bearing or non-load-bearing [44, 45]. This yields the following design value for the exposure:

$$E_{d,g} = \gamma_{G,j} \cdot G_{k,j} \quad (2.1)$$

$$G_{k,j} = g \cdot \rho_g \cdot V_G \quad (2.2)$$

with $g = 9.81 \frac{\text{m}}{\text{s}^2}$, and $\gamma_{G,j} = 1.35$ for unfavorable or $\gamma_{G,j} = 1.00$ for favorable actions. $G_{k,j}$ is often considered as a line load in calculations by replacing the volume V_G with the product of glass width and thickness ($b_{k,j} \cdot d_{k,j}$).

The calculation for the acting wind load is conducted following DIN EN 1991-1-4 [45], a component of the Eurocode 1 (EC1). This standard allows wind load calculations up to a height of 200 m, and in Germany, as specified by the National Annex (NA) of DIN EN 1991-1-4 [45], calculations are allowed up to a height of 300 m. Beyond these heights, alternative calculation methods that involve potency profiles or computer simulations must be used. The norm also allows a simplified calculation of wind loads up to a height of 25 m.

The calculation of wind load involves several factors:

- Surrounding terrain, categorized into 5 terrain categories (cf. Figure 2.4). However, reduced to 4 categories due to the National Annex (NA) eliminating Category 0.
- Wind zones (cf. Figure A.1).
- Building height and geometry of the building.
- Special cases, such as surrounding buildings, etc., are not further addressed here.

The calculation of the effective wind pressure follows a consistent procedure:

First, the basic wind speed v_b is determined as:

$$v_b = c_{\text{dir}} \cdot c_{\text{season}} \cdot v_{b,0} \quad (2.3)$$

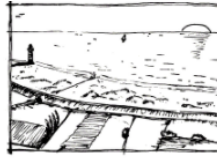
The coefficient for wind direction c_{dir} and for the season c_{season} can be set to 1.0 for long-term structures. The base value of the basic wind speed $v_{b,0}$ can be read from the wind zone map in Figure A.1. Next is the determination of the mean wind speed:

$$v_m(z) = c_r(z) \cdot c_o(z) \cdot v_b \quad (2.4)$$

The roughness coefficient $c_r(z)$ and topography factor $c_o(z)$ can be determined by specialized professionals or simplified by consulting the terrain zone map in Figure 2.4 and relevant tables (Table A.1).

Terrain category 0

Sea, coastal area exposed to the open sea



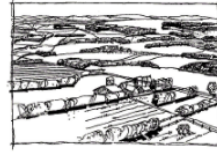
Terrain category I

Lakes or area with negligible vegetation and without obstacles



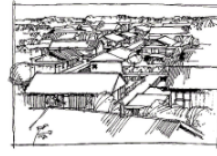
Terrain category II

Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights



Terrain category III

Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)



Terrain category IV

Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m

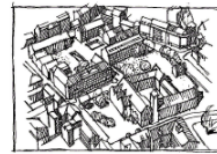


Figure 2.4.: Terrain categories according to DIN EN 1991-1-4 [45].

In addition, the intensity of the turbulence I_v is determined. This factor accounts for the increased occurrence and strength of wind storms or any wind turbulence, particularly in coastal and flat areas.

$$\begin{aligned} I_v(z) &= \frac{\sigma_v}{v_m(z)} = \frac{k_I}{c_0(z) \cdot \ln(z/z_0)} & \text{for } z_{\min} \leq z \leq z_{\max} \\ I_v(z) &= I_v(z_{\min}) & \text{for } z < z_{\min} \end{aligned} \quad (2.5)$$

With the turbulence standard deviation given by $\sigma_v = k_r \cdot v_b \cdot k_I$, where k_r is the terrain factor 2.4 and k_I is the turbulence factor, which can be assumed as 1.0 according to the NA. Similar to the mean wind speed, the values for I_v can be simplified and obtained from Table A.1.

Next, the gust velocity pressure q_p must be determined, which combines both the mean and short-term changes in wind speed in a single expression:

$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) = c_e(z) \cdot q_b \quad (2.6)$$

Here, ρ represents the region-dependent air density. The value for q_p can also be determined using Table A.1. The associated height for determining gust velocity pressure can be read from Figure A.2.

The final wind pressure w_e , acting on the glass panes is determined as follows:

$$w_e = q_p(z_e) \cdot c_{pe} \quad (2.7)$$

The aerodynamic coefficient c_{pe} for external pressure is determined using Table 2.1. The value $c_{pe,10}$ represents the aerodynamic coefficient for a 10m² component, respectively $c_{pe,1}$ for a 1 m² component. Linear interpolation is allowed between these values. Therefore, for a 2 m x 2 m glass panel $c_{pe,4}$ has to be determined. For conventional glass facades, the pressure according to class D (cf. Figure A.3) is applied to determine the thickness of the glass. The suction effect on side E is only relevant for attachment, as the glass panes are symmetric (cf. Section 1.4). However, in cases where, as in this thesis, an asymmetry is introduced through an imprint on the glass plate, both pressure and suction must be separately considered in the calculations to preserve structural integrity.

The final applied exposure is given by:

$$E_{d,w} = \gamma_{Q,j} \cdot w_e \quad (2.8)$$

where $\gamma_{Q,j} = 1.5$ for unfavorable actions and $\gamma_{Q,j} = 0.0$ for favorable actions. Combination factors [45] can be applied for additional variable loads.

Table 2.1.: Aerodynamic coefficients c_{pe} for external pressure according to DIN EN 1991-1-4 [45].

Bereich	A		B		C		D		E	
h/d	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
5	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,7	
1	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,5	
$\leq 0,25$	-1,2	-1,4	-0,8	-1,1	-0,5		+0,7	+1,0	-0,3	

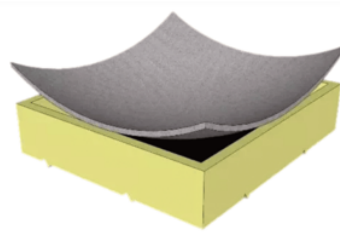
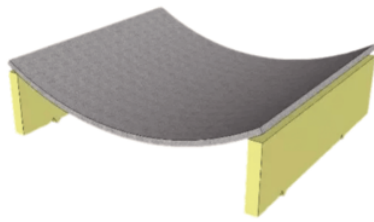


Figure 2.6.: Deformation of a plate supported on two sides and a plate supported on four sides under uniform surface load from above.

2.1.1.3. Supports

In the built environment, three typical types of supports are met for vertical glass elements in the facade:

- Two-sided supports
- Four-sided supports
- Point supports

Combinations of line and point supports appear less often as well.

The two-sided support, classified as a linear support, is regulated by DIN 18008-2 [25]. In a static context, the glass pane is treated as a simple span beam, subjecting it to uniaxial stress, as shown in Figure 2.5. The structural freedom for rotation is achieved through the implementation of a "Navier support", typically realized by an EPDM (ethylene propylene diene monomer rubber) strip or silicone profile [9]. Recent changes to DIN 18008 [24] now permit glass panels to be supported on two adjacent sides rather than strictly on opposite sides.

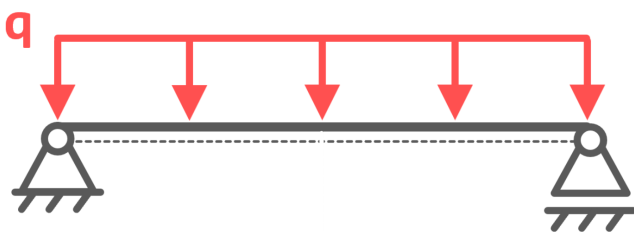


Figure 2.5.: Side view of a slab supported on two sides as a single-span beam under equal-span load.

The four-sided support, also classified as a line support, is regulated by DIN 18008-2 [25] and represents the most common form of support in civil engineering. In this configuration, the glass panel is supported on all four sides using the "Navier support" mentioned earlier. The 4-sided support induces a bi-axial stress state in the plate, which can be statically only modeled using the plate theory.

Point supports are available in various variations, regulated by DIN 18008-3 [39]. The most common type is the surface-mounted point support, where a point fixing is placed and screwed onto the opposite side of the pierced glass. A more elegant execution is the use of countersunk fixing, where the point fixing is recessed through a conical bore in the glass. A relatively new design involves point supports implemented as undercut anchors. Through specific non-penetrating holes in the glass, concealed attachment points are enabled, nearly imperceptible from the front of the glass.

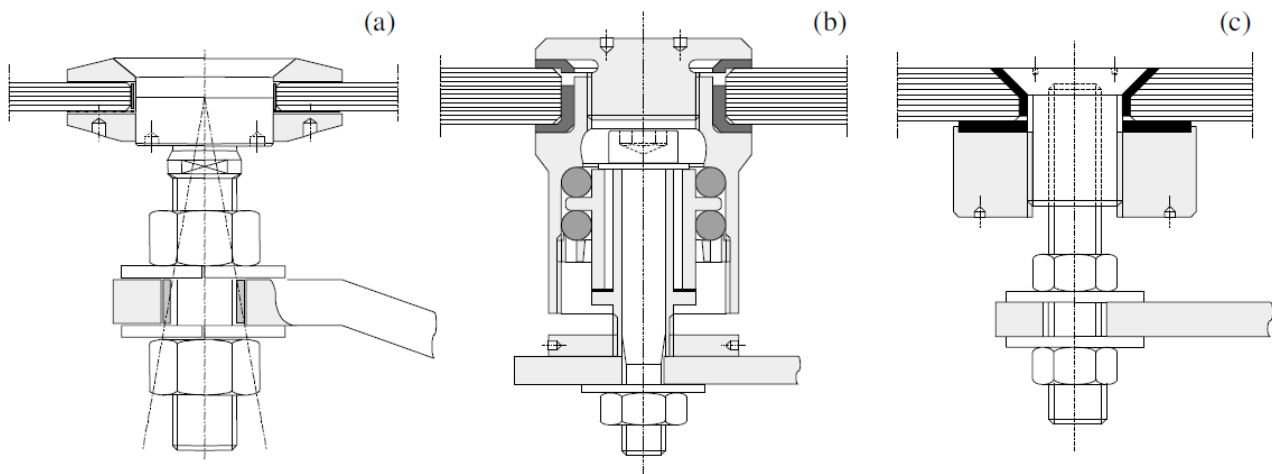


Figure 2.7.: Drilled point holders: Twistable plate holder ((a), type: FXR 1003B, Sadev), torsionally rigid plate holder ((b), type: Manet R EV 50/50, Dorma), countersunk head holder ((c), type: Litewall, Glassolutions Eckelt). Schneider Glasbau [110].

Undercut anchors currently require a minimum glass thickness of 10mm. An additive application process in combination with the undercut anchor can significantly reduce the required glass thickness. Non-intrusive clamp holders, typically securing the glass plates at the corners without compromising the integrity of the glass. Specific requirements for the clamping area and the glass protrusion are outlined in DIN 18008-3 [39]. Additional methods of point fixation include adhesive attachment and lamination of point supports. However, both methods constitute special cases and require an individual evidence (ZiE) or a general building authority approval (abZ/aBG) (cf. Section 2.5). The positioning of the point supports is regulated both in DIN 18008-3 and in the product standards of individual glass products (DIN EN 1863 [43], DIN EN 12337 [30], DIN EN 12150 [29], etc.). By strategically bearing the points, a statically determined and constraint-free support of the glass plate must be achieved to minimize forced deformations. The stress state induced in the glass plate by the point supports is highly complex, making it advisable to perform calculations using FEM models. Alternatively, the calculation method outlined in appendix C of DIN 18008-3 [39], can be employed.

2.1.1.4. Criteria

According to DIN 18008 [24] and DIN CEN/TS 19100-1 [27], based on a semi-probabilistic safety concept, four verifications must be conducted for vertical glass elements:

- Evidence in the Ultimate Limit State (ULS)
- Evidence in the Serviceability Limit State (SLS)
- Evidence of the Fracture Limit State (FLS)
- Evidence of Post Fracture Limite State (PFLS = Residual load-bearing capacity)

For ULS verification, analyses are performed to ensure that the glass withstands the applied design load without fracturing. For this purpose, the resulting principal tensile stresses in the glass are calculated from

the load E_d , and they are compared with the allowable principal tensile stresses on the resistance side.

$$\begin{aligned} E_d &\leq R_d \\ R_d &= k_{\text{Edge}} \cdot k_{\text{LSG}} \cdot \frac{k_{\text{mod}} \cdot k_c \cdot f_k}{\gamma_M} \end{aligned} \quad (2.9)$$

With k_{Edge} representing the coefficient for considering reduced edge strength, k_{LSG} as the coefficient for accounting for a lower probability of failure for LSG, k_{mod} as the coefficient for accounting for the duration of loading, k_c as the coefficient for considering the construction type, and γ_M as the partial safety factor for resistance, which is 1.5 for thermally toughened glass and 1.8 for annealed glass [110].

Within the SLS as specified by DIN 18008 [24], verification exclusively focuses on deformation criteria:

$$E_k \leq C_d \quad (2.10)$$

Here, the load combination E_k , representing the deformation under the design load, is considered without an increase in load due to partial safety factors. The maximum deflection is regulated in the norm to a maximum value of $C_d = l/100$, where l is always the smaller span. For insulating glass $< 2\text{m}^2$, under certain conditions, a maximum deflection of $C_d < l/65$ can also be assumed.

The FLS specifies how glass components must behave during breakage so that injuries caused by contact with fragments are prevented and failure is limited to this glass component only. The terms FLS and PFLS were introduced quite recently by DIN CEN/TS 19100-1 [27], but only summarize what was already prescribed by DIN 18008 [24] and other standards for fracture behaviour and residual load-bearing capacity.

Vertical glazings are deemed to possess residual load-bearing capacity, meaning they are resistant to complete failure of partially damaged glass (DIN 18008-2 Annex B [24]), under the stipulation that they meet the following criteria:

- Glazings must be supported at a minimum of 2 opposing edges.
- The residual load-bearing capacity must not be influenced by holes in the glass.
- In the case of laminated safety glass (LSG), properties according to DIN 18008-1 B2 must be assumed.

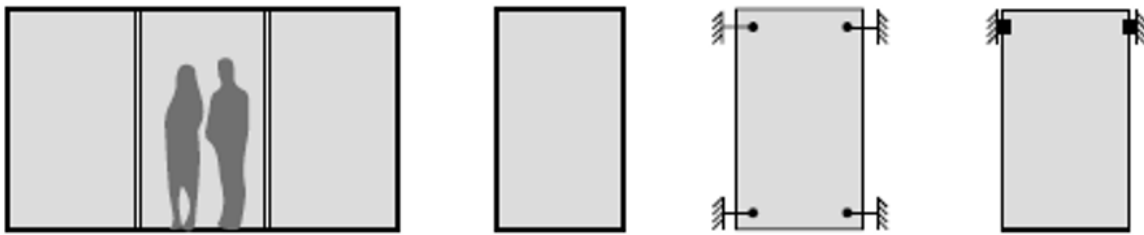
The residual load-bearing capacity must be verified for all vertical glazings in traffic areas. Above a height of 4m over traffic areas in Germany, thermally toughened soda-lime glass (FTG) sheets, heat-soaked according to DIN EN 14179 [37], must be used to prevent spontaneous failure due to nickel sulfide inclusions.

2.1.2. Barrier glazing (V)

Barrier glazing, fall protection glazing, or guardrail glazing refers to glazing designed to prevent people from falling from significant heights. Examples include railings, balustrades, elevator glazing, and full-height glazing. DIN 18008-4 [40] classifies these into three categories:

- Category A: Glazing is required to directly and completely support horizontal live loads.
- Category B: Glazing is required to indirectly support horizontal live loads, as individual panes are connected to each other through a continuous handrail.
- Category C: Glazing is not required to support horizontal live loads.

Examples for category A



Examples for category B



Examples for category C

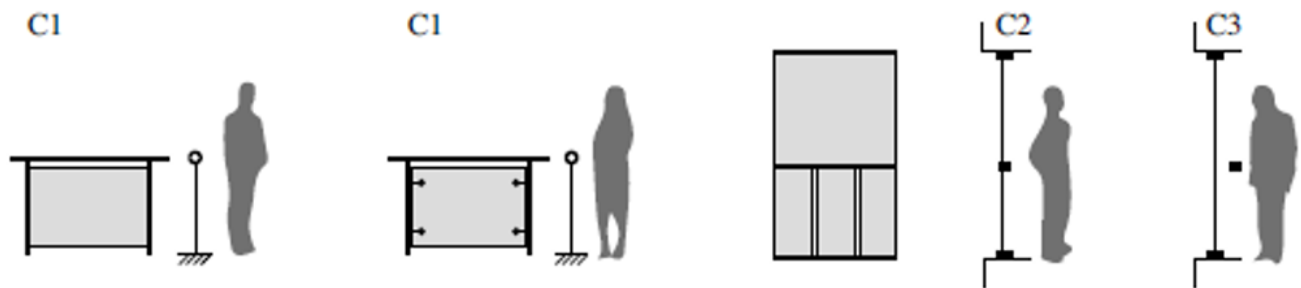


Figure 2.8.: Differentiation of fall-protection glazing in categories A, B and C in accordance with DIN 18008-4 [40]. Schneider Glasbau [110].

Fall protection glazing, like facade glazing, can be supported either on two sides, four sides, or with point supports. However, fall protection glazing (especial Category A & B) is often restrained at their bottom, which is atypical for facade glazing, but provides an exceptionally transparent appearance.

Fall protection glazing is designed, like facade glasses, based on applying their own weight and, if applicable, wind loads. But unlike facade glasses, the significant continuous stress here is yielded by live loads (handrail loads). These are to be assessed according to regional building regulations in the height of 0.9-1.1 m from the bottom edge of the glazing, ranging from 0.5 kN/m to 2.0 kN/m depending on the application. The verification is performed simultaneously with the facade glasses in the ULS using the corresponding formulas 2.9. In the structural design, the impact loads significantly influence the effects in allocating under the ULS. Under such impact loads, the demonstration of residual load-bearing capacity is essential, ensuring that the glazing does not undergo penetration, detachment from its support, or breaks apart into individual fragments. This residual load-bearing capacity is generally proven using the pendulum impact test according to DIN 18008-4 Annex A [39] and can currently only be achieved with LSG. For linear glazings, this verification can also be provided through a simplified calculation or comparison with previously tested glasses.

AM Glass could play a significant role in safety glazing for fall protection. The clamping from railings and parapets face high clamping moments, necessitating robust anchoring. Reinforcing or supporting a glass plate with AM techniques could significantly alleviate stress on the glass. LSG, necessary for restraining impact loads, is compatible with AM Glass, provided that the printing is always done on the outer surfaces. However, capture of impact loads via a surface-wide geometry continues to pose challenges. A notable advantage of railings and parapets utilizing AM Glass is their ease of cleaning compared to high rise facade glazing, which is often more challenging with 3D structures than with flat glass. Due to their proximity to users, it is particularly beneficial to apply complex designs to these plates for aesthetic enhancement, including anything from company logos to functional shelves or structural patterns. The feasibility of 3D-printed handrails or balustrades, as previously mentioned in Section 1.5, further underscores the versatility and potential of AM Glass in enhancing both functionality and design aesthetics.

2.1.3. Interior glazing (V)



Figure 2.9.: Example of interior glazing in an office building [93].

to specific requirements for residual load-bearing capacity to prevent sudden failure of the glass, thereby ensuring the safety of individuals on these traffic surfaces. These requirements dictate that all horizontal glass must be constructed as LSG, in accordance with DIN 18008-2 [25]. On the other hand, horizontal glazing uniquely contends with the additional design load of snow, which, depending on the region, can significantly impact the design. This snow load is specific to horizontal glazing, thus vertical glazing in shed roofs is also considered under horizontal glazing due to the potential accumulation of snow, subjecting them to similar loads.

For completeness, it is necessary to mention interior glazing applications, such as glass doors, folding glass walls, or glass room dividers. These elements bear their own weight, live loads from handrailings etc., and indoor wind loads. The DIN standards do not specify a particular support condition for such installations, but requirements for fracture behavior. The requirement to demonstrate residual load-bearing capacity is obviated by restricting interior glazing to FTG and LSG.

Given that interior glazing serves predominantly aesthetic purposes, the application of AM Glass in this context is justified primarily on aesthetic side.

2.1.4. Horizontal glazing without specific fall-protection function (H)

The distinction between horizontal and vertical glazing, as described at the beginning of this chapter, is made based on two criteria. On one hand, this differentiation is necessary because horizontal glazing is always assumed to be above traffic areas, leading

According to DIN 18008-2 [25], horizontal glazing is categorized into four types:

- Horizontal glazing without specific fall-protection function
- Accessible glazing
- Fall-through protective glazing
- Walk-on glazing

Horizontal glazing without specific fall-protection function represents the most basic type of horizontal glazing. This classification assumes that individuals will neither walk on nor fall onto these glass surfaces, eliminating the need for special impact loads and specific requirements for residual load-bearing capacity.

From a support perspective, all types of supports allowed for vertical glazing in facade elements are permissible here. According to DIN 18008-2 [25], a special rule applies that horizontal glass with a span greater than 1.2m must be supported on all four sides.

Per DIN 18008-2 [25], glass must be designed for planned loads, primarily self-weight, wind, and snow. The design for self-weight is conducted concurrently with that for vertical glazing 2.1.1.3. However, it is crucial to recognize that the self-weight here does not act parallel to the plane of the glass, thus having a significantly greater impact on the design than in vertical glazing. Wind loads are also assessed concurrently with vertical glazing according to DIN 1991-1-4 [45]. It is important to note that roofs often experience high suction loads, which can be greater than the corresponding pressure loads. Snow load calculations are based on DIN 1991-1-3 [45], varying with snow load zones, elevation above sea level, geometry, and other parameters, with loads ranging between 0.6-1.1 kN/m². Furthermore, horizontal glazing must be designed for an exceptional design situation if one of the panes in the LSG assembly fails. DIN 18008-1 [24] mandates that each pane must independently withstand all loads under the safety factors for exceptional design situations. Additionally, LSG made from FTG is prohibited for horizontal glazing due to inferior residual load-bearing properties.



Figure 2.10.: Picture of horizontal glazing of the Queen Elizabeth II Great Court by Evgenija Mitin [9].

2.1.5. Accessible glazing (H)



Figure 2.11.: Accessible glazing with sign: "Enter for cleaning purposes only! Do not enter in case of fire!". Schneider Glasbau [110].

Accessible glazing refers to glass installations designed to be accessed for maintenance, including cleaning operations. According to DIN 18008-6 [42], accessible glass must only be accessed by a maximum of one person at a time and is thus designed to accommodate a live load. DIN 4426 [26] specifies a point load of $Q_k = 1.5 \text{ kN}$ over an area of $100 \text{ mm} \times 100 \text{ mm}$ in unfavorable load case, which should not be reduced by combination factors. All other loads are to be applied in the same manner as for horizontal glazing without specific fall-protection function. In addition, accessible glass must be designed to withstand impact loads, combined with sufficient residual load-bearing capacity. A single pane within the LSG assembly must be capable of bearing standard loads such as self-weight, wind, and live loads.

2.1.6. Fall-trough protective glazing (H)

Fall-through protective glazing is designed not for deliberate access but to withstand the impact of a person falling during maintenance activities. The distinction between fall-through protective and non-specified requirements is made based on Figure A.4.

The design process for fall-through protective glazing is conducted similarly to that for accessible glazing, with the notable allowance that the load-bearing capacity of both panes can be considered for mitigating impact loads.

In the realm of horizontal glazing, AM Glass can play a significant role. Due to loads such as self-weight, wind, and snow, these structures are heavily stressed normal to the plane, resulting in significant bending moments and deflection. The deflection must be limited to ensure a sufficient support width is maintained, preventing the glass from dislodging from its bearings. This is one of the reasons that horizontal glazing spanning more than 1.2m must be supported on all four sides, as mentioned earlier.

A practical application involves reinforcing the upper LSG pane on the top side, placing the AM material in the compression zone of the component, which benefits from the higher compressive strength of glass. AM Glass could theoretically accommodate loads such as self-weight, wind, and snow. However, capturing impact loads and live loads is more challenging due to their non-stationary nature, making it difficult for a non-uniform structure to absorb them effectively. The residual load-bearing capacity would need to be demonstrated for combinations of self-weight + wind + snow and self-weight + wind + Q_k + impact load, under the condition that, as usual for accessible glazing, these are not accessed during snowfall. It is also feasible to design a pane without considering impact load and live load as mentioned in Section 2.1.4, but this approach is not advisable.

A three-dimensional structure on the weather-exposed surface necessitates increased maintenance, and the access needed for cleaning operations demands additional effort.

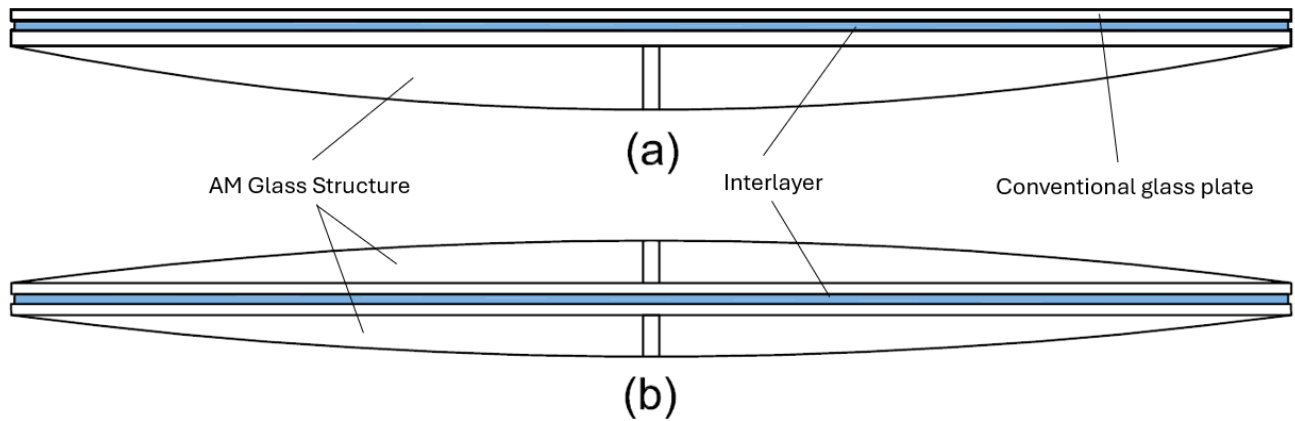


Figure 2.12.: Sketch of an LSG laminate with AM glass reinforced panel on one side (a) or AM glass reinforced panel on both sides (b).

2.1.7. Walk-on glazing (H)

Walk-on glazing refers to glass installations designed to withstand regular pedestrian traffic under normal use. According to DIN 18008-5, accessible glazing must be designed for both the loads applicable to horizontal glazing, as previously mentioned, and a traffic load of 5 kN/m^2 . Additionally, the design must account for the load case from self-weight and a point load with a contact area of $50 \text{ mm} \times 50 \text{ mm}$ in the most unfavorable position, as well as impact loads. The residual load-bearing capacity must be experimentally verified by testing, as no computational proof is stipulated. By adhering to specific structural fall protections, the residual load bearing capacity can also be neglected [42]. DIN 18008-5 [41] specifies the construction as LSG with three panes, where the top pane should not be considered in the load-bearing capacity calculation and serves as a wear layer. Beyond load-bearing requirements, criteria for serviceability and personal safety, such as deflection limits and, depending on the location, slip resistance of the top glass layer, are also mandated.



Figure 2.13.: Example of a walk-on glazing [93].

At first glance, AM Glass seems to have limited applicability for walk-on glazing. Logically, printing on the middle pane of the LSG is not feasible. If positioned on

the underside, the AM Glass part would be in the tension zone, thereby reducing its performance. If this is implemented by increasing material, the residual load-bearing capacity, in case of failure of this pane, is hard to envisage. Printing on the top surface of walkable glazing is impractical for pedestrian traffic, which requires flat surfaces. However, in the context of custom constructions for walk-on glazing, specific applications for AM Glass emerge. The stair treads could be transparently connected to the stringer using AM Glass, as previously indicated in Section 1.6. Fully transparent glass boxes, such as "The Ledge" in Chicago's Willis Tower (cf. Figure 2.14), could be innovatively connected at the corners. Similarly, swimming pools, like the acrylic glass example in London's Embassy Gardens, could be reinforced with AM Glass. A non-planar surface on the top side of the glass would not significantly affect usability in water. Another concept involves creating slip resistance for walk-on glazing through thinly printed lines. The implementation of AM Glass in walk-on-glazing could also serve an aesthetic purpose.

2.1.8. Inclined glazing



Figure 2.14.: "The Ledge" in Chicago's Willis Tower. Picture by Viator [19].

According to DIN 18008-1, inclined glazing is classified as horizontal glazing, but essentially represents a hybrid of horizontal and vertical glazing. The inclined configuration requires specific considerations for drainage and snow loads, which can accumulate at certain points on an inclined surface. Most of these inclined glazings are implemented as horizontal glazing without specific fall-protection function (cf. Section 2.1.4). However, depending on the slope, they may also need to be classified as accessible or fall-through protection glazing (cf. Sections 2.1.5, 2.1.6). The use of AM Glass in such installations does not result in significant consequences, but alterations in snow accumulation and water flow should be anticipated when applying AM on the upper side. Otherwise, the same considerations as mentioned in Section 2.1.1.2 apply.

2.2. Optical requirements

The transparency of glass is its most distinctive feature, making it a unique material. Therefore, the optical properties of glass represent a critical requirement that must be assessed and considered.

The standard DIN EN 410 [47] regulates the optical requirements for glass in construction. For the AM Glass process on flat glass, the relevant key parameters are the light transmission and reflection rates, indicating the amount of light that the glass allows to pass through and reflects. Other parameters, such as energy transmission rate, heat emission rate, UV transmission rate, and color rendering, should not significantly change due to the additive process. The formulas for light transmission and reflection rates in the standard apply to flat glasses and do not easily adapt to non-planar glass surfaces. Product standards such as DIN EN 572-2 provide guidelines for optical assessment, but only for scratches, defects, and inclusions.

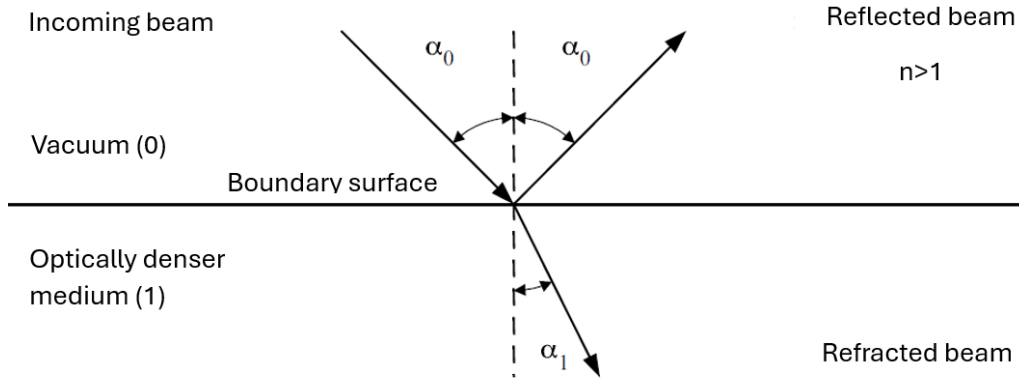


Figure 2.15.: Reflection and refraction of light during the transition to a denser medium. From Schneider Glasbau [110].

Another approach is described in ISO 11485-2 [74], which assesses the quality of curved glasses. However, it does not specify measurement methods for optical errors and anisotropies. Instead, it aims to limit optical errors by minimizing deviations from the intended curvature. This approach acknowledges the current difficulty in comparing devices such as polarimeters and the general challenge in documenting and evaluating optical errors.

From a physical perspective, general requirements for AM Glass can be identified. Reflections on glass surfaces are particularly noticeable because they reduce transparency at certain points and create reflection patterns on curved glass surfaces. The behavior of total reflections and refractions can be described using Snell's law:

$$n = \frac{c_0}{c_1} = \frac{\sin \alpha_1}{\sin \alpha_2} \quad (2.11)$$

where $n \approx 1.52$ for soda-lime glass. The Fresnel equations calculate the light reflection rate for glass as follows:

For perpendicular polarization,

$$R_s = \left(\frac{E_{0r}}{E_{0e}} \right)_s^2 = r_s^2 = \left(\frac{n \cos \alpha_1 - \cos \alpha_2}{n \cos \alpha_1 + \cos \alpha_2} \right)^2 \quad (2.12)$$

and for parallel polarization,

$$R_p = \left(\frac{E_{0r}}{E_{0e}} \right)_p^2 = r_p^2 = \left(\frac{\cos \alpha_1 - n \cos \alpha_2}{\cos \alpha_1 + n \cos \alpha_2} \right)^2 \quad (2.13)$$

For vertical incidence ($\alpha = 0$), the reflectance for soda-lime glass is approximately 4% regardless of polarization. Considering light passes through two boundaries of the glass and ignoring absorption, the total reflectance for flat glass is about 8%. The reflectance increases with the angle of incidence until it reaches total reflection at approximately 42° . Curved glass surfaces continuously change their angle of incidence, leading to varying reflection behavior and visible reflection patterns. These patterns can cause geometric distortion of reflected

objects, drawing the viewer's attention. Additionally, light can be focused or scattered at certain points, creating patterns of light and shadow.

Such reflection patterns may be desirable in some applications for aesthetic reasons. However, in most cases, minimal reflection and a uniform reflection pattern are preferred to ensure undisturbed transparency of the glass. This has implications for additive application on glass plates: The interface area should be limited, as it will cause optical distortions, and it may not be desired across the entire plate width. The radii of the print should either be very large (to change the reflection behavior minimally over large areas) or very small (to create strong, but localized, changes in reflection behavior). Additionally, it is worth considering making parts of the additive print planar to limit the reflection pattern.

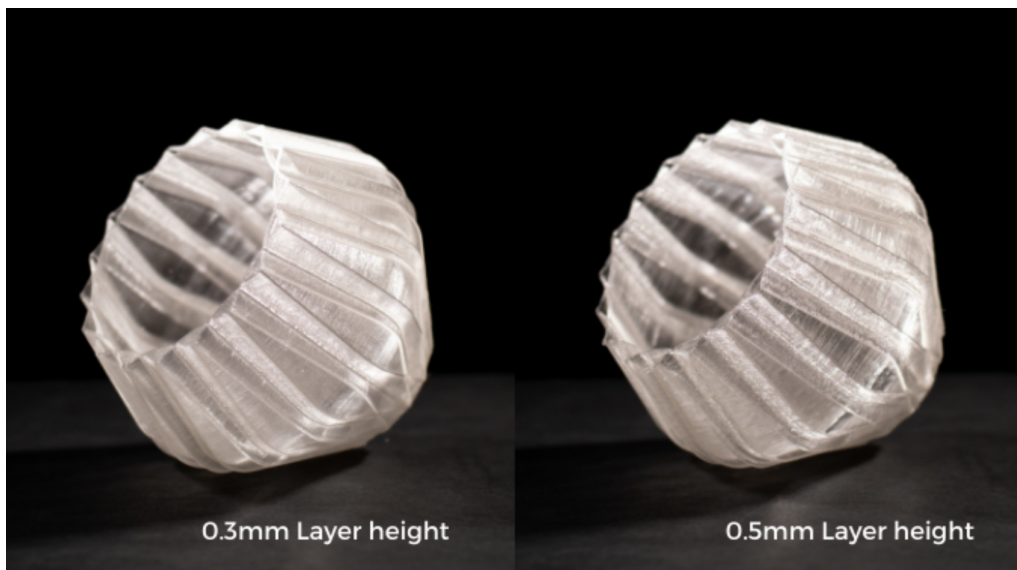


Figure 2.16.: Two identical objects printed from PETG with slightly different layer height. Even a small change in the layer height already influences the transparency.

Especially for AM with FDM, the layer notches should be considered. As shown in Figure 2.17a, many small layers with untreated notches can lead to a white/translucent appearance, while objects with larger layers appear more transparent (cf. Figure 2.17b).

If post-processing of the layer notches, such as polishing or flame treating, is not planned for AM Glass specimen, a larger layer thickness is highly recommended. The smaller the number of notches, the smaller the optical distortions. Therefore, small, barely visible notches should be a goal for mechanical considerations as well as optical considerations.

In flat glasses optical anisotropies are noteworthy, often resulting from induced mechanical stresses in HSG or in glass components under significant mechanical load. The proposed reduction of flat glass deflection through AM may not only have construction-physical and practical applications but also potentially reduce optical anisotropies.



(a) A "benchy" printed by Maple Glass Ltd. with 1 mm layer height [2].



(b) A "wave" printed by Evenline with approx. 5 mm layer height [52].

Figure 2.17.: Different transparency of AM glass in relation to the layer height.



Figure 2.18.: Optical anisotropies of facade glasses. Picture by Gentner Verlag GmbH [62].

2.3. Economic requirements

In the scientific field, economic requirements are often overlooked. However, for the success and subsequent implementation of a technology, economic criteria are crucial.

2.3.1. Production price

A key economic consideration is the production or sales price: Currently, the average cost of an untreated float glass plate made from soda-lime glass is (converted) ca. 0.5-1 US-\$ per kg in sales [116] depending on glass plate thickness. Depending on the further processing of this glass plate into the glass products mentioned in Section 1.4, this price can rise to around 30 US-\$ (as of February 2024 - only as an order of magnitude, market prices are highly variable).

There are only a few price estimates available for glass 3D printing technology. For the SLA process by Glassomer (see Figure 1.5), prices can be requested through the service provider protiq [4]. Here, the costs are approximately 43,000 US-\$ per kg of quartz glass. However, it is important to consider that the material price of high-purity quartz glass can quickly exceed 1,000 US-\$ per kg. The company Evenline [52] (cf. Section 1.2) currently offers various pre-designed glass 3D printed objects at a cost of about 200 US-\$ per kg of soda-lime glass. Although this may not represent the actual production cost, it provides a reference. The significant price difference between these two technologies is a reason why, for construction, and in this thesis, the FDM or DED process is preferred.

Even when focusing on the more affordable processes, it is crucial to remember that in the context of the built environment, these technologies are currently very cost-intensive. For the technology to be competitive, the author estimates that the price per kg for untreated 3D printed glass plates customized through AM glass should not exceed 20 times the current price per m² for standard float glass, i.e., 20 US-\$/kg. For prestige buildings, price expectations up to 50 times, i.e., 50 US-\$/kg, are conceivable. To obtain reliable values, a professional market analysis is recommended.

2.3.2. Production time

Another aspect concerns production time: A typical float glass line produces approximately 700 t (cf. Section 1.4) of float glass per hour depending on the set glass thickness. An additive process is unlikely to ever match this speed. However, from an economic perspective, production time should not be overlooked. The greater the production capacity, the faster the return on substantial investments in machinery, the lower the personnel costs for machine operation, and the reduced cumulative machine hours.

2.3.3. Implementability

Equally important is the implementability into existing processes. Implementing an FDM or DED process into float lines or heat-strengthening machinery is extremely sensible and will be revisited in Section 5.2. How feasible and complex these implementations are without significantly altering the existing, often very expensive, processes will determine the existing glass industry's acceptance of this new technology.

2.4. Neglected requirements

Due to the constraints of this thesis, a series of requirements for bent-stressed glass plates, or glasses in built environment in general, have been neglected. These include:

- Exposure to fire according to DIN EN 1991-1-2 [45].
- Effects of temperature according to DIN EN 1991-1-5 [45].
- Impacts during construction according to DIN EN 1991-1-6 [45].
- Manual impacts according to DIN EN 1991-1-7 [45].
- Vibrational loads due to earthquakes according to DIN EN 1998-1 [46].
- Loads due to residual stresses.
- Requirements for natural frequency according to DIN EN 19100-2 [28].
- Practical construction requirements such as cleaning, etc.

2.5. Law requirements and possibilities

The ultimate goal of any research or technology in civil engineering is its application in the built environment. This objective often faces legal regulations that impose specific requirements.

In Germany, these regulations are more complex and stringent compared to other countries. For the approval of non-standard construction products, for which no accepted technical standards exist, such as the novel process of additive manufacturing of glass, Germany offers the following types of approvals:

- abZ - General Building Authority Approval
- abP - General Building Authority Test Certificate
- ZiE - Approval in Individual Cases

An overview of these approval types is presented in Table 2.2. Further approval options exist for construction methods.

2.5.1. abZ - General Building Authority Approval

The abZ is issued by the German Institute for Building Technology (DIBt) for construction products or methods, confirming their compliance with German building regulations. Obtaining it requires extensive experimental investigations and expert opinions that unequivocally verify the product's suitability for its intended use [110]. Due to its complexity and associated costs, an abZ is justified for larger production batches but serves also as a selling point since no further ZiEs are required. The abZ allows the product to be approved throughout Germany regardless of the construction site and is generally valid for 5 years, but can be extended beyond this. The corresponding approval at European level is the ETA (European Technical Assessment). The future handling by DIBt of highly variable construction products, such as those produced by AM, remains to be seen. Insisting that approved construction products must be identical could significantly hinder innovation.

Table 2.2.: Overview of approvals and evaluations for construction products in Germany. As of December 2023.

Approval	Description	Validity	Country	Effort	Particularities	Responsible Institution
AbZ (General Building Authority Approval)	Confirms conformity with German building regulations.	Variable, often 5 years	Germany	High	Extensive testing and documentation required.	German Institute for Building Technology (DIBt)
ETA (European Technical Assessment)	Confirms conformity with EU building regulations. Enables CE marking.	Variable, often 5 years	EU Member States	High	Enables distribution within the EU for products outside harmonised standards.	Designated Technical Assessment Bodies (TABs) in the member states
AbP (General Building Supervisory Test Certificate)	Evidence of suitability of a construction product or method based on specific tests.	No fixed regulation, depends on the testing body	Germany	Medium to high	Issued by recognized testing bodies.	Recognized testing bodies (e.g., material testing offices)
ZiE (Approval in Individual Cases)	Individual permission for the use of a construction product in a specific project.	Only valid for the specific construction project	Germany	Variable/Low	Demonstration of structural stability by tests and calculations	Supreme Building Supervision Authorities of the federal states

2.5.2. abP - General Building Authority Test Certificate

An abP is applied when testing regulations exist or the failure of the component is expected to have minor consequences. It is issued by recognized testing facilities based on experimental investigations. Since it usually pertains to specific applications, the effort involved is typically less than for an abZ. However, an abP often comes with conditions that limit the site of use and include monitoring requirements. The validity period is usually determined by the testing facilities on a case-by-case basis.

2.5.3. ZiE - Approval in Individual Cases

The ZiE is granted by the supreme building supervision authority of the respective federal state in Germany upon the builder's request and is limited to the specific construction project [110]. Typically, structural stability is demonstrated through tests and calculations. The scope and extent depend on both the construction project

and the building supervision authority. Compared to an abZ, the effort is significantly less, and it allows for a focus on the product's individuality. Due to its individuality and lower costs, the first construction products made of additive glass in Germany will likely be approved via a ZiE. However, the effort involved should not be underestimated and could be a stumbling block for many innovations with limited financial resources.

2.5.4. Building Class e

The emerging building class e in Germany deserves mention within the context of approvals. Here, "e" stands for "einfach" (simple) or "experimentell" (experimental). Buildings in this class may deviate from statutory provisions, technical building regulations, and recognized rules of technology where sensible and without compromising the safety of the building and its occupants. Careful consideration is required to determine which regulations can be neglected, as they are established with meaningful and deliberate intent. For experimental construction products, this can offer advantages, especially when current standards are not applicable, and obtaining building authority approval for initial trials is too burdensome. However, whether civil law can align with deviations from recognized technical rules and how liability is handled remain contentious issue [92].

2.5.5. Focus on Standards

Regardless of the chosen approval type, aligning the development process or products with existing standards offers significant advantages. Standards define accepted technical specifications and guidelines for a construction product. Compliance with standards can facilitate the demonstration of suitability and safety, increasing confidence in conformity with building regulations. This can reduce the need for additional evidence, thus expediting the approval process and reducing associated costs. Therefore, consideration of legal approval should be incorporated into the development stage, and inquiries made to building supervision authorities regarding expected requirements and evidence for the product. If possible and sensible, the technology and testing methods should be adjusted accordingly.

This is why this chapter focuses heavily on existing standards and the resulting requirements. These requirements will also be assumed in the Chapter 3 for optimization to achieve realistic and approvable results. The testing procedures created in Chapter 4 are also based on existing standards, specifically DIN EN 1288 [34] for large glass plates and DIN EN 843 [51] for the bending strength of small ceramics. During the further development of additive manufacturing of glass, attention should also be paid to currently developing standards, especially those related to additive manufacturing. An example is DIN EN 52948 [48] from November 2023, which outlines testing procedures for additively manufactured metal components.

Under special circumstances, construction products can also be installed without approval, or their use may be targeted only in countries with less stringent approval requirements. However, aligning with stringent requirements, such as those in Germany, is recommended to minimize liability risks. Approval in countries with less stringent requirements is generally easier to obtain when complying with stricter standards.

2.6. Assumptions, exposures and criteria for this thesis

To optimize glass plate structures with additive manufacturing of glass, which is discussed in Chapter 3, this section identifies a hypothetical application site. On the basis of this site, the corresponding assumptions,

exposures, support conditions, and criteria are determined.

2.6.1. Assumptions



Figure 2.19.: Fictional illustration of a skyscraper in Frankfurt am Main with varying sizes of different square glass panels in the facade.

A fictional skyscraper in Frankfurt am Main, Germany (50.10918 N, 8.70318 E; WGS84) serves as the building model. Its facade consists of a fully glazed post and beam system. The glass considered for further calculations is a completely vertical single glass, so it is neither part of a laminated nor an insulated glass assembly and is untreated and not tempered. The nominal dimensions of the glass are 2 m x 2 m or 3 m x 3 m. Square shapes are chosen for simplicity. The dimensions are selected to be large enough to warrant optimization (as mentioned in 1.5) and small enough to be manufactured on a float glass line. Soda-lime glass, typical for construction, is selected. A maximum available print height on the glass plates of 200 mm is given for practical construction reasons. Further requirements according to Section 2.4 are also neglected here.

2.6.2. Exposures

First, the wind load on the component is determined. Further assumptions include the glass being located at a height of 100m above ground level. The facade is oriented to offer a full windward side, and it is assumed that no surrounding high buildings significantly influence the wind.

Frankfurt am Main falls within wind zone 1 according to the wind zone map (see Figure A.1), and Terrain Category IV is assumed for the specified location, assuming no influence from surrounding buildings on wind load. Additional assumptions include full wind loading on Zone D and that the building is significantly taller than wide. The importance of suction on Zone E cannot be overlooked due to the asymmetry of the glass plates (cf. Section 2.1). The calculated loads are $E_{d,w,1,4m^2} = 1.32 \text{ kN/m}^2$ and $E_{d,w,1,9m^2} = 1.08 \text{ kN/m}^2$ for pressure, and $E_{d,w,2} = -0.93 \text{ kN/m}^2$ for suction, with $\gamma_{Q,j} = 1.5$ for both cases. Detailed calculations are provided in Appendix A.2, referencing Section 2.1.

The self-weight of the construction will be considered in subsequent calculations, but most FEM/optimization software already incorporates self-weight loading, so external application of this load is omitted.

Live loads or impact loads related to the use of the glass panels in this skyscraper are neglected.

The typical earthquake loads for Frankfurt am Main are also excluded, as are the requirements shown in Section 2.4, including inherent stresses, frequency effects, and long-term stability.

2.6.3. Support Conditions

The support of the glass panels are assumed as the typical configurations for post and beam facades: two-sided support at the top and bottom, and four-sided supports on all edges. The assumptions made regarding "Navier"-supports in Section 2.1 remain in place.

2.6.4. Criteria

In this hypothetical application, requirements for the ULS and the SLS are set. Residual strength is overlooked, as it is primarily irrelevant for optimization. Optical criteria are also ignored but revisited in Section 3.6.

Equation 2.9 to determine the tensile strength and thus the governing resistance in the ULS for flat glass cannot be directly transferred to additive manufacturing. Therefore, the assumed strength values, the calculation model, and the physical properties of additive manufactured soda-lime glass are discussed in Chapter 3. A partial safety factor of $\gamma_M = 1.8$ for float glass is assumed.

In the SLS, a maximum allowable deflection of $C_d = l/100$ is assumed following Section 2.1. For the 2 m x 2 m panel, this results in a maximum deflection of $C_{d,4m^2} = 2 \text{ m}/100 = 0.02 \text{ m} = 20 \text{ mm}$ and for the 3 m x 3 m panel $C_{d,9m^2} = 3 \text{ m}/100 = 0.03 \text{ m} = 30 \text{ mm}$. Increasing the maximum allowable deflection, as described in 2.1.1.4, is not possible due to the large panel size ($A > 2 \text{ m}^2$).

3. Optimization of glass plate structures

In this chapter, efforts are made to identify optimal printing geometries for the AM process, based on the requirements outlined in Section 2.6, with the aim of reinforcing flat glass panels. Initially, the material properties are determined respectively estimated. Subsequently, relevant topology optimization algorithms are examined, and various software solutions are evaluated for problem-solving. The resulting workflow is then applied to create optimized geometries for glass panels supported on both two and four sides.

3.1. Material model and physical properties

3.1.1. Soda-lime float glass

For calculations and optimizations of any kind, knowledge of both the mechanical and physical properties of the material is essential.

As indicated in Table 3.1, these properties can vary significantly depending on the type of glass. Even within the same type of glass, the properties vary because each manufacturer uses slightly different compositions. However, variations within the glass types are often overlooked, as is the case in this work.

Table 3.1.: Comparison of physical properties of different types of glass. Schott AG Mainz [110].

Property	Soda-Lime Glass	Borosilicate Glass	Quartz Glass
Density ρ [kg/m ³]	2,500	2,200-2,300	2,200
Young's Modulus E [MPa]	70,000	63,000	75,000
Poisson's Ratio ν [-]	0.23	0.20	0.17
Thermal Expansion Coefficient α_T [$10^{-6}/K$]	9.0	3.3	0.5
Specific Heat Capacity c_p [J/(kg·K)]	720-800	830	1,052
Thermal Conductivity λ [W/(m·K)]	1.05	1.2	1.47
Refractive Index n [-]	1.52	1.47	1.46

For the optimizations in this chapter, the properties of soda-lime float glass are assumed as described in DIN EN 572-1 [49]:

The primarily relevant mechanical properties for optimizations are:

- Density $\rho = 2,500 \text{ kg/m}^3$
- Young's modulus $E = 70,000 \text{ MPa}$

- Poisson's ratio $\nu = 0.2$ (various literature suggests that $\nu = 0.23$ [110]. This assessment is adopted to achieve more realistic results).
- $f_{g,kk} = 45$ MPa (for non-tempered glasses and only for short-term quasistatic loads such as wind load. A reduction through the safety factor for float glass $\gamma_M = 1.8$ must be applied).

Using classical material laws, the bulk modulus ($K = \frac{E}{3(1-2\nu)}$) and the shear modulus ($G = \frac{E}{2(1+\nu)}$) can also be determined:

- Bulk modulus $K = 43.21$ GPa
- Shear modulus $G = 28.46$ GPa

The behavior of the material is assumed to be linear elastic up to the fracture point, which is highly accurate within the construction temperature range (normally between -20°C to 100°C for facades). Glass behaves completely isotropic regarding all properties.

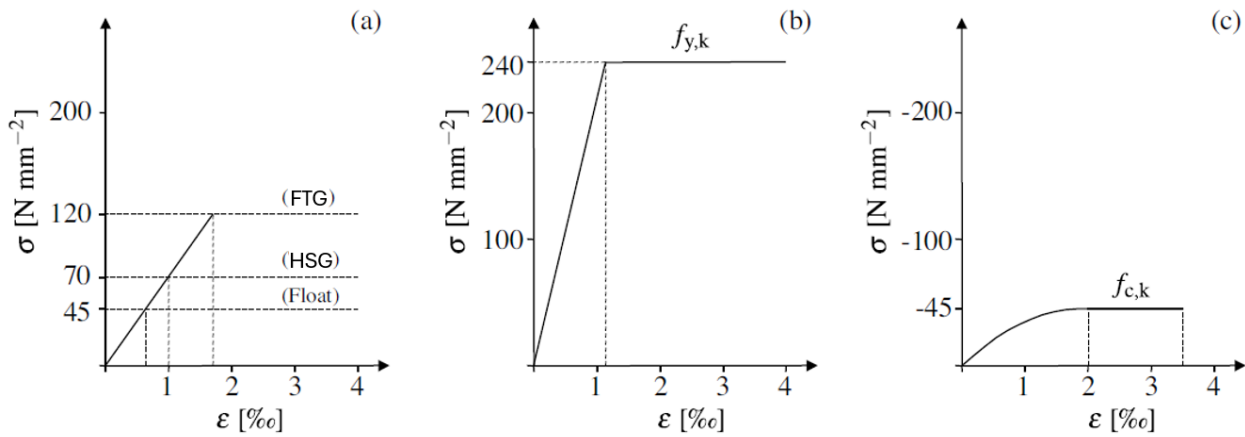


Figure 3.1.: Idealized stress-strain behaviour of glass (a) in comparison with steel (S235, b) and concrete (C45/55, c) in the uniaxial tensile test. Schneider Glasbau [110].

Furthermore, it is assumed that the temperature is 20°C and the relative humidity is between 30 and 60%. Influences of edge strength are neglected. Assuming that the base plates are cut before the printing process and that the plates are heated to at least T_g during the process, it is expected that the influence of edge strength is less than that of normal float glass. This assumption has to be verified experimentally.

3.1.2. 3d-printed soda-lime glass

Although soda-lime float glass is used as the material in the 3D printing process, the mechanical properties discussed in the previous section of this chapter cannot be directly applied as is. This is due to process conditions that may not necessarily (or only rarely) alter the material's physical properties themselves, but the produced geometry/surface geometry through predominantly notches globally changes the characteristics of the component.

This behaviour is important to investigate and estimate in order to have a basis for subsequent optimizations that are as realistic as possible. The references and assumptions listed here are checked via the experiments in Chapter 4 and discussed in Chapter 5.

3.1.2.1. Material model

In 3D-printed geometries, particularly those created with FDM or DED techniques, an anisotropic material behavior is often observed [88, 66]. Anisotropic behavior means that the model exhibits different (physical) properties in different directions. A subcategory of anisotropy is orthotropy, which indicates that, within a chosen coordinate system, the model has distinct constant (physical) properties along each of the three axes, and normal strains and shear strains are decoupled. A special case of orthotropy is transverse isotropy, where two of the three (physical) properties in orthotropy are identical.

In numerous scientific studies on FDM, DED, and also SLM processes, primarily involving polymers or metals, an orthotropic or transversely isotropic material behavior has been identified [88, 66, 131]. This is attributed to two main effects:

- A poor material bond between individual layers applied. In metals, this is due to an uneven crystal structure resulting from cooling effects [66]. For polymers, there is often insufficient linkage of polymer chains between layers. Similar effects can occur in glass; temperature differences during the printing process can lead to internal stresses between layers, as identified by Klein [77], leading to a reduction in strength. Contaminations or temperatures generally below the joining area (approximately 850-1100°C for soda-lime glass) can result in poor material bonding. The effect of inadequate nuclear order/linkage is not expected in glass.
- Surface effects, caused by layer notches, are significantly more decisive. Experiments with metal and polymer FDM printing have shown that these layer notches almost always act as intentionally introduced notches that originate breaks and significantly reduce strength [131]. In 3D printing of glass, such deliberately introduced notches are expected to significantly reduce strength perpendicular to the notches, especially since glass is extremely brittle. Confirmations of this can be found in Inamura et al. [73] and Klein [77].

The question of whether the observed strength reductions in polymers and metals can be approximated through orthotropic or transversely isotropic material behavior is currently answered as follows: If the printed lines are aligned in one direction, an orthotropic material behavior is clearly assumed. If the individual lines are not aligned or are crosswise arranged by overlapping layers as shown in Figure 3.2, a transversely isotropic material behavior can be assumed with sufficient accuracy [88].

In the literature, there are no existing approaches to classify additively manufactured glass within a material model. Glass, fundamentally, as described in Section 3.1.1, inherently exhibits completely isotropic properties, which means that it has uniform physical properties in all directions. This characteristic is consistent across all known glass products to date. The strength of these isotropic glass products is defined by their surface's notch sensitivity under tensile stress. The notch effects result in stress concentrations at the crack base under tensile load, leading to the brittle glass fracturing. Given that these notches are randomly distributed across the local flat surface of a standard glass product without any specific orientation, this strength behavior is isotropic.

The behavior of these notch openings can be described through the types of crack opening according to Gross et al. [63] in Figure 3.3, which lay the foundation for linear elastic fracture mechanics. For glass, under the assumption of single-mode strain, only Mode I is of interest, since it possesses the highest stress intensity

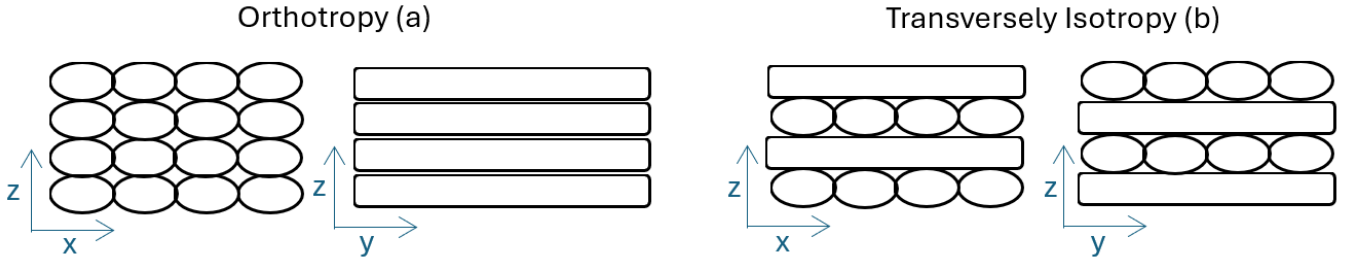


Figure 3.2.: Individual rods of an FDM process are deposited in one direction, resulting in orthotropic material behavior, and deposited crosswise, resulting in transversely isotropic material behavior.

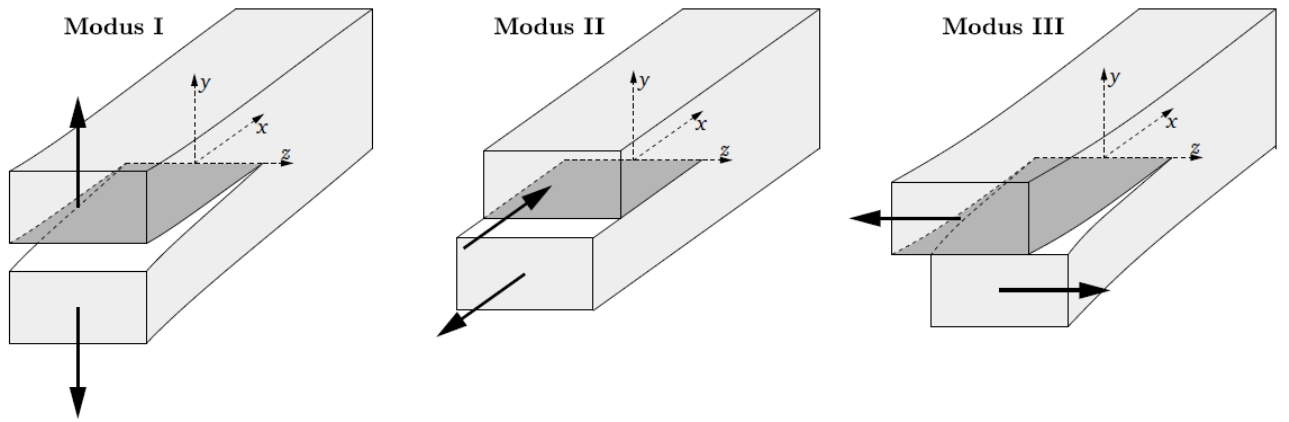


Figure 3.3.: Crack opening modes according to Gross et al. [63]: Mode I separation due to tensile loading; Mode II separation due to longitudinal shear; Mode III separation due to transverse shear.

coefficient K_I alongside the lowest fracture toughness K_{Ic} [110]. It is anticipated that the process of AM Glass, by intentionally introducing notches in a specific direction, will favor failure in Mode I. This hypothesis is based on presumed greater crack length of the notches and also the frequent alignment of notches longitudinal to the AM Glass notch. This assumption needs to be verified and will be discussed conclusively in Chapter 5.

Failure of these critical notches due to shearing (Mode II and Mode III) is not expected due to the lower fracture toughness K_{IIc} and K_{IIIc} for these modes [107]. Under loading in these directions, a failure under Mode I outside of the critical notches, similar to that of isotropic/conventional glass, is anticipated. The effect of mixed-mode strain remains unclear.

Based on these considerations, this chapter assumes a transversely isotropic strength behavior for 3D-printed glass bodies, with reduced strength perpendicular to the AM notches and identical strengths longitudinal to the AM notches. This assumption remains contingent on the varying orientation of the layers, as shown in Figure 3.2.

It is important to mention that this transversely isotropic material model primarily pertains to the glass 3D printing process utilizing FDM or DED techniques. Experience with other materials has shown that, for instance, the SLA process exhibits no anisotropy. Furthermore, appropriate post-processing combined with extremely accurate process control could potentially make the FDM or DED process for glass nearly isotropic.

Typically, in the simulation of anisotropic materials, both the Young's modulus and Poisson's ratio are varied depending on the axis. Strictly speaking, due to geometric changes of 3D-printed glass, an adjustment of at least the Young's modulus should be made. However, this adjustment is neglected under the assumption that the notches are quite small and do not significantly influence the Young's modulus. This assumption would need to be investigated through testing.

3.1.2.2. Strength properties

For the subsequent optimizations, maximum allowable stress properties are defined. Three approaches are discussed:

- Experimental results of Inamura et al.
- Experimental results of Chhadeh et al.
- Theoretical strengths with calculations according to Tada.

Inamura et al. [73] conducted initial mechanical investigations on objects printed with the MIT FDM glass printer in 2018. They printed vertical objects from soda-lime glass and cut test specimens from these prints. In total, Inamura tested four specimens using a three-point bending test, two of which were annealed and two tempered. They found an average strength of $\sigma = 41 \text{ MPa}$ for the weak axis and $\sigma = 51 \text{ MPa}$ for the strong axis. Surprisingly, there was no significant difference in strength between the annealed and tempered specimens, which could be attributed to the reduced edge strength due to the cutting process. But due to the small number of specimens, the results are statistically inconclusive.

Chhadeh et al. [18] carried out additional mechanical tests in 2023 with specimens that were printed on a base plate at LZH Hannover using the DED process (cf. Figure 1.7). This process involved printing quartz glass onto a quartz glass plate. The three-point bending tests performed by Chhadeh do not allow conclusions regarding the strengths of AM Glass, as the crack origin in the specimens was located at the edge of the glass plate and not within the AM area. The results of the conducted shear tests provide reference values for the strength along the plane (primarily Modes II and III, resulting in mixed-mode strain with Mode I) but fail to address the anticipated weaker strength normal to the plane.

Due to the lack of reliable values or experiments, it is feasible to estimate the strength values. Here it involves determining crack coefficients from Tada's handbook for linear-elastic fracture mechanics [120] and reducing the strength based on chosen crack geometries.

The estimation is relevant for failure in Mode I (cf. Figure 3.3), assuming a long surface crack on a semi-infinite body for this modeling as shown in Figure 3.5 (a). In a chemically inert environment, the Mode-I stress intensity factor is represented as:

$$K_I = \sigma_a \cdot Y \sqrt{\pi \cdot c} \quad (3.1)$$

Here, K_I represents the stress intensity factor, σ_a the stress load, Y a geometry factor, and c the crack depth.

An overview of various geometry factors (Y) for the case at hand is presented in Table 3.2. The overhang in layer notches, as shown in Figure 3.5 (c), predisposes a preference for the geometry factor Y regardless of the stress distribution's shape at the crack. Consequently, the worst-case value $Y = 1.122$, similar to flat glasses, is adopted. However, it remains uncertain whether the surface geometry contributes to increased stress σ_a in the crack and its distribution. Due to layer deposition, a greater crack depth compared to float glass is expected in the notches. This crack depth is estimated at $270 \mu\text{m}$, and therefore is assumed to be approx. 4

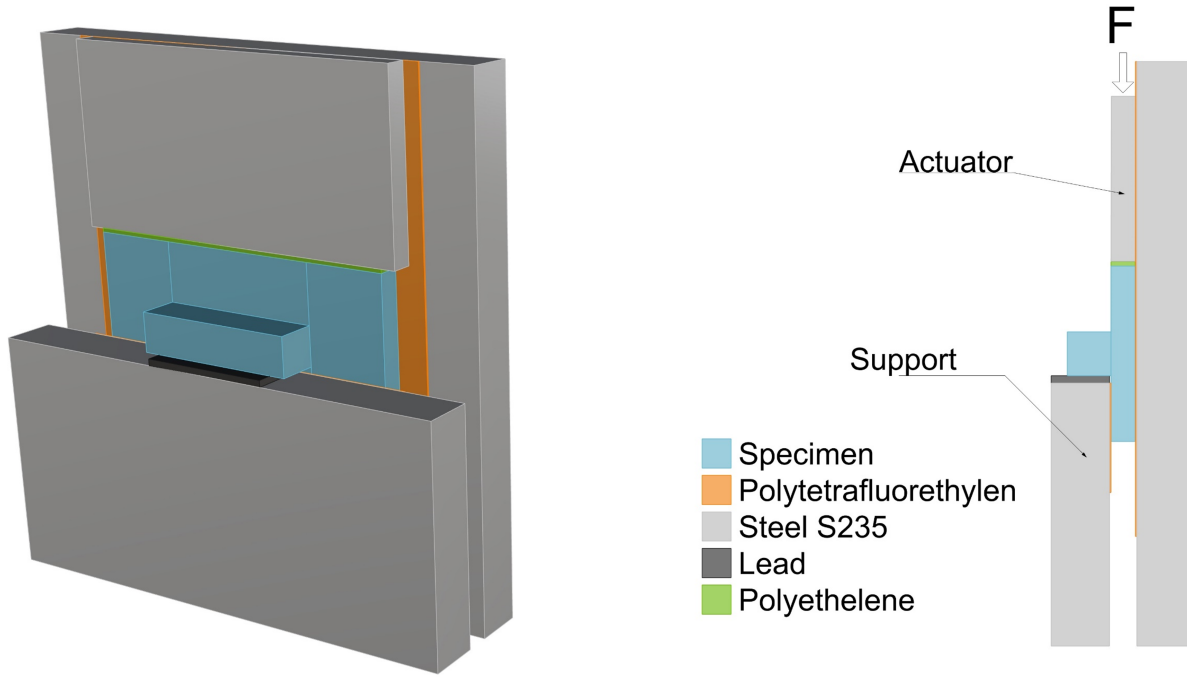


Figure 3.4.: Experimental setup of shear tests on AM Glass components printed on glass plates by Chhadeh et al. [18].

Table 3.2.: Geometry factors Y for different overhang angles (see Figure 3.5) and for different applied stress distributions in the crack (see Figure 3.6b). Y was calculated based on the approaches according to Tada [120].

Overhang:	0°	10°	20°
Y for const. σ_a :	1.122	1.054	1.006
Y for linear σ_a :	0.438	0.396	0.366

times larger than the case with flat glass. If this crack depth is accurate for a theoretical 3D printing process, the following maximum stress load in z-direction is derived:

$$\sigma_a = \frac{K_{Ic}}{Y\sqrt{\pi \cdot c}} = \frac{0.75 \text{ Nmm}^{-2} \text{m}^{1/2}}{1.122\sqrt{\pi \cdot 0.00027 \text{ m}}} = 23.0 \text{ MPa} \quad (3.2)$$

with $K_{Ic} = 0.75 \text{ Nmm}^{-2} \text{m}^{1/2}$ for soda-lime glass in Mode I [84].

The assumed strength in XX- and YY-directions (Coordinates as in Figure 3.2 - like normally used in AM), based on float glass strength ($f_{k,x} = f_{k,y} = 45 \text{ MPa}$), is approximately twice that of the determined σ_a for the ZZ-direction. These values are adjusted by the partial safety factor for float glass ($\gamma_M = 1.8$) and the wind stress loading coefficient ($k_{mod} = 0.7$), as indicated in 2.9. Furthermore, a safety factor is introduced for AM Glass to compensate for the current lack of strength data for AM Glass. This safety factor is estimated at $\gamma_{AMGlass} = 1.2$. Therefore, the strength assumed for this chapter is the following:

$$R_{d,z} = \frac{f_{k,z} \cdot k_{mod}}{\gamma_M \cdot \gamma_{AMGlass}} = \frac{23 \text{ MPa} \cdot 0.7}{1.8 \cdot 1.2} \approx 7.5 \text{ MPa} \quad (3.3)$$

and

$$R_{d,x,y} = \frac{f_{k,x/y} \cdot k_{mod}}{\gamma_M \cdot \gamma_{AM_{Glass}}} = \frac{45 \text{ MPa} \cdot 0.7}{1.8 \cdot 1.2} \approx 15 \text{ MPa} \quad (3.4)$$

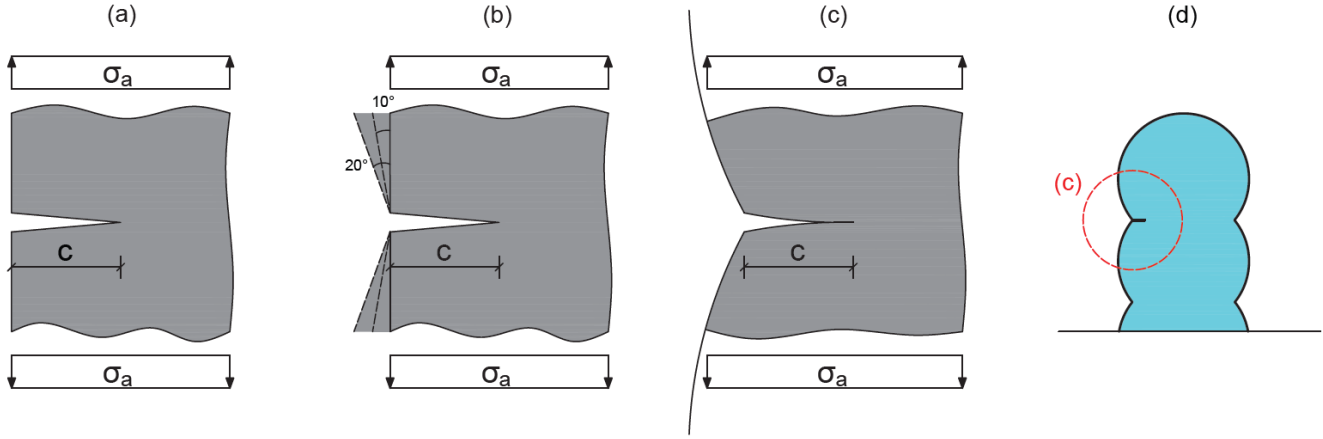


Figure 3.5.: Surface crack on semi-infinite body under Mode I loading: Crack geometry for a flat surface (a), for different overhang angles (b) and for a realistic surface of AM Glass (c), where (d) shows the corresponding cross-section of AM Glass layers.

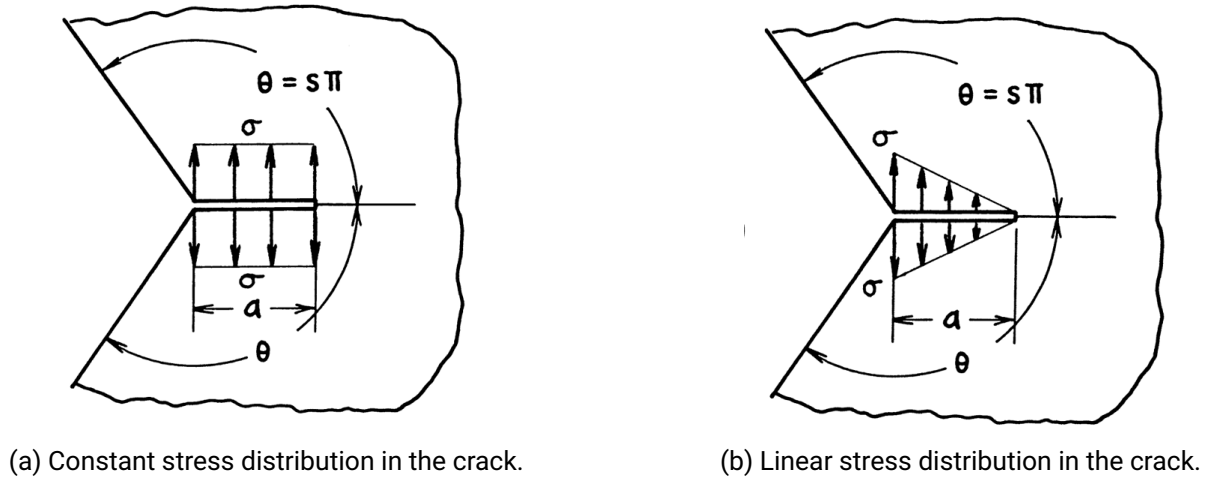


Figure 3.6.: Two-dimensional stress solutions for cracks with overhanging configuration from Tada [120]

It is proposed that the AM Glass safety factor be assigned on a process-specific basis and determined through medium-term experiments. Depending on the efficacy of the AM Glass process, the safety factor could be < 1 if the assessed strength of AM Glass exceeds that of float glass. This safety factor could facilitate the process-specific certification of AM Glass without the need for component testing (cf. Section 2.5).

These strength values are assumed for initial optimizations. All other physical and mechanical properties are adopted from the isotropic material. The verification of these values will be conducted in Chapter 4.

3.2. Topology optimization algorithms

3.2.1. Basics

Topology optimization (TO) is a computational technique used in engineering to distribute material within a given design space optimally, based on predefined load conditions and objective functions. This approach seeks to maximize or minimize a performance criterion, such as stiffness or weight, under a set of constraints, thereby enabling designers to explore innovative structural configurations and material distributions.

The classic form of a TO problem can be expressed as [95]: Given an initial design space D , the objective is to identify an optimal topology that minimizes an objective while satisfying several constraints,

$$\begin{aligned} & \underset{\Omega \subset D}{\text{minimize}} \quad f(\Omega, \mathbf{u}) \\ & \text{subject to} \\ & g_i(\Omega, \mathbf{u}) \leq 0, \quad i = 1, \dots, N, \\ & \mathbf{K}\mathbf{u} = \mathbf{f}, \end{aligned} \tag{3.5}$$

where:

- D : Design space
- Ω : Optimized design
- f : Objective
- g_i : Constraints (such as volume, displacement, etc.)
- $\mathbf{u}$: Displacement vector
- $\mathbf{K}$: Stiffness matrix
- $\mathbf{f}$: External force vector

One of the most prevalent objectives in TO is compliance, where the approach is relatively straightforward. However, for the design of functional components, it becomes essential to also focus on minimizing stress, a task made challenging by the local and non-linear relationship of stress to design variables. This situation often leads to a significant number of constraints for problems of even moderate complexity [67], while the non-linearity complicates the optimization process's convergence. Owing to these difficulties, efforts directed towards strength optimization have been less frequent compared to those aimed at stiffness, with even fewer considering the use of anisotropic materials [95, 67].

A general flowchart for topology optimization approaches is given in Fig. 3.7

Subsequently, a concise overview of some of the most renowned topology optimization algorithms is provided.

3.2.2. Solid Isotropic Material with Penalization (SIMP)

The most used TO method is Solid Isotropic Material with Penalization (SIMP). SIMP introduces a pseudo-density variable for each element in the design domain, interpolating between solid and void states, respectively between 1 and 0. The material stiffness is penalized in intermediate densities to discourage their presence in the final design. The mathematical model involves modifying the elasticity tensor as a function of the density, $E(\rho) = \rho^p E_0$, where E_0 is the stiffness of the solid material, ρ is the density, and p is the penalization factor.

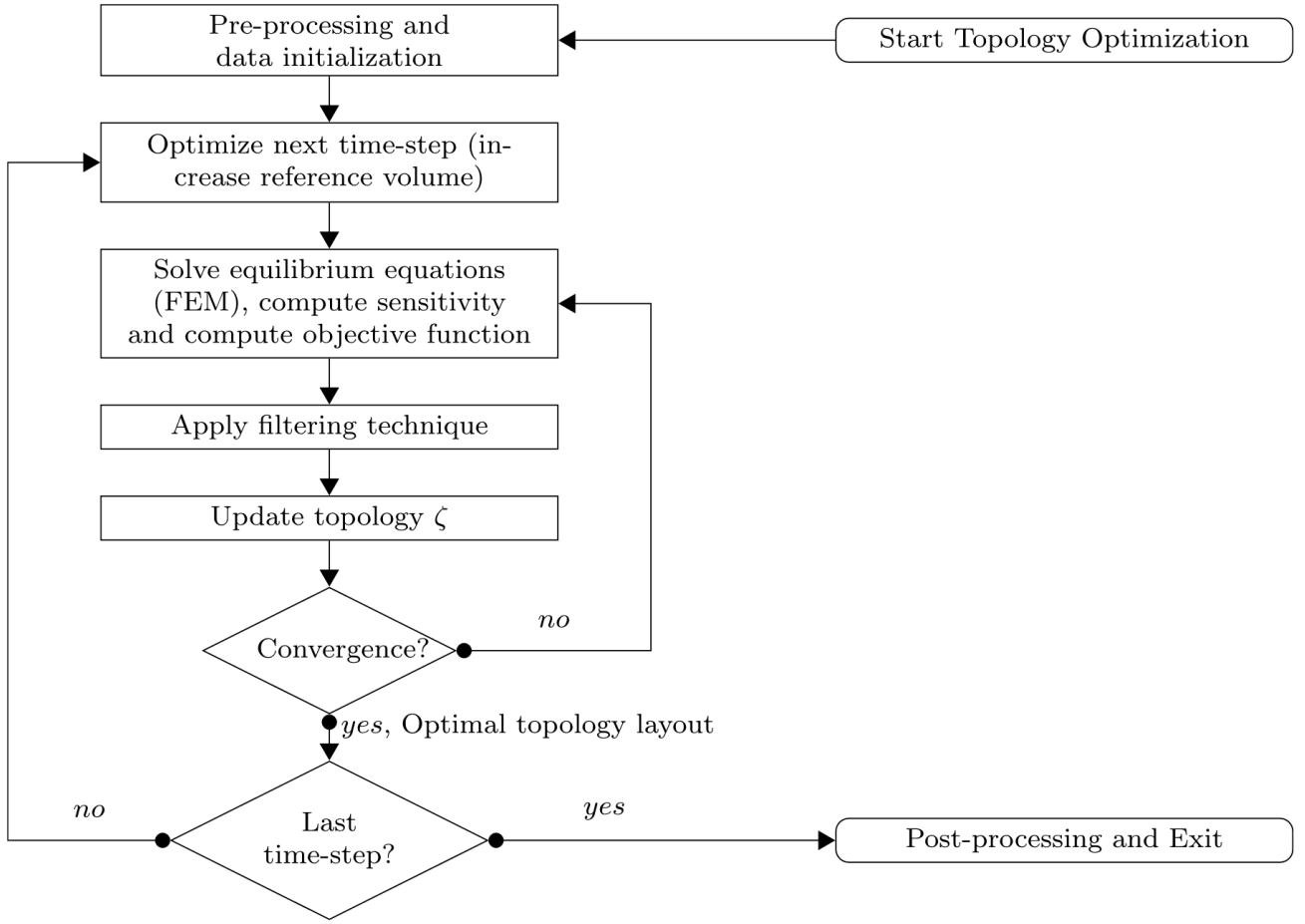


Figure 3.7.: Flowchart for general topology optimization approaches. Yago et al. [128]

SIMP is widely used due to its simplicity and effectiveness in achieving clear, manufacturable designs for isotropic materials. It is particularly effective for problems with a single load case and where compliance (total displacement of a structure under applied loads) minimization is the goal.

3.2.3. Level-Set method (LS)

The level-set (LS) method is another popular approach for TO, where the boundaries of the design are defined as zero level sets of a scalar level-set function. In the conventional form, the Hamilton-Jacobi partial differential equations have to be solved to update design boundaries:

$$\frac{\partial \phi}{\partial t} + F|\nabla \phi| = 0 \quad (3.6)$$

ϕ denotes the Level-Set function representing the geometry of the structure to be optimized. t refers to time or an iteration step, F is a velocity function indicating the interface's motion speed, and $|\nabla \phi|$ is the gradient of the Level-Set function, highlighting the direction of steepest ascent. More in-depth information on the

mathematical foundation of LS can be found in [99]. This method allows the shape to change smoothly during the optimization process, adjusting the structure's design to improve its performance. It is highly beneficial for problems requiring precise control of smoothness and complexity.

Some methods are described to implement this method to anisotropic material problem, but due to their complexity they are yet to be exploited in efficient algorithms [95].

3.2.4. Evolutionary Structural Optimization (ESO) and Bi-directional ESO (BESO)

Evolutionary Structural Optimization (ESO) algorithm iteratively removes material based on stress criteria. Bi-directional ESO extends the idea of ESO by allowing not just the removal of material but also the addition of material in areas where it can significantly enhance performance. This process continues until a balanced, optimized structure is achieved that meets the design goals, such as minimum weight or maximum stiffness. ESO and BESO is favored for its simplicity and intuitive approach. However, it may not always converge to the global optimum and might be more suited for preliminary design phases or simpler optimization problems.

3.2.5. Moving Morphable Components (MMC)

Moving Morphable Components (MMC) focuses on optimizing shapes and topologies by moving, adding, or removing predefined components within the design space. By the use of predefined components MMC provides a direct link between design variables and geometric features, simplifying the optimization process and enhancing the ability to produce practical design [23].

3.2.6. Topology optimization algorithms for anisotropic materials

While publications on isotropic TO have been available for 30 years, publications on TO algorithms for anisotropic materials with corresponding implementation into functional, 3-dimensional models have only been available since 2016 [129].

Most of these approaches are based on the Tsai-Hill or Tsai-Wu strength criteria. Tsai-Hill is a simpler/less flexible strength criteria for anisotropic material and can only consider linear stress-strain relationships without accounting for differences between tensile and compressive strengths. Based on these strength criteria, a variety of approaches have been developed [95][129][115], which are mostly advancements of existing isotropic material algorithms. As this field is quite new, no dominant algorithms have emerged yet, nor has a categorization been established as is the case with isotropic optimization. The computation of these algorithms is highly complex due to the multitude of mathematical parameters involved. In the case of Tsai-Hill for orthotropic material, these include:

- 3x Young's Modulus E in 3 spatial directions
- 3x Shear Modulus G
- 3x Poisson's ratio ν
- Density ρ
- 3x maximum allowable stress in 3 axes (necessary depending on the algorithm and objective)

-
- Additional information on fiber size, etc.

It is generally noted that there is a significant leap from the formulation of fundamental algorithms to their implementation in functioning software. This step, unlike the fundamental algorithms, is poorly documented and often remains a corporate secret. Paramatters®, with their software CogniCAD™, are the first ones capable of performing anisotropic (specifically orthotropic) topology optimization, and have not released information that allows for conclusions about the functioning of their software. Upon inquiry, the author was only confirmed that the Tsai-Hill criterion is used and some form of continuous fiber angle optimization (CFAO) is employed. CFAO was developed for the optimization of fiber-reinforced composite materials and enables efficient alignment of fibers within a material. CFAO typically relies on gradient-based optimization methods or genetic algorithms. In addition to CogniCAD™, it is currently only possible to optimize anisotropically via Optistruct®, although this is not implemented by default, but can be achieved via appropriate detours.

3.2.7. Explanation of typical setting parameters

Typical setting parameters for optimizations with TO softwares, as used in section 3.4, are explained below:

- Objective: Specifies the goal of the optimization, such as minimizing material use while maintaining structural performance. It's the primary target the optimization algorithm seeks to achieve.
- Constraint: Sets the conditions the design must adhere to, such as overhang, symmetry, or maximum displacement.
- Max. Iterations: Limits the number of iterations the algorithm performs, balancing between computational time and the need for a convergent solution.
- Min. Objective Change: Determines the minimum change in the objective function between iterations required to continue the process, helping to identify when the solution has sufficiently converged.
- Min. Density Change: Similar to the minimum objective change, this threshold identifies convergence by monitoring changes in material density distribution between iterations.
- Boundary Penalty: Discourages material concentration at the design space boundaries, promoting more practical and evenly distributed solutions.
- Threshold: Determines what portion of the material distribution is considered solid in the final output, affecting the topology's crispness and manufacturability.

3.3. Available and tested software

The software underpinning topology optimization plays a pivotal role in the success of the optimization process. This importance extends beyond the mere selection of an algorithm, discussed in the preceding chapter, to encompass computational demands, configuration options, and the broader capabilities for setting constraints and objectives.

An overview of the software evaluated or utilized is provided in Table 3.8. This table contrasts the capabilities of the software based on user experiences within the context of this thesis.

Software	Version	License	Goals		Constraints					
			min. Compliance	min. Mass	Compliance	Deformation	Stress	Mass	Overhang	Symmetry
ANSYS	2023 R3	Education	Yes	No	No	Yes	No	Yes (min. 10%)	Yes (27-89°)	Yes
Altair Inspire	2022.3	Education	Yes	No	No	No	No	Yes (min. 15%)	Yes	Yes
Altair OptiStruct	2022.3	Education	Yes	No	No	No	Yes	Yes	Yes	Yes
Autodesk Fusion360	2023	Full	Yes	No	No	No	No	Yes (min. not tested)	Yes (not tested)	Yes
nTop	4.20	Education	Yes	No	No	No	(Yes, iso)	Yes (min. 10%)	Yes (30-89°)	Yes
Hexagon MSC Apex GD	2023.3	Test	Yes	No	No	No	No	Yes (min. not tested)	Yes (not tested)	Yes
Paramatters CogniCAD	-	Expert	Yes	Yes	Yes	Yes	Yes, iso+aniso	Yes (min. 20%)	Not working	Yes
Grasshopper	-	-	Yes	No	No	No	No	Yes	No	Yes
Matlab from Rutsch	-	-	-	Yes	Yes	Yes	Yes	No	No	Yes

Software	Version	License	Material			Linearity	
			isotropic	anisotropic	multimaterial	linear	non-linear
ANSYS	2023 R3	Education	Yes	No	No	Yes	No
Altair Inspire	2022.3	Education	Yes	No	Yes	Yes	Yes
Altair OptiStruct	2022.3	Education	Yes	No	Yes	Yes	Yes
Autodesk Fusion360	2023	Full	Yes	No	No	Yes	No
nTop	4.20	Education	Yes	No	Yes	Yes	No
Hexagon MSC Apex GD	2023.3	Test	Yes	No	No	Yes	No
Paramatters CogniCAD	-	Expert	Yes	Yes	Yes	Yes	No
Grasshopper	-	-	Yes	No	No	Yes	No
Matlab from Rutsch	-	-	Yes	No	No	Yes	No

Figure 3.8.: Overview of most commercial TO software and their capabilities based on user experience.

3.3.1. Fundamental challenges in TO software for this task

In addressing the task at hand with TO software, several fundamental challenges emerge:

- The goal of minimizing material usage within a large design space poses a significant hurdle, as the mass goal for an optimized glass plate structure lies between 0.1 and 1% of the design space for plate dimensions up to 3 m x 3 m.
- The aim for a resolution of a few millimeters, to reach performant structures. Pushed computational capabilities to their limits.
- The unique aspect of the design involving the load-bearing and bearing plate being identical, which introduces specific challenges in transmitting forces without direct contact between them.
- The integration of the optimized mass to the large base plate with non-necessary mass to meet constraints
- The impact of nonlinear calculations remains uncertain.
- Fulfilling overhang angle constraints.
- Consideration the maximum stress/strength of the material is uniquely addressed by Optistruct® and CogniCAD™
- Finite element method (FEM) anomalies possible with single-edge bearings
- Joint bearings introduce challenges in contrast to fixed bearings
- The limited documentation on the software’s functionalities necessitates a critical examination and verification of the results.

3.3.2. SOTA TO software with minimum mass goal under stress and deformation constraints

Optimizing glass plates in this thesis necessitates adherence to stress and deformation constraints, diverging from typical TO goals of compliance minimization under given material constraints. Instead, the aim is to minimize mass while adhering to maximum stress and deformation limits.

Such numerical algorithms are current under research, primarily in academic filed . Rutsch from the Institute of Cyber-Physical Simulation (CPS) at TU Darmstadt is expected to unveil novel algorithms by mid-2024, capable of maintaining stress and deformation constraints. An alternative approach is embodied in the software CogniCAD® by Paramatters.

3.3.3. Paramatters CogniCAD®

CogniCAD®, introduced at Formnext® in 2018, targets lightweight optimization tailored for additive manufacturing. It streamlines the workflow from importing initial geometries to exporting optimized designs, facilitating engineering requirements optimization, such as stress and deformation constraints, and uniquely offers comprehensive anisotropic topology optimization.

The operational details of CogniCAD® remain proprietary, with no information disclosed upon inquiry, likely to protect trade secrets.

For this thesis, Paramatters' co-founder and CTO, Dr. Michael Bogolomy, kindly provided access to CogniCAD® and computational resources for testing. The software promises to be the solution to the occurring problem. It aims to minimize the mass of glass plate structures while meeting stress and deformation criteria, including the capability for Tsai-Hill stress limit specification to account for the orthotropic strength behavior of AM glass and perform orthotropic TO, which in this case would be introduced by slightly different Youngs moduli of AM Glass through the notches. Multi-material optimization is a standard feature in CogniCAD®, allowing for different strengths and properties at the junction between AM components and the base glass plate in comparison to the AM part and the base plate.

With test files of fixtures, as they are common in TO for mechanical engineering, the software works error-free, extremely fast and user-friendly. The anisotropic topology optimization is performant and even outputs an optimized g-code for the alignment/printing direction of the individual layers.

In over 160 experiments attempting to optimize glass plate structures, all available settings were tested, including dimensions, overlaps between non-design spaces and design spaces, support conditions, material parameters, and optimization settings. Consultations with the developers were sought for support conditions and domain overlaps.

Fourteen versions of base geometries were developed for the experiments. Version 1 represents the initial geometry (plate + design space). Subsequent versions involved designing supports as separate geometries, varying their dimensions and the extent of overlap with the base plate and design space. Both two-sided and four-sided supports, as well as point supports at the plate's four corners, were evaluated. Variations within these versions included material parameters, support settings (entire bodies or surfaces and their rotational freedoms), and optimization settings (overhang, goals, constraints, mesh size). Optimization processes were outsourced to a server, enabling numerous simulations to be run simultaneously, significantly simplifying the testing process. Validation was conducted through FEM analysis included in the optimization, CogniCAD®'s FEM validation tool and external validation via Ansys®.

Figure 3.9 shows the user interface of the software and the results of Version 12 in testing. Figure 3.8 shows the settings that can be made for optimization.

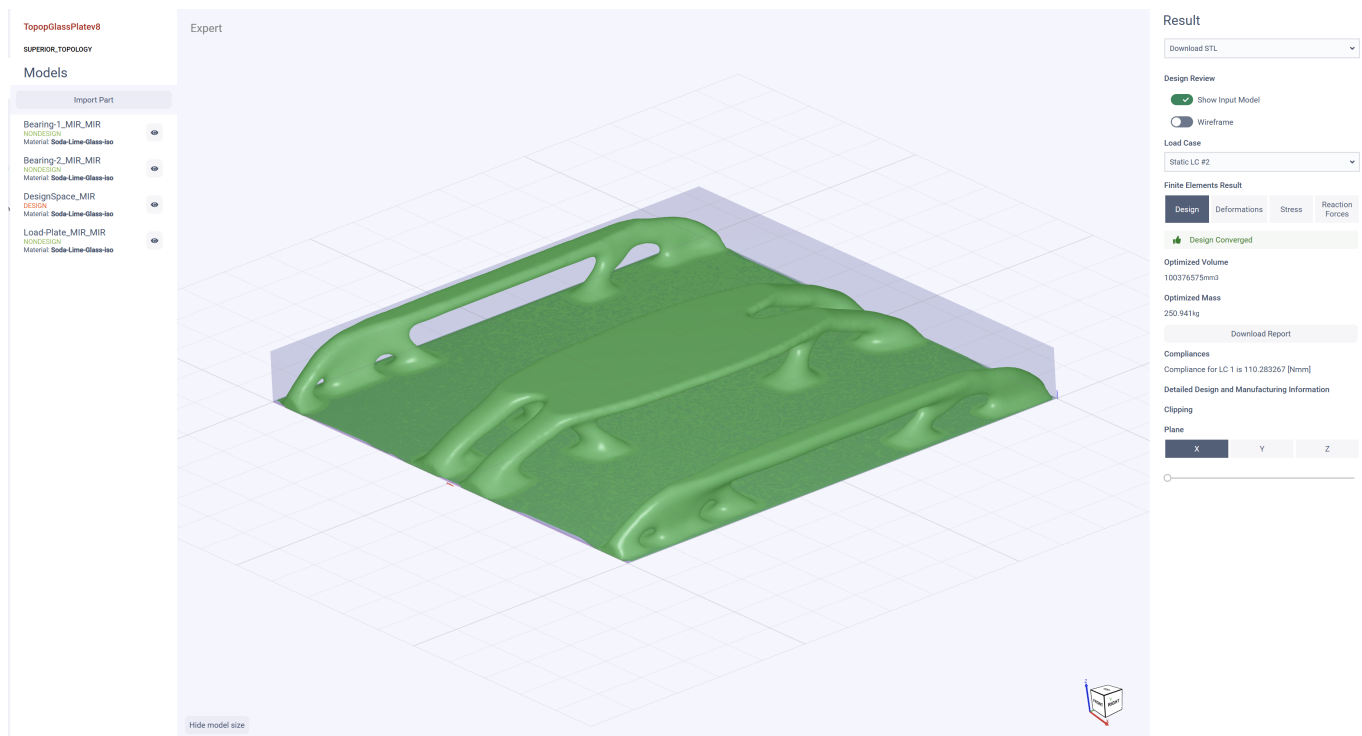


Figure 3.9.: Interface of Paramatter's CogniCAD™ with the results of the test v12.1

However, the optimization results from CogniCAD® were found to be non-viable due to:

1. Significant geometric changes with minor setting adjustments such as symmetry conditions or AM overhang angles
2. Inconsistencies in AM overhang angle adherence
3. Variable deformation cases with unchanged settings
4. Deformation and stress values provided by CogniCAD® could not be validated through independent FEM calculations
5. FEM calculations supplied by CogniCAD® for validation also proved inaccurate
6. Frequent optimization failures with errors, lacking explanations or error message insights

Figure 3.10 presents the deformation from the FEM analysis for Version 12 (3.9). Although the optimization outcome did not meet the initial requirements, the results from the internal FEM analysis could not be corroborated by analyses conducted with Ansys®. Minor modifications to the inputs of Version 12 resulted in errors, while others led to greater deviations from the input requirements. The software significantly lacks explanations in this regard.

The developers could not pinpoint a cause for these issues. The performance gap between CogniCAD® and its competitors, coupled with the name "Cogni"CAD, suggests a basing on deep learning (DL) algorithms,

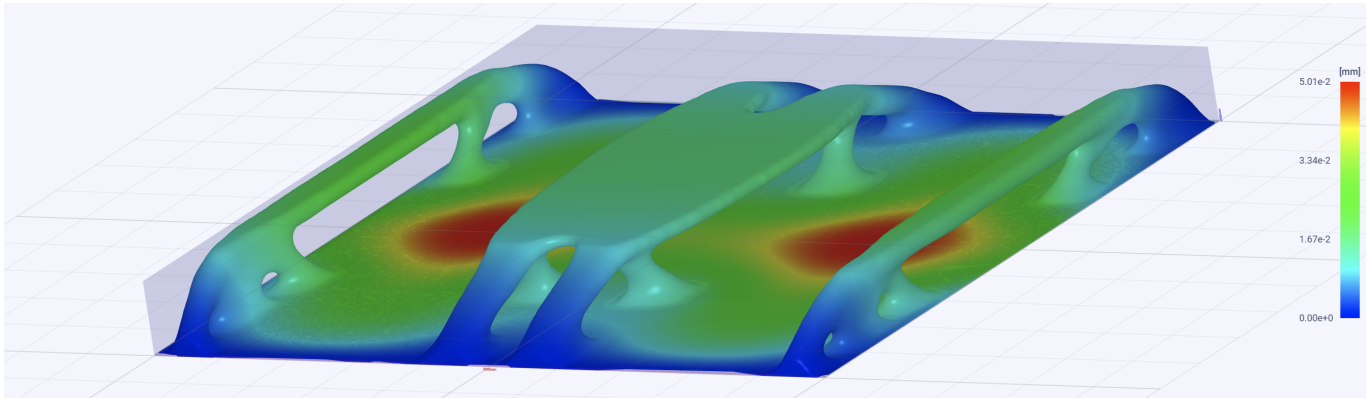


Figure 3.10.: Deformation of v12.1 in the dimensions of 3000 mm x 3000 mm according to the FEM analysis of CogniCAD®. The FEM results could not be validated via Ansys®.

potentially in conjunction with numerical algorithms. Such approaches are documented in literature, with a general methodology depicted in Figure 3.11.

The uncommon structures of glass plates, differing significantly from the typical small, fixed components in mechanical engineering, suggests a lack of appropriate training data for the DL algorithm to produce reliable results for the desired optimization case.

Further investigation in this domain is recommended, approaching developers with legitimate interest and financial incentives under confidentiality agreements to learn more about how the software works. Should the DL-based TO assumption hold, training the software with suitable data could yield reliable optimizations for this application, offering immense advantages in glass plate structure optimization by fully leveraging the material under specified requirements.

Key advantages with this software include:

- Lower computational demand compared to numerical algorithms
- Accurate and unrestricted selection of overhangs/manufacturing constraints
- Multi-material modeling, particularly for interfaces
- Orthotropic modeling for both strengths and other material properties
- Simultaneous optimization for stress and deformation
- Simplified workflow

Long-term, such software could revolutionize engineering and architectural practices by enabling quick, individualized glass plate optimizations for individual impacts, conditions, and AM processes, avoiding any material wastage. The calculation time is approx. 30 min. for isotropic modeling under the given case. The ease of workflow with CogniCAD® significantly outpaces other TO software, which generally requires extensive TO knowledge, elaborate preparation and post-processing steps, and substantial computational resources. The shift of this process to planning and executing engineering or architectural offices is tangible with CogniCAD®.

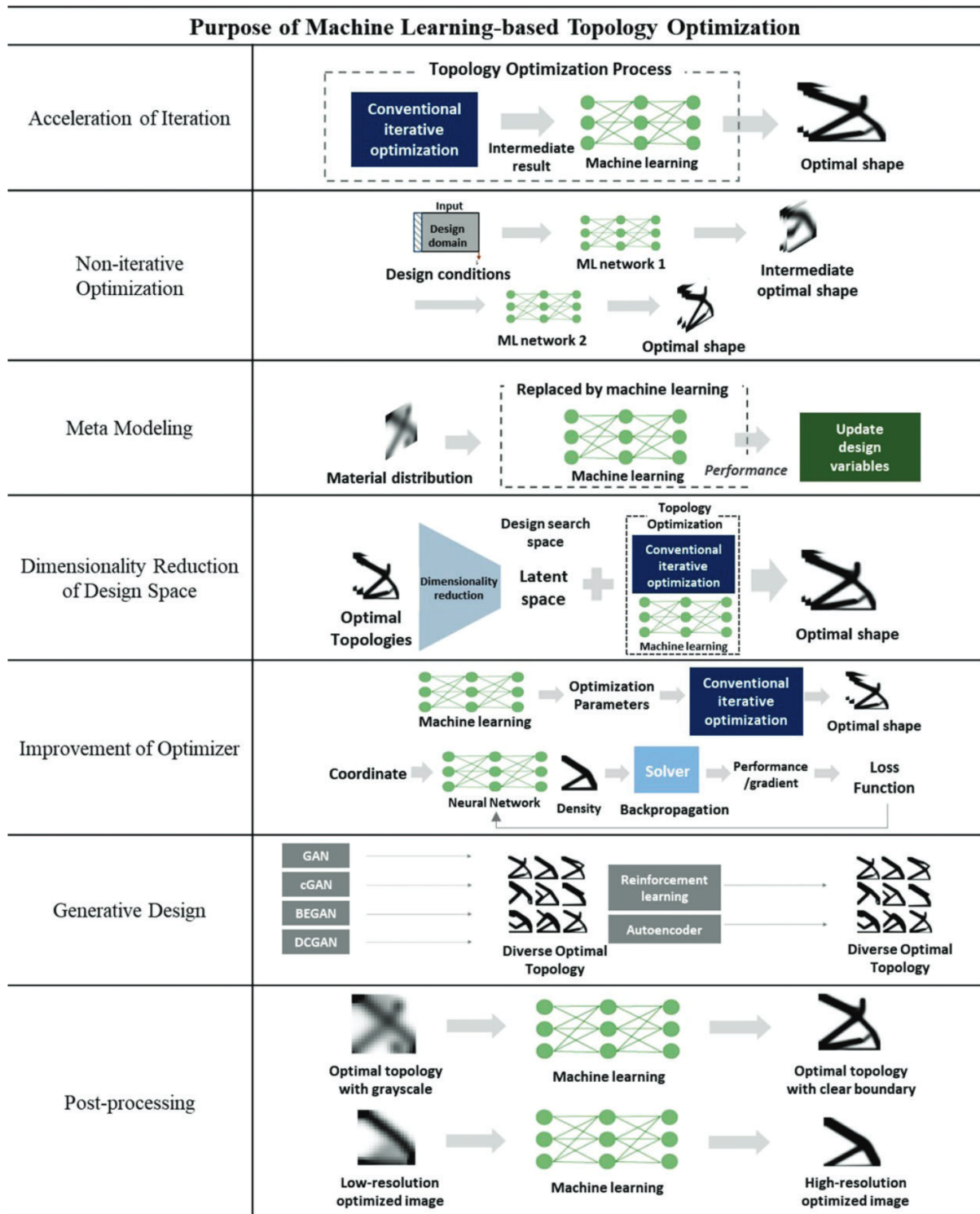


Figure 3.11.: Visualization of the methodology of TO with machine learning purpose. Shin et al. [114]

3.3.4. Matlab Code by Felix Rutsch

Felix Rutsch from the CPS Institute at TU Darmstadt has developed a Matlab-based (a numerical calculation environment) program following the latest developments in TO, capable of considering both stress and deformation constraints to minimize component mass. To solve the TO problem, Rutsch employs the Augmented Lagrangian Method to convert the problem into an unconstrained one. The optimization is then carried out using a gradient-based approach through the steepest descent method. A corresponding publication is in preparation.

This script is currently only capable of 2-dimensional optimization. Rutsch kindly provided this program for this thesis. Initial approximations and optimizations were created in the following chapter and an attempt was made to extend them to 3-dimensional space. An implementation of the algorithm in 3-dimensional space is planned for the medium term.

3.3.5. Ansys®

All software from this point on belongs to the category of traditional topology optimization (TO) software, which can only optimize towards maximum compliance.

Ansys® is one of the largest simulation software suites for practically all engineering fields. It includes a topology optimization function as one of its module components. With Ansys®, design, post-processing, validation, and parameterization around topology optimization can be easily implemented within the same software environment.

The underlying algorithm is the Solid Isotropic Material with Penalization (SIMP) method as a dual approach. This allows for a number of constraints to be specified, which are quite limited:

- Mass target of 10%-99%.
- Overhang constraint, only adjustable from 27°-89°.
- Symmetry condition.
- Deformation condition.

During tests, error messages occurred when attempting to run the solver across multiple kernels. The cause and solution were not identified, limiting computational performance with Ansys®.

3.3.6. Altair Inspire® and Optistruct®

Altair Optistruct® is recognized as the first commercially available software to implement TO. It has evolved significantly but requires in-depth knowledge in both software and TO for effective use. As a result, it has been implemented in Altair Inspire®, which is designed to make TO easier to use with Optistruct.

Experiments with Altair Inspire on glass plates under uniaxial and biaxial stress revealed limitations, including:

- Inability to reduce mass below 20%
- High computational demands limiting mesh size/minimum element size
- Significant differences between nonlinear and linear TO outcomes

-
- Dependence of optimized structures on the design space boundary, with limited customization options for boundary penalties or other settings.
 - Unintuitive results after design space reduction or specifying optimized structure locations

However, Inspire consistently applied the set constraints, uniquely achieving this among the tested software, especially regarding AM overhang.

Altair Optistruct® was for a few experiments also tested, offering limitless customization but complicating usability. Despite these capabilities, Optistruct® struggled to optimize below 20% mass. In addition, the computing effort was higher than with other tested software. Licensing restrictions for educational purposes on servers/high-performance computers limited further exploration with Optistruct®.

With adequate expertise and computing resources, further TO investigations could be justified in this domain. However, since compliance is also primarily minimized here by specifying a mass and not, as is the case with CogniCAD®, the mass is minimized based on stress and deformation conditions, the question is whether the effort is worthwhile here.

3.3.7. nTop®

nTop® is one of the new pieces of software among TO and its implicit modeling sets it apart from the competition and thus offers a number of advantages.

Implicit modeling is a fast and efficient way to model complex part geometry. It does not explicitly calculate edges or vertices (b-rep), doesn't use a mesh, but instead uses a single mathematical scalar field to describe a 3D solid body. This offers many advantages, particularly in terms of computing power, with complex interfaces such as in the case of AM and with Boolean or optimization functions.

Another advantage of nTop® is that an entire workflow is built from programming modules. This means that the initial implementation takes longer, but individual settings and adjustments can be adopted with little effort. These adjustments then automatically run through the workflow to the end. This makes the design process easier, especially if it is not trivial, as is the case here.

In this study, limitations were identified during testing. Even with superior software performance, mesh reduction was constrained by available computational resources. This limitation is partly due to the cubic relationship between element size and number in three-dimensional space and partly because TO algorithms require computational resources disproportionately to the number of elements. Another drawback of nTop software is that constraints are not mandatory. Attempts to optimize often resulted in notifications that certain AM overhang angles could not be implemented, particularly at lower angles, for reasons that remain unclear but are similar to restrictions in ANSYS for small overhang angles.

3.3.8. Other software

Other software packages were also evaluated. Following a brief explanation why they were not further used or investigated in this thesis.

3.3.8.1. Autodesk Fusion360®

TO in Fusion360®, primarily a secondary feature, shows limited performance with minimal customizable design constraints. Consequently, nTop® was integrated into Fusion360® as an extension in 2022 to enhance TO efficiency. However, this thesis relies on nTop® itself, as Fusion360®'s advanced construction features are not required.

3.3.8.2. Hexagon MSC Apex Generative Design®

Apex Generative Design®, a software tailored for specific customers and part of the Apex ecosystem, offers a user-friendly environment with construction features. Its capabilities do not exceed those of comparable software like Ansys®, and licensing is not straightforward, with limited access through the educational version. However, Hexagon's extensive development team, one of the largest globally, may present a potential solution for this unique challenge.

3.3.8.3. Grasshopper® with tOpos

Grasshopper®, often found in the area of modern, parameter-based and computer-aided constructions supports TO with add-ins like Millipede or tOpos, allowing for customizable workflows. However, these plug-ins offer limited settings and lack selectable constraints. Grasshopper® remains a consideration, especially for implementing new algorithms like from Rutsch et al. in a functional environment, providing an accessible platform in conjunction with Rhino for designing topology-optimized, AM-manufactured glass plates.

3.3.8.4. Vrand/Omniquest Genesis®

Genesis® is recognized as the premier software among TO specialists, leading to high licensing costs. A trial version was not obtainable for this thesis. Based on various reports and user experiences, Genesis® might be more capable of addressing this problem compared to other commercial software, yet it requires appropriate licenses and expertise. The feasibility and effort involved warrant further scrutiny.

3.4. Two-sided supported glass plates

3.4.1. Longitudinal consideration as a beam element

To better understand and validate the numerical results of topology optimization, analytical preliminaries for the given problem are conducted. This example is based on the principle that the placement of additional material at points of higher moment or deflection reduces deflection.

This is modeled as follows: A bi-supported plate undergoing uniaxial bending is approximated here by a bi-supported Euler-Bernoulli beam. The following assumptions are made:

- No warping occurs
- Only a one-dimensional stress state occurs

- The effect of shear forces is neglected
- The material is homogeneous and isotropic
- The deflection is so minor that second-order theory can be neglected
- The self-weight is neglected

However, this approximation is only valid as long as the width of the glass plate is significantly less than its length. It is assumed, though, that a violation of this rule does not negatively affect the stiffness of the considered element, as plate and membrane effects positively influence stiffness behavior.

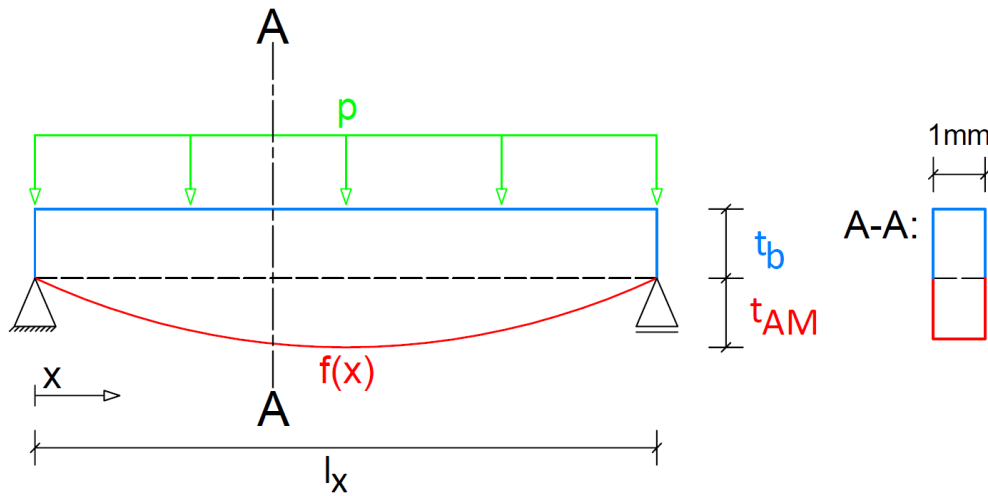


Figure 3.12.: Schematic sketch of a beam element with AM reinforcement following a quadratic curve.

The beam under consideration is schematically shown in Figure 3.12. p represents the acting surface or line load. l_x is the span of the plate. t_b is the thickness of the base plate. t_{AM} is the thickness of the additive manufacturing deposit at its highest point. The curvature of the beam is

$$w'' = -\frac{M_y(x)}{EI_y(x)} = \frac{6 \cdot p(x^2 - l_x \cdot x)}{E(t_b - \frac{4t_{AM}}{l_x^2}x^2 + \frac{4t_{AM}}{l_x}x)^3} \quad (3.7)$$

With the moment line

$$M_y(x) = -\frac{1}{2}p(x^2 - l_x x) \quad (3.8)$$

and the form of the AM deposit, aiming to approximate the moment line

$$f(x) = -\frac{4t_{AM}}{(l_x)^2}x^2 + \frac{4t_{AM}}{l_x}x \quad (3.9)$$

To determine the deflection, the differential equation was analytically solved using a MATLAB script, which is included in the appendix. A deflection curve for a constant plate thickness of $t_b = 18$ mm (blue) and for a base plate thickness of $t_b = 4$ mm with a maximum deposit height of $t_{AM} = 14$ mm (red) is given in Figure 3.13. This was done using a plate length of $l_x = 2$ m, a surface load of $p = 0.00132$ MPa, and a Young's Modulus of $E = 70,000$ MPa, as described in Section 2.6. The deflection for the element with the deposit is significantly larger, albeit with less material usage.

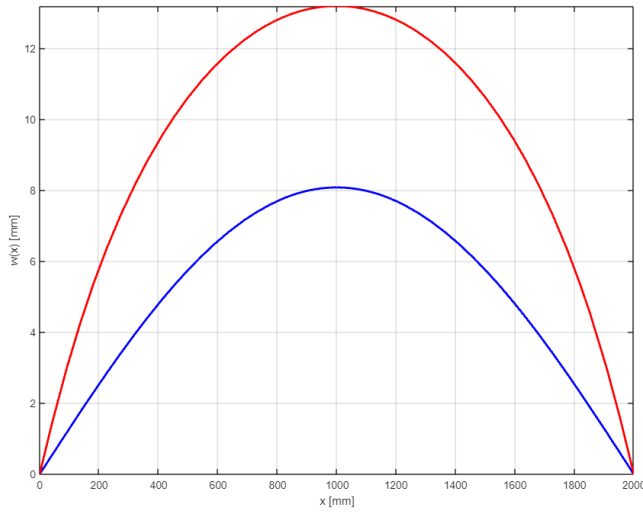


Figure 3.13.: Bending lines of a plate with a constant plate thickness of 18 mm (blue) and a 4 mm base plate with 14 mm imprint height (red).

To achieve identical deflection curves, the maximum deposit height would need to be increased to $t_{AM} = 17.57 \text{ mm}$ (see Appendix Script A.1). Compared to using a $t_b = 18 \text{ mm}$ plate, the example (4 mm plate + 17.57 mm deposit) results in material savings of 12.83% (see Appendix Script A.2).

Subsequently, a base plate thickness of $t_b = 18 \text{ mm}$ is assumed under the same conditions, and the resulting deflection is calculated. In Fig. 3.14, the base plate thicknesses vary between $t_b = 0$ and 18 mm , with the deposit height adjusted so that the deflection matches that of the $t_b = 18 \text{ mm}$ plate. Material savings are read off the y-axis. It is observed that the greatest material saving of 12.84%, for the chosen deposit geometry, occurs at $t_b = 4.02 \text{ mm}$. However, it also shows that as the base plate becomes extremely thin, the deposit becomes inefficient.

This analysis demonstrates that varying the cross-section along the longitudinal axis according to the moment line, compared to a constant cross-section,

can lead to material savings. Considering the self-weight should further increase material savings, as each unit of material saved also reduces the load due to self-weight.

For topology optimization, it is expected that more material will be placed in the center of plates and less material towards the supports, similar to the deposit geometry in Equation 3.9.

3.4.2. Transverse Consideration of the Cross-Section

The bending stiffness of a plate, as defined in plate theory, is:

$$D = \frac{Eh^3}{12(1 - \nu^2)} \quad (3.10)$$

where E is the material's Young modulus, h is the plate thickness, and ν is the material's Poisson's ratio. This bending stiffness D dictates the stiffness behavior of a plate under plate theory but is only applicable to constant, rectangular cross-sections. For non-constant cross-sections, the problem becomes significantly more complex and beyond the scope of this work.

In contrast, the stiffness of an Euler-Bernoulli beam depends on its EI . The moment of inertia I for rectangular cross-sections is given by:

$$I = \frac{bh^3}{12} \quad (3.11)$$

The cubic dependency on height is identical to that of the plate, except that load redistributions, represented in formula 3.10 by ν , do not occur. The principle of static height, meaning placing material as far away from the neutral axis as possible to increase bending stiffness overproportional, thus applies equally to plates and beams.

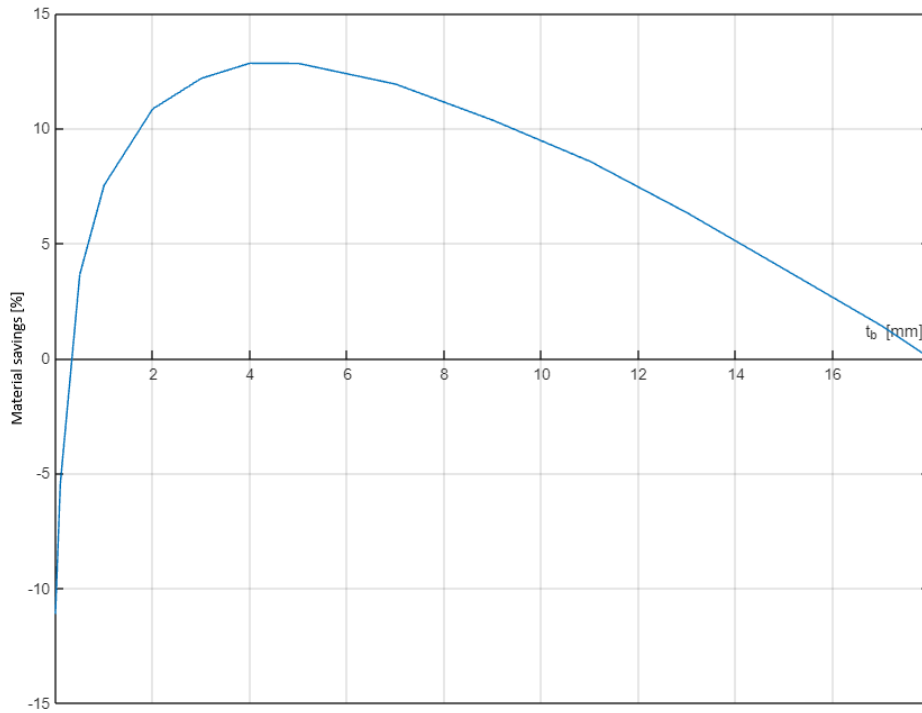


Figure 3.14.: Material savings by varying the base plate thickness and simultaneously adjusting the imprint height t_{AM} so that the deflection is identical to a glass plate with a thickness of 18 mm.

Therefore, it is expected that for limiting deflection with minimal material use in TO, much material will be placed far from the neutral axis, as long as design constraints allow.

3.4.3. Local stresses

The loading of the cross-section shown in Fig 3.15 with a constant moment M allowed the following conclusions to be drawn from FEM calculations:

- The wider the print width w , the lower the local stresses on the print surface (Spearman's rang correlation $\rho = -0.96$).
- The greater the print height h , the higher the local stresses on the print surface ($\rho = 0.91$), but the lower the overall deformation ($\rho = -0.69$).
- The radius r_2 has no impact on the local stresses occurring at the interface (dashed line in Figure 3.15). This is consistent with the theory of a linear uniaxial stress state. The significant correlation ($\rho = 0.84$) between r_2 and local stress are based on the fact that, with an increase in the radius, the corresponding area of the radius moves in positive z-direction with associated increasing stress values. The minimum values, which occur at the interface between plate and AM print, does not change.

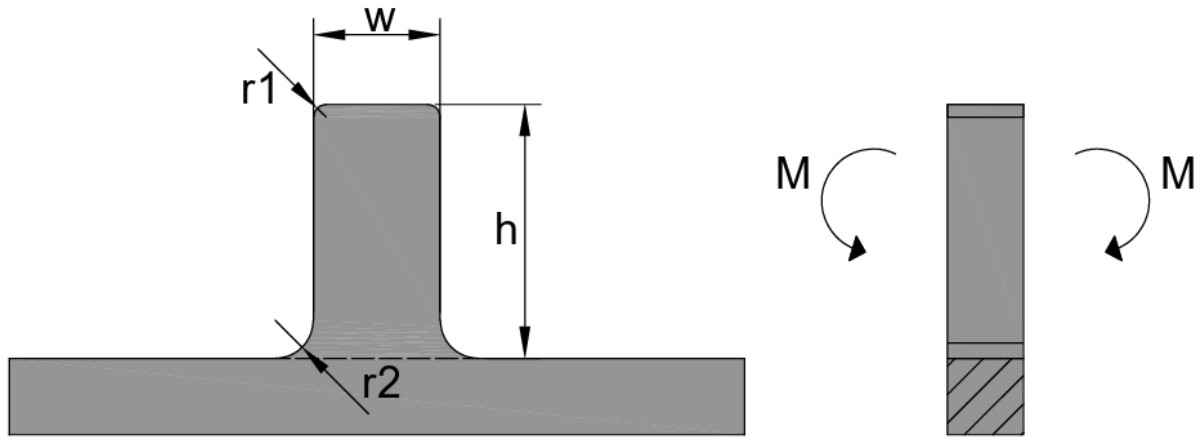


Figure 3.15.: 1 cm wide strip of a rectangular imprint with variable height h , width w and radii r_1 and r_2 on a 4 mm base plate under constant moment load M .

The printed volume is kept constant for comparability. This cross-section is intended to represent the print of a thin-walled stiffening element on a glass plate. The FEM calculations and parameter correlation values can be found in the appendix A.3.

Based on the calculations, it is assumed that in topology optimization, to reduce deflection, a certain print height will appear. To reduce stresses and comply with the given stress criteria, it is assumed that the width will be adjusted at corresponding locations.

3.4.4. Topology optimization 2D

For the 2-dimensional optimization of a specific plate geometry, Felix Rutsch's TO program was utilized with the inputs given in Section 2.6 and 3.1. The resolution was selected as a element size of 4 mm, resulting in a grid of 500 x 50 elements for possible 200 mm print height. The top row of elements was assigned a density of 1 to reconstruct the base plate. The support is configured as a simply supported beam with a span of 2000 mm. Goal for this optimization is minimizing the mass.

The corresponding optimized geometry can be found in Figure 3.16. It was found that the given load is very small relative to the desired stiffness and strength, requiring very little material and resulting in bars smaller than the mesh resolution. Due to the large design space, increasing mesh resolution is challenging as computational effort increases disproportionately with higher resolution. The stress constraint was primarily adhered to during optimization; the deformation constraint could have been omitted.

For a span of 6 m, one half of the corresponding optimized geometry in Figure 3.17 shows the formation of a truss structure, adhering to the above conditions. However, it's noted that the two larger nodes, marked in red, are not fully converged.

The approach with a 2000 mm span was manually reconstructed and validated using FEM. The reconstructed plate has a thickness of 4 mm at the edges, increasing to 15.9 mm towards the center. The FEM results, found in the appendix A.5, show a maximum deformation of 19.8 mm and thus complies with the deformation

$$V_f = 0.0529$$

Figure 3.16.: Resulting geometry of 2D TO of a plate with a span of 2000 mm under deformation and stress constraints aimed at minimizing the component's mass. V_f stands for volume fraction and indicates the proportion of the material volume in the total volume of the design space.

$$V_f = 0.0387$$

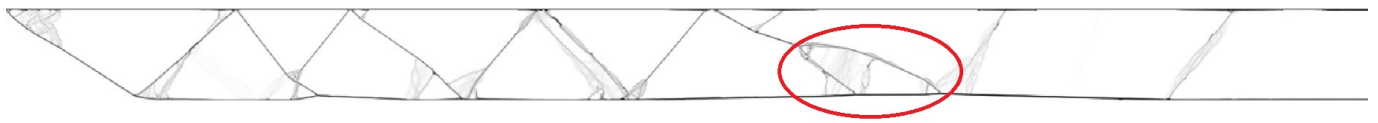


Figure 3.17.: Half site of 2D TO results of a plate under deformation and stress constraints aimed at minimizing the component's mass for a span of 6000 mm. The area marked in red has not converged fully.

criteria from Section 2.6. The maximum value of the first principal stress is $\sigma = 16.4$ MPa, exceeding the given constraint, primarily due to plate effects not considered in the 2D optimization.

An equivalent plate with constant plate thickness, under given conditions and deformation < 20 mm, requires a thickness of 14 mm. The optimized plate thus requires 14% less material. Considering also the stress constraints, the plate must have a thickness of $d = 17$ mm to meet the conditions, equivalent to a material saving of 29%.

3.4.5. Used software for 3D topology optimization

The 3D topology optimization proved to be a challenging problem for several primary reasons:

- A very large design space with low element resolution leads to extremely high computational effort.
- Lack of algorithms that can adequately attach the optimal material under constraints to the base plate, or lack of training data for TO with Deep Learning approaches (CogniCAD™).
- An extremely low mass goal, operating within 1% of the design space.
- Aside from Paramatters CogniCAD™ and Altair Optistruct®, a lack of options to consider global stress values, which are primarily decisive for this problem (cf. 2D-TO in 3.4.4).

As mentioned in the previous section, CogniCAD™ was unable to meet the desired requirements and did not provide understandable, reliable results for this problem. However, CogniCAD™ remains a solution if trained with appropriate data or rather if the software is adjusted by the developers for this purpose.

All other software is based on classical TO algorithms and is subject to numerous restrictions, making it impossible to fully solve the desired problem. This represents the current state of technology, which the subsequent attempt will deal with. This assumption is based on tests conducted as described in Figure 3.8 in the previous chapter, as well as basic information about the limitations associated with TO algorithms. This assumption does not claim to be exhaustive but reflects experiences with the most well-known TO software as a user.

The following points were primarily decisive for the choice of software used here:

- Efficiency of optimization tasks. Given the limited computing capacities available and the need for many iterations, how long the optimization processes take with similar mesh sizes was crucial.
- Reliability. The optimized geometries must be reliable and functional. Optimizations that are inconclusive, do not match FEM validations, or violate non-negotiable conditions (such as design space size, passivity of the base plate, etc.) are not productive.
- Adjustability. For this specific problem in this thesis, the software must be flexible and allow settings that are not typically needed by basic TO users.

Based on these points, the software Ansys® and nTop® were chosen. These software meet the mentioned points sufficiently, but other limitations must be accepted:

- Failure to meet a 0° overhang angle. This is the biggest restriction. While Ansys® does not allow setting an overhang angle below 27°, nTop® can vary the overhang angle freely; however, this constraint is not binding. If the software deems it impossible to achieve this overhang angle, it automatically ignores this constraint.
- No stress constraints. Since the stress condition usually becomes decisive before the deformation in this optimization task, it is a significant disadvantage that this condition is omitted.
- Optimization not for minimum mass but only for maximum compliance. This increases the number of optimization iterations until a suitable mass requirement is found that still meets the compliance/deformation condition.
- Failure to meet mass goals estimated at about <1% of the design space mass. While Ansys® allows settings under 10%, the problem does not converge. With nTop®, settings up to 5% of the design space were possible, but this compromises the plausibility of the results, suggesting a divergence of the problem (cf. Section 3.4.6.1).

Before accepting these limitations, an investigation into why they occur and whether they could be resolved was conducted.

3.4.5.1. Overhang angle constraint

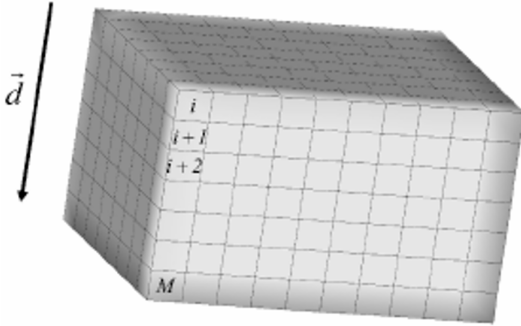


Figure 3.18.: Illustration of the "prescribed demolding direction" option. Harzheim Strukturoptimierung [67]

The overhang angle, mainly implemented for AM processes in TO, imposes a significant restriction on the design freedom for the TO algorithm. The overhang angle describes the angle of the overhanging component to the printing bed. It's important to distinguish between the overhang angle restriction for AM processes and a prescribed demolding direction. A 0° overhang angle does not differ from a prescribed demolding direction in the z-direction in the end result, but it does in the programmatic implementation. A prescribed demolding direction, as implemented in Optistruct®, is achieved by adding the following restriction for the density ρ of individual elements, as shown in figure 3.18[67]:

$$0 \leq \rho_i \leq \rho_{i+1} \leq \rho_{i+2} \leq \dots \leq \rho_M \quad (3.12)$$

This constraint ensures that material removal can only occur from the direction of $\vec{d}$.

For AM overhang, this restriction is often implemented based on angle, where the angle to the vertical (AM build direction) is checked individually for random element assemblies [64]. This check is significantly more computationally intensive and difficult for the algorithm to implement, which could be why Altair Inspire® or OptiStruct® could maintain a 0° overhang condition, something neither Ansys® nor nTop® could achieve.

3.4.5.2. Global stress constraint

A global stress constraint can be included in the optimization problem with the following formulation [67]:

Minimize weight such that

$$\begin{aligned} \sigma_i &\leq \sigma^U \\ x_i^L &\leq x_i \leq x_i^U; \quad i \in I_E \end{aligned} \quad (3.13)$$

with x_i representing the normalized density of element i , with x_i^L and x_i^U denoting the lower and upper limits. I_E denoting the set of indices corresponding to all elements adjacent to element i , and σ^U signifying the upper bound of global stress. This approach leads to a significant number of constraints for the optimizer, reducing its efficiency as the number of constraints increases. These constraints are then either ignored or converted into penalty terms, though the details of this process in commercial software are not well-documented [67].

3.4.5.3. Optimizing for compliance

Optimizing for maximum compliance rather than minimum mass is based on the mathematical formulations used in classical topology optimization (TO) (see Section 3.2). Adapting these formulations to the optimization goal minimum mass is challenging because the TO algorithm lacks a directive to generate a mechanically efficient structure. However, this issue might be circumvented with suitable approaches. CogniCAD™ already possesses this capability.

3.4.5.4. Mass goal

A mass goal of 10% of the design space is a typical limit in TO, beyond which many optimizers start to experience structural holes in the design, complicating problem convergence. Therefore, commercial software often does not allow optimization below this threshold.

The information about these limitations and the reasons for them are related to the classical TO and how this is reflected in the literature. However, the exact functionality of commercial software is rarely known [67].

To rule out user errors and ensure the reported limitations in Ansys® and nTop® software are accurate, inquiries were made to experts on the respective software.

For Ansys®, an inquiry was made to Mr. Danish Hassan, a leading expert and designer in TO with Ansys®. Hassan confirmed these limitations and could only speculate about the reasons behind these restrictions. Hassan also mentioned that because the optimizer in Ansys® can only perform linear optimization, structures, especially at low mass targets, might have their deflection/compliance overestimated.

nTop® provided better feedback itself, automatically indicating that the algorithm was unable to meet the overhang condition while also fulfilling the given mass requirement. It appears that the software is not designed to connect a large passive region (base plate) with efficiently placed material (density=1) while adhering to numerous restrictions. These issues are similar to those faced by Ansys® and the general problems mentioned at the beginning of the chapter.

3.4.5.5. Manual reconstruction

Since adjusting the algorithms was not feasible within this work (and likely challenging outside this work to gain access or persuade developers for modifications), an alternative approach was developed. It's important to note that TO typically only provides design suggestions, which need to be adjusted by the designer for specific manufacturing capabilities and purposes, as well as validated through subsequent FEM analyses [67]. A TO software that can effectively handle many restrictions reduces the designer's workload, but this is rarely the case in practice.

Therefore, the following approach was pursued: As seen in Figure 3.19, a TO geometry based on Ansys® TO shows a distribution of densities. The gray area (high density) represents efficient material placement. The red area (density 0) exists solely to meet the restrictions. Since both Ansys® and nTop® failed to shape this red area according to the requirements after numerous experiments, the AM overhang and global stress distribution restrictions were removed, while symmetry conditions and the passive region requirement were retained. The design of the red area, typically done by software, was performed manually based on FEM simulation results to maintain the efficient placement of high-density material while also meeting design restrictions (AM overhang, stress conditions, minimum element size). Stability aspects (buckling, more specifically, flexural-torsional buckling), were overlooked at this stage.

The manual reconstruction process therefore followed the following aspects:

- Approximation of the TO shape via ribs, which correspond to the profile of the TO in the z-direction and thus enclose efficient material (gray- cf. Figure 3.19).
- The outer sides of the ribs are tried to be kept flat due to optical requirements.
- Minimum thickness of ribs = 10 mm to ensure manufacturability and stability.

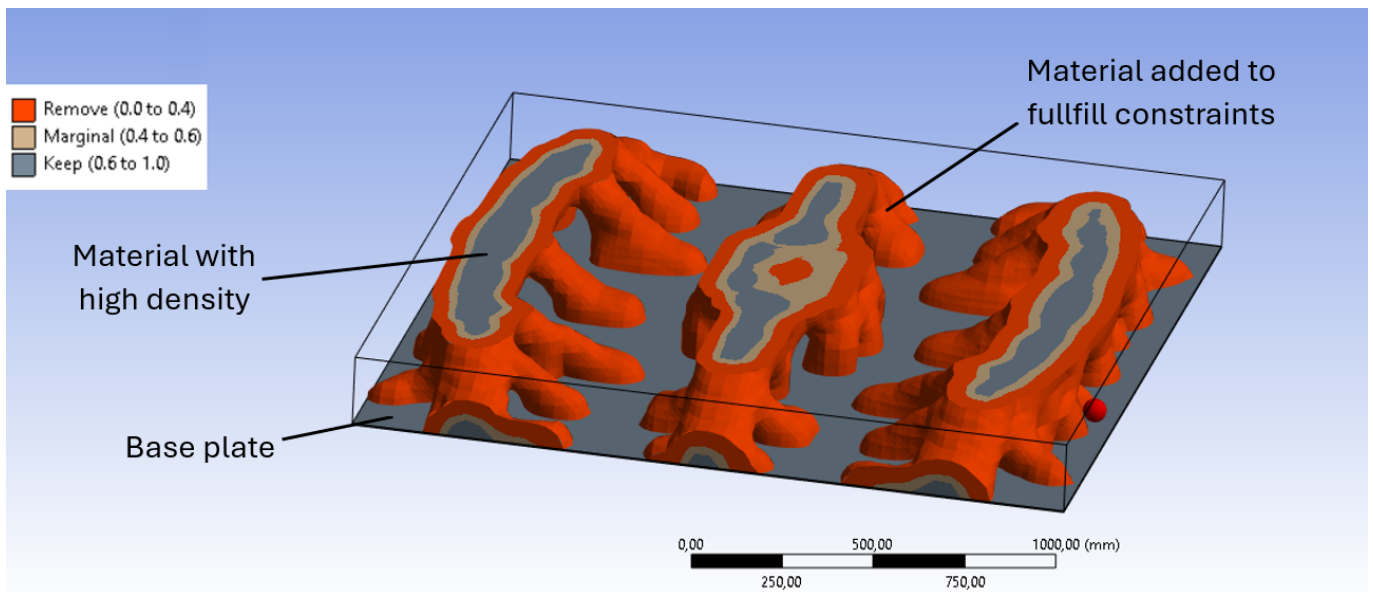


Figure 3.19.: Result of a TO with Ansys®. The gray material represents areas of high density and thus high efficiency of the material. The red material has a density of 0 and is only there to fulfill the given constraints. In this example, Ansys® did not succeed placing the red material, because the mass target was exceeded and overhang constraint not fulfilled.

- Stress peaks are eliminated by locally changing the shape of the geometry or by adding material via individual iteration steps.
- Depending on the geometry and TO design proposal, the global geometry is slightly modified at the designer's discretion.

It should be noted, however, that such a manually adjusted process may not be as efficient, and the resulting geometry may not perform as well as a well-functioning algorithm. Chapter 3.6 discusses how this step could be optimized or improved.

3.4.6. Topology optimization 3D

3.4.6.1. Geometry 1a

Optimization under nTop® was performed for the initial geometry, adhering to all constraints. The nTop® script can be found in the appendix A.6. Settings included:

- Initial geometry: A base plate of 3000 mm x 3000 mm x 4 mm with a design space of 3000 mm x 3000 mm x 200 mm, hinged on two opposite edges, one edge fixed in all directions, the opposite edge free to move towards the center of the plate. Two rows of nodes per edge were selected to avoid FEM singularities. Material: as described in Chapter 3.1.
- Mass target: 5%
- Constraints: Passive region, symmetry (double-symmetrical plate), AM overhang=0°, maximum stress $\sigma_{max} = 15$ MPa.

- Optimization settings: Goal: maximum compliance, mesh size=25mm, boundary penalty=0.1, number of iterations=120, min objective change=0.0002, min density change=0.005.

One side of the structure is shown in Figure 3.20. Since the structure is double-symmetrical, the same geometry appears on the opposite side. However, validations (in the appendix A.7) showed this structure to be neither efficient nor sufficient to meet deformation and stress conditions. Surprisingly, the problem converged according to the solution output, but it is suspected that performance suffered due to strict adherence to constraints. Slightly different settings led to divergence. Increasing the mass target allowed for convergence again.

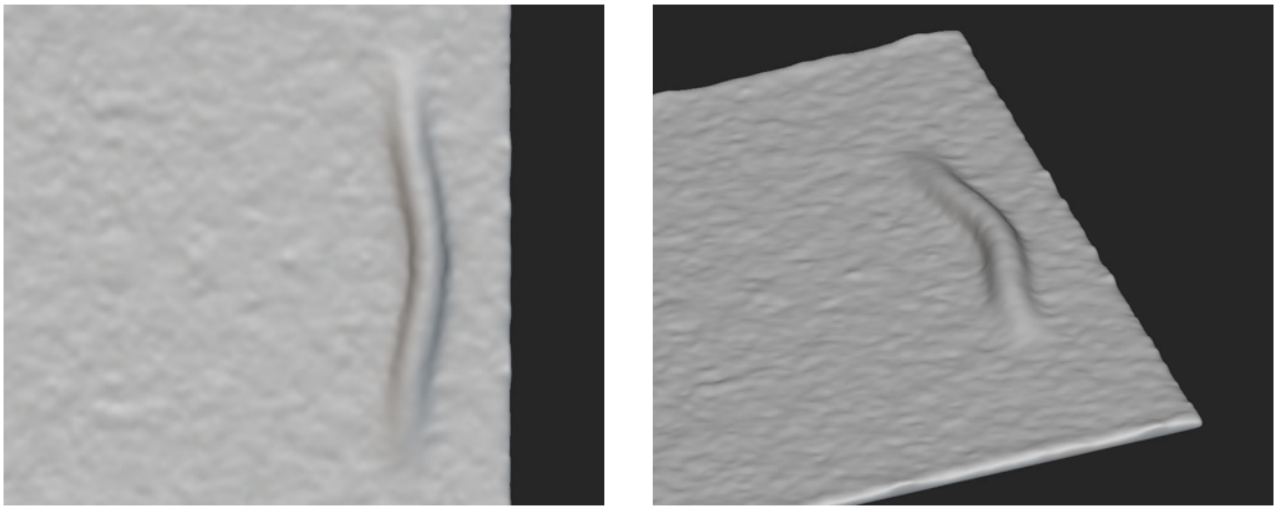


Figure 3.20.: One site of geometry 1a as the result of a TO with nTop®.

3.4.6.2. Geometry 1b

With the same settings as the previous but with the mass target increased to 20%, nTop® reported software issues with implementing the overhang. This reconstruction meets overhang, stress, and deformation conditions, but is not efficient due to the high print mass. Subsequent experiments aimed to reduce the optimized mass.

3.4.6.3. Geometry 1c

Optimization with Ansys produced similar structures to Geometry 1b using nTop (see Figure 3.19). As discussed above, Ansys® failed to design the red area to meet conditions. Reconstruction was omitted here, particularly as 3 individual ribs (reconstruction of the dense grey area) use too much material as in the case of geometry 1b.

3.4.6.4. Geometry 1d

The optimization settings from geometry 1a were retained, but the mass target was increased to 15%, and stress and overhang constraints were removed. This resulted in efficient structures, but they did not provide reinforcement across the entire passive base plate (cf. Figure 3.21). Potential reasons include the low mass target preventing full convergence of reinforcements in the plate center or nTop®'s inability to account for deformation in passive regions.

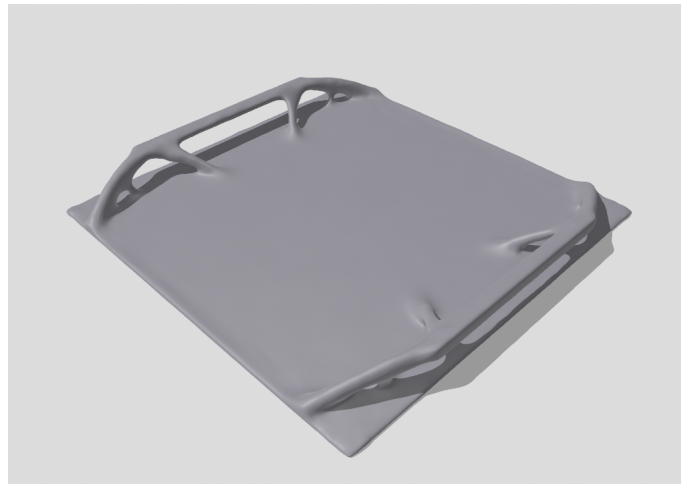


Figure 3.21.: Geometry 1d as the result of a TO with nTop®.

The design proposal to stiffen the plate with two lines was implemented in reconstructions, taking advantage of at least two reinforcing ribs to activate the plate's membrane effect, which is limited with only one rib. The rib positions were adopted from the design proposal's attack points on the base plate. Through numerous iterations of FEM simulations, outreaches towards the plate's center were constructed, aligning in shape and orientation with the design proposal, proving highly effective in FEM validations.

After meeting the deformation and overhang conditions, it was necessary to address stress peaks that exceeded assumed material strengths at various points, considering both suction and compression loads. This was manually iterated, adjusting the geometry where needed, shown in Figure 3.22, and also adding material at certain locations, especially near edges, to not exceed assumed weaker strength in the z-direction.

Corresponding FEM validations are available in the appendix A.9.

The optimized geometry weighs a total of 164 kg for a dimension of 3 m x 3 m and a base plate thickness of 4 mm. An equivalent plate would require a thickness of 26 mm to meet the set requirements and would weigh 585 kg for these dimensions. Thus, the optimized geometry requires 72% less material. Moreover, deformation reduces from 15 mm (equivalent plate with 26 mm thickness) to 5 mm, and stress in the z-direction decreases from 14.52 MPa to under 7.5 MPa.

Construction of 2 m x 2 m plates was also required by Section 2.6. These were constructed with identical global geometries and locally adjusted via FEM simulations to reduce stress peaks. The appearance of this geometry does not significantly differ from the 3 m x 3 m variant, with the base plate thickness remaining at 4 mm, although it could be reduced through constructive adjustments. However, this is not recommended due to practical considerations such as manufacturability and manual impacts. This version weighs 74 kg,

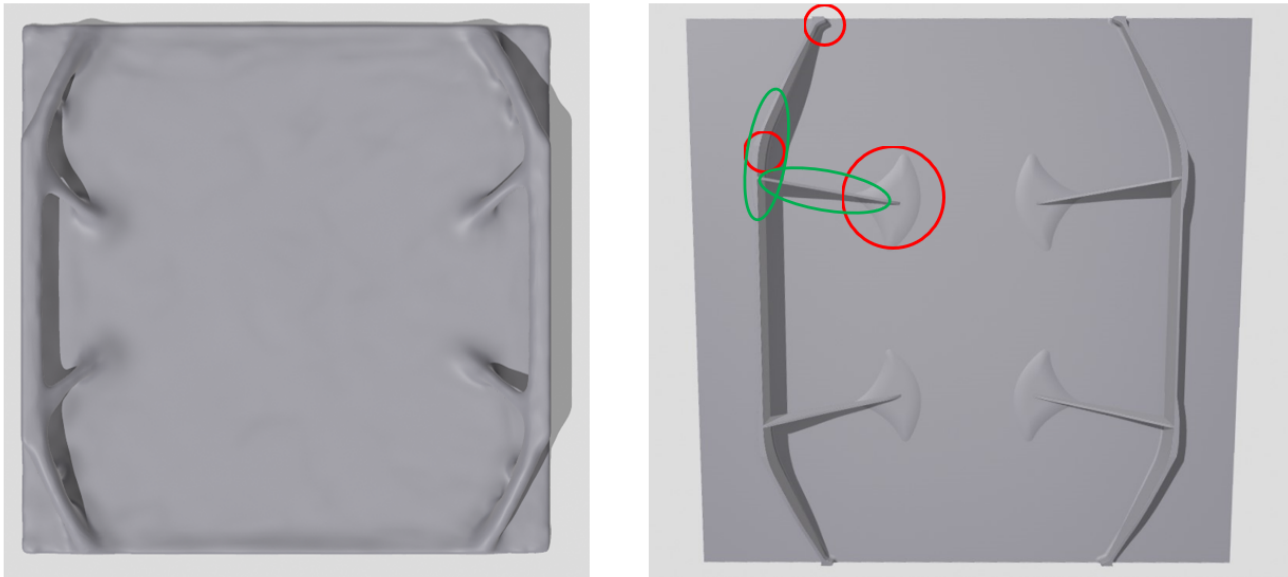


Figure 3.22.: On the left side the result of the TO, on the right side the corresponding reconstruction. The two ribs have been moved inwards to take over the original attack points. Markings in red indicate the points where material had to be added due to pressure loads, in green due to suction loads.

thus requiring 56% less material than an equivalent conventional glass plate with a thickness of 17 mm and a weight of 170 kg.

3.4.6.5. Geometry 1e

Due to aesthetic concerns from some observers about Geometry 1d, as well as the post-processing to remove stress concentrations affecting its optical appearance (notably strong reflections/print area around the cantilevers, see Chapter Optics 2.2), an alternative, more aesthetically pleasing approach was devised. The cantilevers of Geometry 1d were transformed into continuous ribs, significantly increasing the total mass of the plate by 12 kg to 176 kg. Relevant FEM validations can be found in the appendix A.13. Thus, this aesthetic variant of Geometry 1d requires 70% less material compared to a comparable conventional glass plate, making it slightly less efficient than the original Geometry 1d.

A visualization of geometry 1e attached to a post and beam system can be found in Figure 3.23.



Figure 3.23.: Visualization of geometry 1e (3.4.6.5) [104].

3.4.6.6. Comparison of various plate dimensions

In addition to the realistic applications of 2 m x 2 m and 3 m x 3 m constructions, plates were also scaled to dimensions of 1 m x 1 m, 4 m x 4 m, and 5 m x 5 m, even if these are currently of no practical relevance due to the limitation of the plate dimensions of the float process (cf. Section 1.4). Partial FEM validations were conducted, but the constructions were not optimized. Hence, they are not as optimally designed as possible with this method, but they provide insights into potential savings for other plate sizes.

Savings plotted against plate dimensions are shown in Figure 3.24. Color light-green represents savings with the global Geometry 1d, color dark-green with the aesthetic version 1e. Additionally, three rough estimates are plotted: Points in color orange, the potential savings of Geometry 1d if optimizations, rather than mere scaling, were performed for 4 m x 4 m and 5 m x 5 m sizes; in color purple, an estimate for a nearly perfect functioning TO that requires 5% less material in the AM area than version 1d; and in color blue, an estimate for a manually constructed version without overhang constraints, saving between 9 and 12% material in the AM area depending on plate size. These estimates are based on considerations and experience with the constructions, but they do not claim to be definitive.

As depicted in Figure 3.24, the optimized cases 1d and 1e, along with their respective estimations for dimensions 2 m x 2 m and 3 m x 3 m, demonstrate that the savings do not significantly differ from each other. Even substantial alterations to the print geometry, such as the addition of complete ribs in geometry 1e, result in only minor performance losses. This is because the mass of the print constitutes less than 50% of the total mass, increasing for example the imprint mass by 5% for geometry 1d, therefore only results in a performance loss of approx. 2%.

Table 3.3.: Weight savings of 2-sided mounted panels with AM imprint compared to conventional glass panels. The values in black represent validated optimizations for the dimension. The values in orange are not optimized but validated, and the values in grey are estimates.

Dimensions [m ²]	Savings [M.-%] Geometry 1d	Savings [M.-%] Geometry 1e	Savings [M.-%] w/o overhang restrictions	Savings [M.-%] Perfect TO	Thickness [mm] eq. conv. plate	Thickness [mm] AM base plate
1x1	48	47	48	50	9	2
2x2	56	54	58	59	17	4
3x3	72	70	75	75	26	4
4x4	71	68	80	77	34	6
5x5	68	67	81	78	42	8

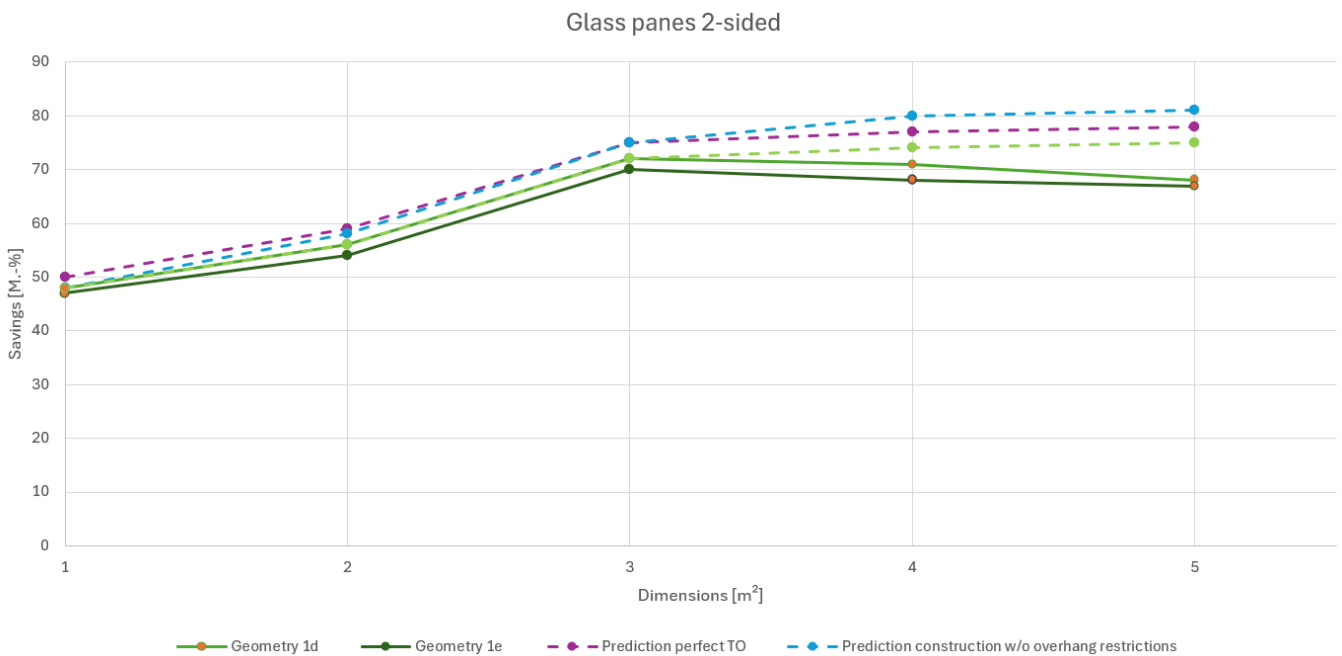


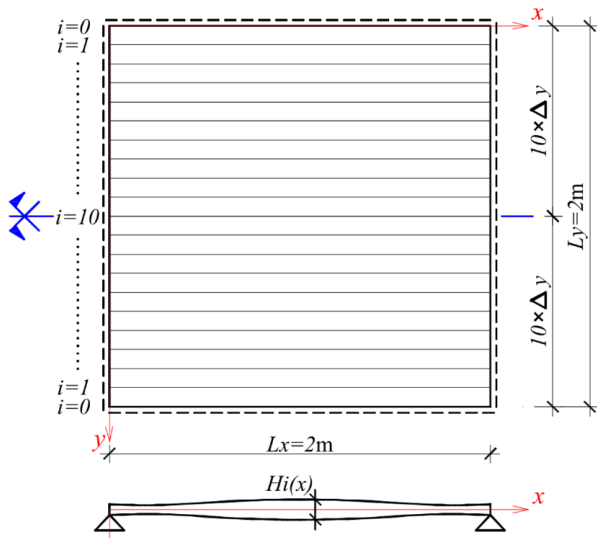
Figure 3.24.: Weight savings of various square panels with AM imprint compared to conventional glass panels. Dashed lines represent estimates. Points in orange are not optimized for corresponding dimension, but only scaled.

3.5. Four-sided supported glass plates

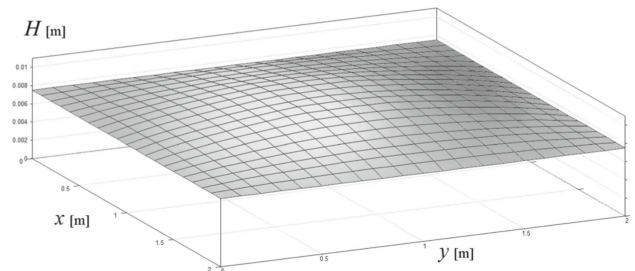
3.5.1. Analytical approach

An analytical approach for plates under biaxial bending stress is not undertaken in this work due to its complexity. However, there are individual publications on this topic, such as the work by Kropiowska et al. [81] on the optimal design of plates with variable thickness based on the minimum principle. Here, it is shown

that placing more material in the center of the plate significantly increases its efficiency (stiffness to material effort), as is also the case with plates under uniaxial stress.



(a) Front and side view of the analyzed plate.



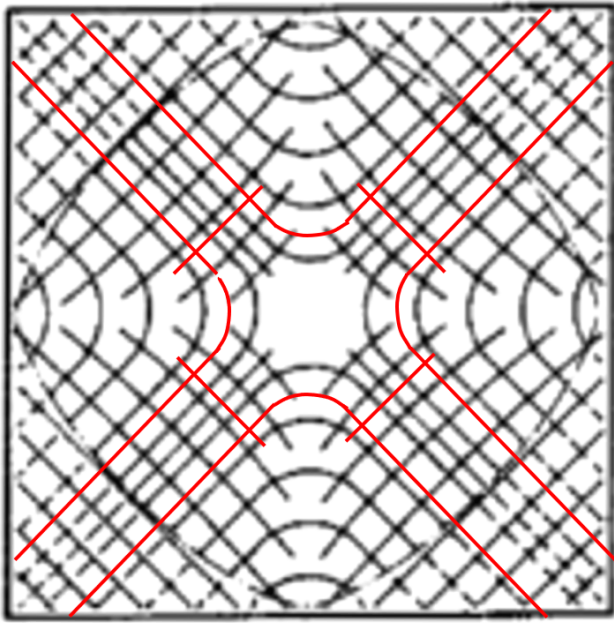
(b) Illustration of the slab thickness function $H(x)$.

Figure 3.25.: Analytical optimization of 4-sided supported plates according to Kropiowska et al. [81].

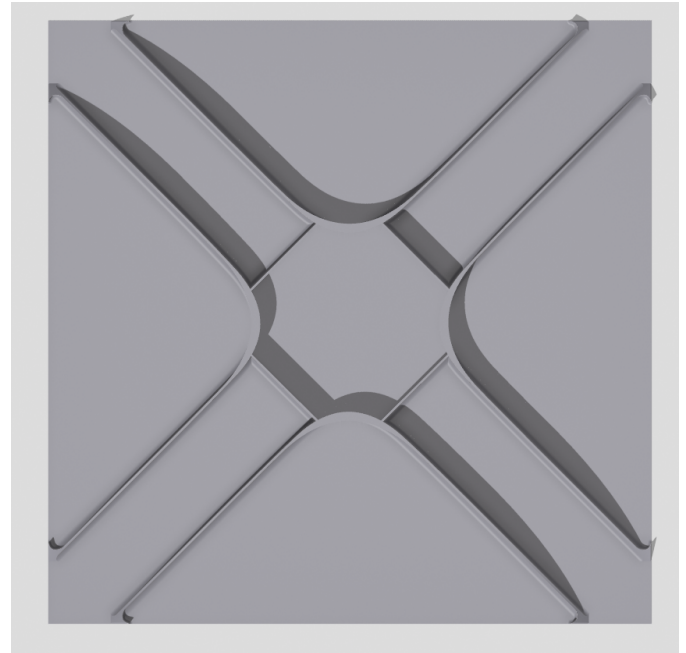
3.5.2. Main moment direction - Geometry 2a

Similar to Trummer et al. [119] for the optimization of reinforced concrete slabs, an attempt is also made here to reconstruct an optimal geometry using representations of the main moment directions for slabs supported on all sides. In contrast to Trummer, the reconstructed geometry is not extruded without changing the structure in the direction of the slab normals, but as described by Kropiowska et al. [81], an attempt is made to position more material in the center of the plate than at the plate edges. The curve that flattens the ribs in the z-direction is based on the curve described by Kropiowska et al. [81].

A reconstruction of this approach is shown in Figure 3.26. Initially, a 6 mm thick base plate was chosen for a 3 m x 3 m plate. All other dimensions are based on the TO or the requirements set out in Section 2.6.



(a) Main moment directions for 4-sided hinged plates under equal surface load.



(b) Reconstruction of the main moment direction via the red lines of (a).

Figure 3.26.: Design of a stiffening structure based on principal moment directions. The contour in the z-direction is based on the thickness function $H(x)$ of Kropiowska et al. [81].

Relevant FEM validations are provided in Appendix A.16.

This method was successful after some iterations, creating a plate that weighs 235 kg, thus saving 35% of material compared to a conventional plate of 16mm thickness weighing 360kg. Further iterations could potentially reduce the base plate thickness to 4mm, aiming for savings of approximately 45-47%.



Figure 3.27.: Visualization of a geometry based on a TO with Ansys®, which, similar to geometry 2a, turned out to be inefficient due to too many ribs [104].

3.5.3. Topology optimization

The TO for plates under biaxial stress (supported on four sides) followed the same process to the optimization of plates under uniaxial stress (3.4). The reconstructions were based on various TO outputs, with Geometry 2e created purely from the constructor's experience based on simulation and optimization results without a specific TO proposal.

3.5.3.1. Without overhang - Geometry 2b

Using nTop® software, a plate reinforcement was developed with specific settings:

- Base geometry: Base plate measuring 3000 mm x 3000 mm x 4 mm with a design space extending to 3000 mm x 3000 mm x 200 mm, flexibly supported on all four edges to allow inward movement (cf. Section 2.1). To mitigate FEM singularities, a double layer of nodes was employed along each edge. The material specifications are detailed in a preceding chapter 3.1.
- Mass goal set at 15%.
- Constraints: Included a passive region, symmetry constraint for a bi-symmetric plate, and a maximum allowable stress of $\sigma_{max} = 15 \text{ MPa}$. Overhang constraints have been removed.

- Optimization settings: Focused on achieving maximum compliance, with a mesh size of 25 mm and other parameters consistent with those used for plates under uniaxial bending 3.4. Boundary penalty increased to 0.2.

Apart from the changes shown here, the program structure in nTop does not differ from that for 2-sided panels A.6.

The design was refined with nTop's integrated tools to meet requirements, excluding the AM overhang constraint, resulting in deformations of merely about 3mm under the specified load. Upon closer examination and subsequent FEM validations, it was observed that the design is not devoid of stress concentrations and has areas that likely offer potential for further material savings. This highlights that TO primarily provides initial design suggestions, especially under multiple constraints, and may not always yield the perfect geometry, as evidenced here even without the AM overhang restriction.

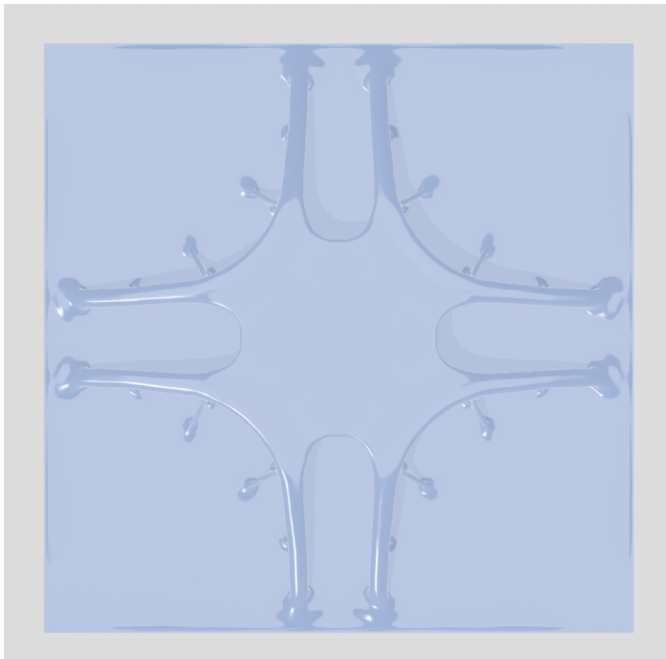


Figure 3.28.: Top view of Geometry 2b.

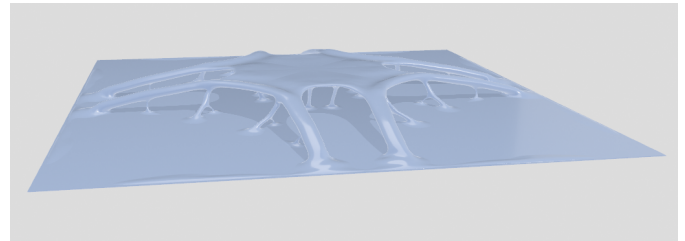


Figure 3.29.: Side view of Geometry 2b with an imprint height of 200 mm.

The geometry has a total weight of 178 kg, facilitating a material savings of 51% compared to an equivalent conventional glass plate of 16 mm thickness. Utilizing a 6 mm base plate increases the weight to 223 kg, reducing the savings to 38%. However, due to the design's thin struts that may fail under compression and other considerations such as optics, this geometry might not be feasible for actual implementation. Its performance is marginally better than designs based on main moment directions but not as efficient as Geometry 1d (3.21), which is supported on two sides only.

3.5.3.2. Geometry 2c

The geometry developed here was inspired by the TO results obtained with nTop®, as illustrated in Figure 3.30. The settings were the same as for Geometry 2b, but the threshold was increased to 0.55 and the

boundary penalty lowered to 0.1.

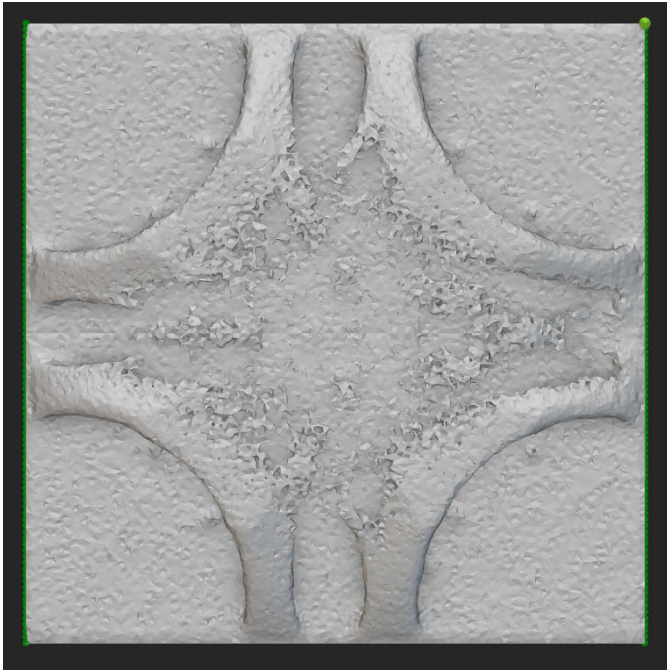


Figure 3.30.: Top view of the uncleaned result of the TO with nTop® for the Geometry 2c.

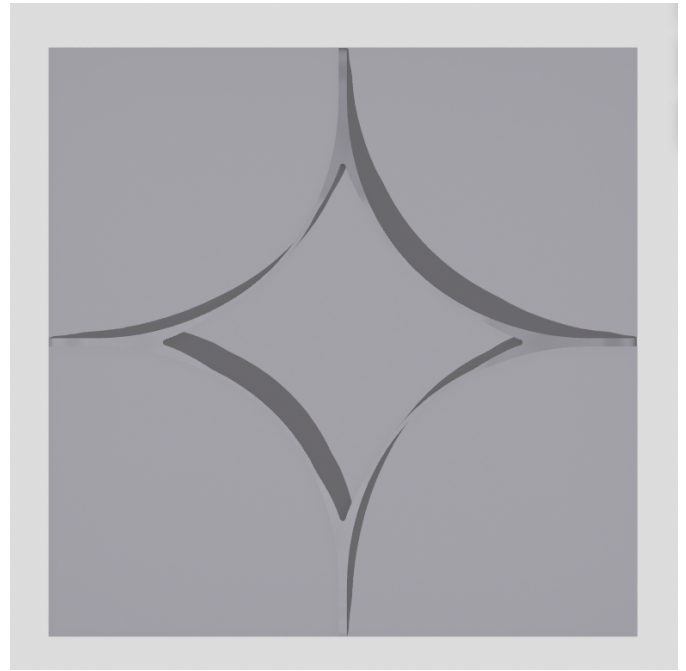


Figure 3.31.: Top view of the reconstruction of the TO output for Geometry 2c with shapr3D [113].

The corresponding reconstruction can be found in Figure 3.31 and was performed with the help of shapr3D [113]. Instead of constructing four individual curves as in the TO, these were combined towards the edges in the reconstruction in order to save material. In addition, a mechanical connection between the curves is necessary, as these would otherwise fold out under load. The shape in the z-direction corresponds 1:1 with the TO and proves to be extremely efficient in the validation cycles. Due to tension problems on the underside of the glass plate, a 6 mm thick base plate was chosen for the reconstruction.

Stress peaks were reduced over a large number of iterations. The corresponding FEM validations can be found in the appendix A.18. 3d images of this geometry can be found in the FEM validations A.18 as well as in the following Figures 3.32 and 3.33.



Figure 3.32.: Visualization of geometry 2c [104].



Figure 3.33.: Visualization of the rear side of geometry 2c within a post and beam system [8].

Weighing 184 kg, the geometry realizes a 49% material savings compared to a conventional glass plate of equivalent size but 16 mm thickness, which would weigh 360 kg. It also features reduced deformations of up to 6 mm and a minimized z-direction stress to 5 MPa, predominantly occurring on the underside of the plate, outside the area enhanced by AM.

3.5.3.3. Geometry 2d

For this geometry, the mass target was increased to 20%, with only one symmetry condition applied. The threshold has been reset to 0.5. All other settings remain consistent with Geometry 2c. The resultant geometry and its reconstruction can be found in Figure 3.35.

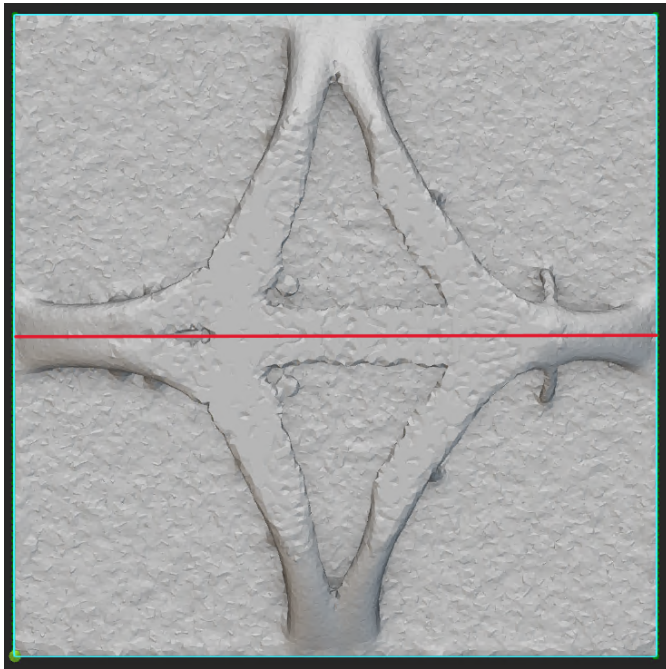


Figure 3.34.: Top view of the result of the TO with nTop® for the Geometry 2d. The red line indicates the symmetry constraint.

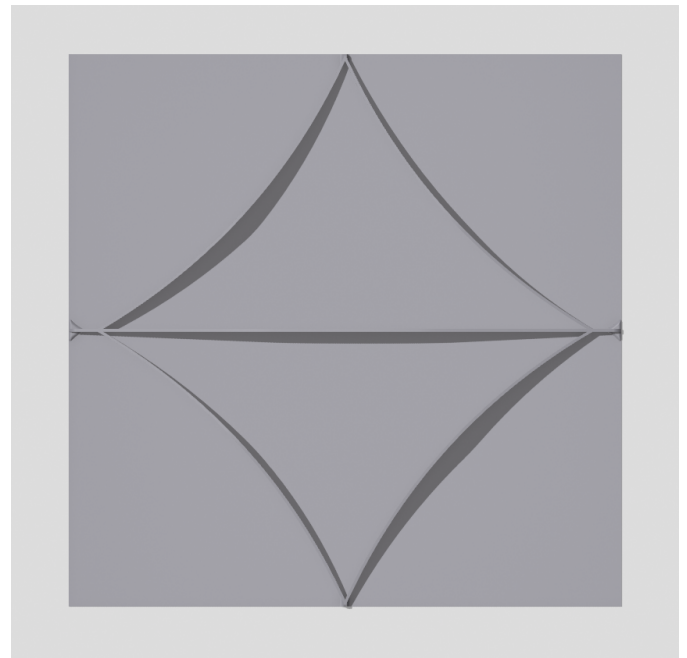


Figure 3.35.: Reconstruction of the TO output for Geometry 2d.

Similarly, a 6 mm thick glass plate was selected as the base plate. The FEM validations are detailed in the appendix A.24.

The total weight of the geometry is 181 kg, achieving a 50% material reduction compared to a conventional plate of equivalent size with a 16 mm thickness and a weight of 360 kg. Deformations are reduced to 3 mm.

A visualization of this geometry can be found in Figure 3.36.



Figure 3.36.: Visualization of geometry 2d [104].

3.5.3.4. Geometry 2e

This geometry is not derived from TO design proposals but rather from the constructor's experience with TO constructions. A cross shape, spanning from the corners of the plate, was selected as the basic geometry. Its further form is inspired by Geometries 2c, 2d, and 2f.

A depiction of the construction is available in Figure 3.37. Here too, a 6 mm base plate was utilized. The associated FEM validations are provided in the appendix A.30.

This geometry has a total weight of 175 kg, thereby requiring 51% less material than an equivalent conventional plate. Deformations are reduced to 6 mm.

A visualization of this geometry can be found in Figure 3.38.

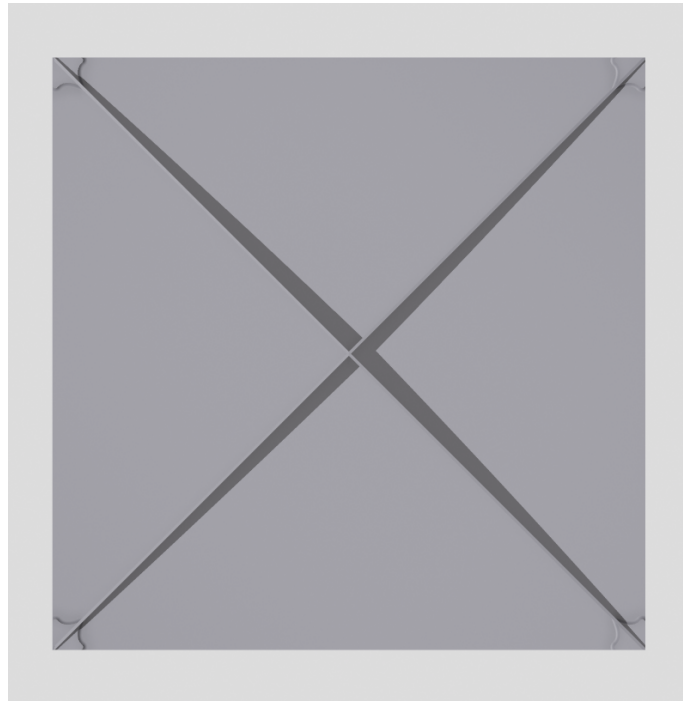


Figure 3.37.: Top view of Geometry 2e.



Figure 3.38.: Visualization of geometry 2e [104].

3.5.3.5. Geometry 2f

For this geometry, the mass target was set to 15%, with the boundary penalty adjusted to 0.3 and the threshold increased to 0.65. The resulting geometry and its reconstruction can be found in Figure 3.39.

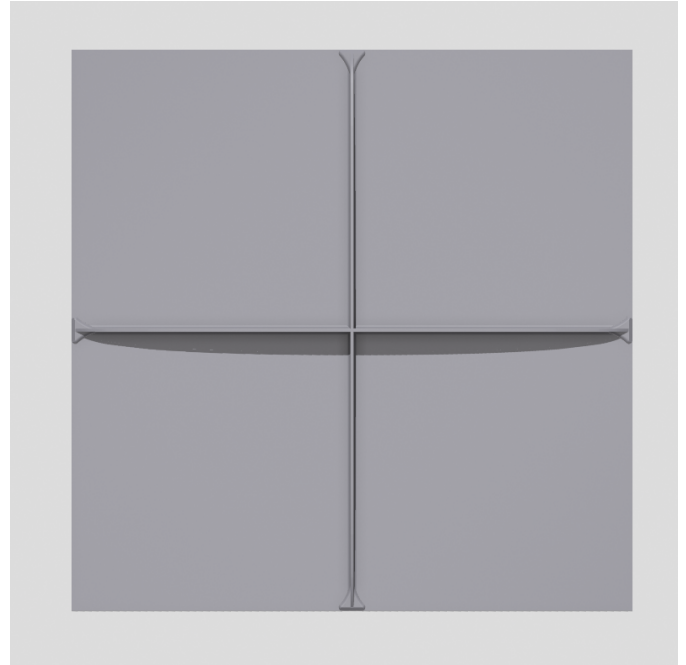
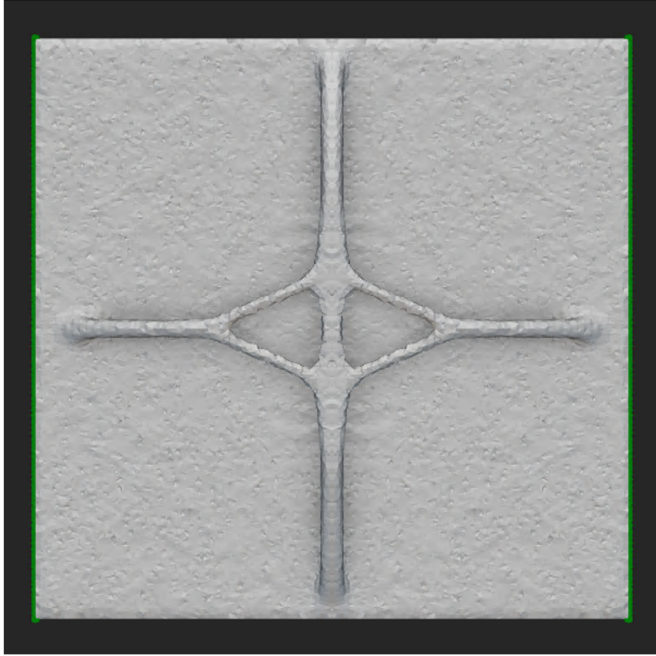
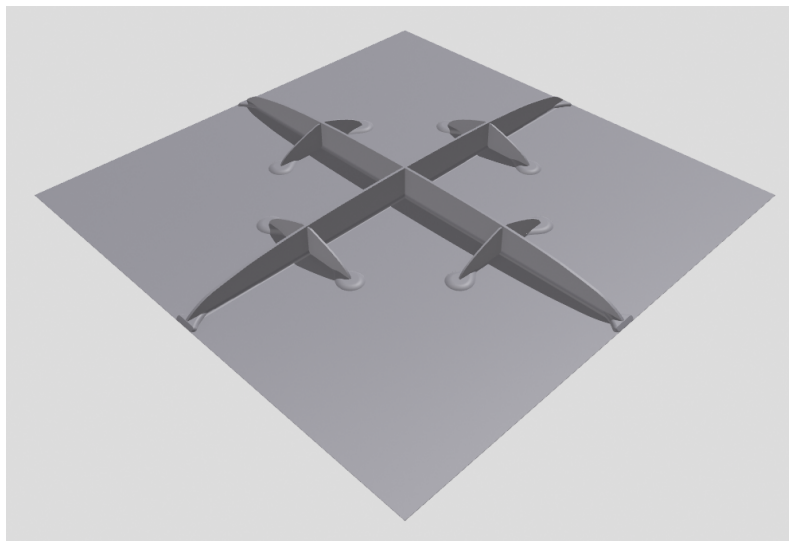


Figure 3.39.: Top view of the result of the TO with nTop for the Geometry 2d. Figure 3.40.: Top view of Geometry 2f.

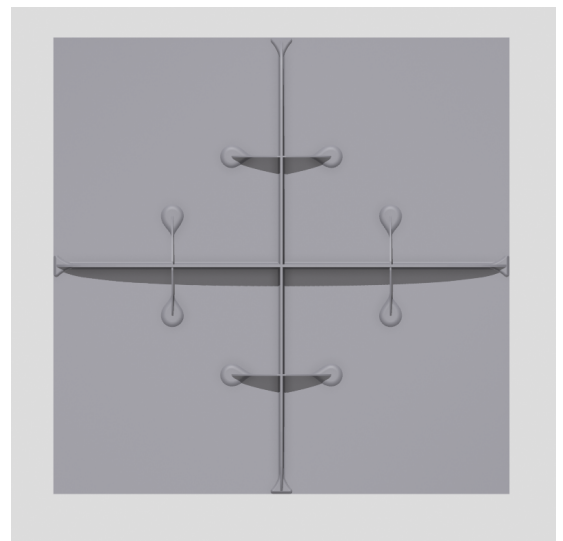
Initially, a 6 mm base plate was selected, consistent with Geometries 2a-f. The related FEM validations are available in the appendix A.30.

The total weight of the construction is 173 kg, thus achieving a 52% material saving compared to an equivalent conventional plate. Deformations have been reduced to 8 mm. Given that this plate construction is still heavier than Geometry 1d, which is only supported on two sides, efforts were also made to reduce the thickness of the base plate to 4 mm.

To this end, outriggers were designed to reduce the deflection of the plate fields and thus the stress, particularly on the underside of the plate. The designed geometry is shown in Figure 3.41.



(a) 3D view



(b) Top view

Figure 3.41.: Geometry 2f with outriggers and 4 mm base plate.

The related FEM validations are found in the appendix A.3. The results for shear stresses are also given at this point. The maximum shear stress of approx. 9 MPa is located in the corner of the panel, but individual parts of the AM imprint also exhibit increased shear stress. The shear strength of these AM parts remains to be investigated.

Reducing the thickness of the base plate led to significant material savings, with the additional requirement for AM print material being negligible. The print mass increased from 38 kg to 48 kg, yet the new total weight of the construction, due to the reduction in base plate thickness by 2 mm, is only 138 kg. The material savings thus amount to 62% compared to a conventional equivalent glass plate with a 16 mm thickness and a total weight of 360 kg. This plate is also 26 kg lighter than the construction of 1d in the dimensions of 3000 mm x 3000 mm.

A visualization of Geometry 2f.1 can be found in Figure 3.42.



Figure 3.42.: Visualization of geometry 2f.1 [104].

3.5.3.6. Comparison of results and distinctions in losses

As evident from the highly varied geometries, experiments with both nTop® and Ansys® have shown that minor adjustments in settings can result in significantly altered geometries. It is suspected that there exists a multitude of geometries that at least represent a sufficient local minimum for the problem's solution.

Furthermore, Figure 3.43 illustrates the differences in savings between the various versions, showing that with a base plate thickness of 6 mm, the versions 2c-2f do not significantly diverge in material savings.

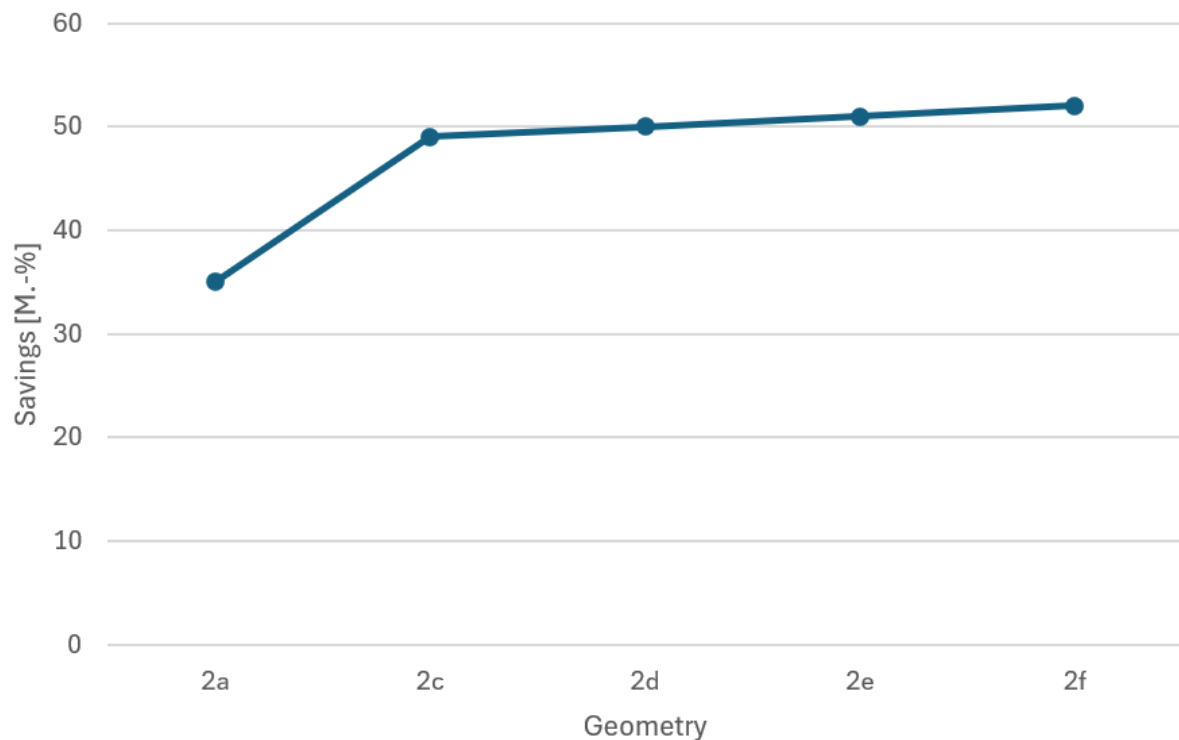


Figure 3.43.: Overview of the weight savings of the geometries listed in this section with a base plate thickness of 6 mm in comparison to a conventional glass plate. Apart from the approach with the main moment direction 2a, the savings do not differ significantly.

3.6. Summary and possible improvements in optimization process

The savings among the significantly differing geometries do not diverge by more than 3% (see Figure 3.43) for the geometries under biaxial stress, indicating that the choice among these geometries seemingly has little impact on the component's performance. In contrast, the chosen thickness of the base plate has a more substantial effect, as seen with Geometry 2f.

For the two-sided supported plates, the optimum appears in a geometry featuring two ribs spanning the entire length. The geometries suggested by Ansys® and nTop®, which include three ribs, are significantly less efficient. While the option to utilize only one rib exists, it does not adequately capitalize corresponding membrane effects, thereby also compromising efficiency. The shape of these ribs in the x/y direction (parallel to the plate), as well as the arrangement and shape of corresponding stiffening elements, have less impact, as demonstrated by geometries 1d and 1e.

Pursuing a global minimum for this problem might be feasible with adequate resources using Optistruct® or Genesis®. Predicting the performance enhancement of such a global optimum compared to the current geometries is uncertain. However, it's a common aspect of TO that any closer approach to an optimum involves increased effort. This effort needs to be considered, as even if an efficient TO could save an additional 5 kg of AM material compared to Geometry 2f, the savings would only increase by 1% from 52% to 53%.

A drawback of this approach, unlike with mass-produced items like a car's control arm, is the variability of influences in a building. A universally optimal solution or geometry will vary significantly due to changing conditions. Therefore, the effort to find a performant geometry must be manageable and ideally carried out by the user, engineering office, or specialized designer. This is not feasible with Optistruct® or Genesis®, considering the expertise and time required for implementation.

Beyond mechanical aspects, other constraints in construction should not be overlooked. These were highlighted in Chapter 2, primarily focusing on visual appearance, cleaning feasibility, aesthetics, but also including safety requirements, stability issues, building physics requirements, among others outlined in Chapter 2. These constraints cannot be incorporated through TO.

Hence, a proposal for optimizing such plates is made (see Figure 3.44): Under an engineer's consultation, the architect and/or client develops a preliminary design of the plate geometry, which meets non-mechanical constraints and is guided by mechanically performant design suggestions developed by an advised engineer, similar to this thesis. TO can serve as a tool for the engineer. A TO with a functioning overhang constraint could significantly reduce the engineer's workload to create such suggestions. For these design recommendations, considerations should extend beyond merely mechanical aspects to include crucial attributes such as cleaning feasibility, optical appearance, safety requirements, and additional stipulations as detailed in Section 2.4.

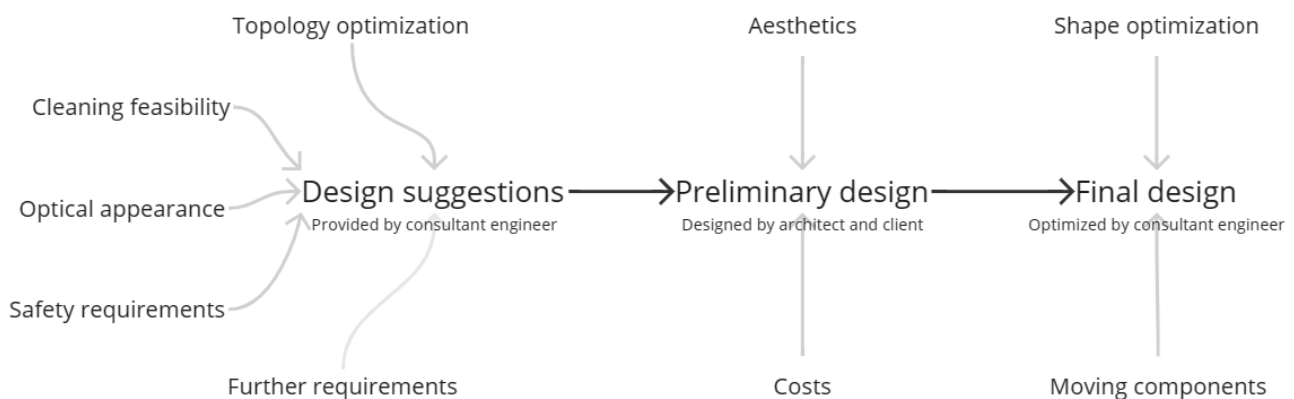


Figure 3.44.: Proposal for a workflow to create optimal and usable AM glass sheet geometries.

Upon defining a preliminary design, the engineer must minimize or eliminate any occurring stress concentrations that exceed the AM material's or the base plate's strength. This is achieved through shape optimization. Minor, computer-aided shape modifications, which hardly affect the global structure, can optimally address stress concentrations, maximizing material use. This includes not only potential notches but also the global elevation of ribs in the z-direction.

3.6.1. Shape optimization

Shape optimization is a significant segment of structural optimization, aimed at modifying a component's geometry to achieve its optimal form. Primarily, it targets the reduction of stress concentrations, utilizing mainly two methods:

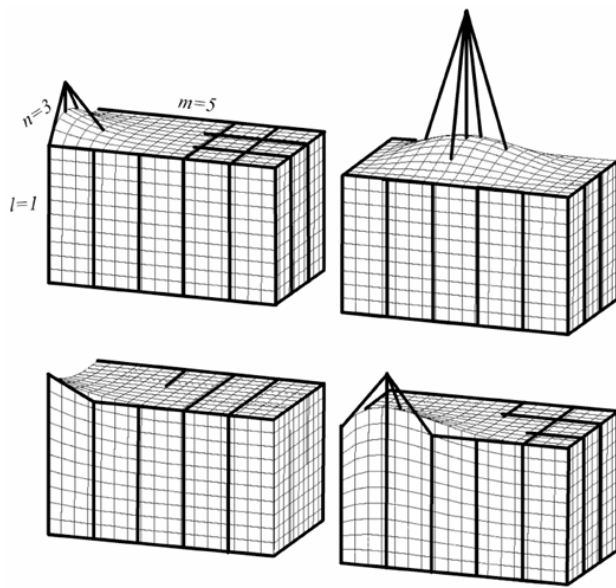


Figure 3.45.: Changing of the surface geometry by varying the shape basis vectors. Harzheim Strukturoptimierung [67]

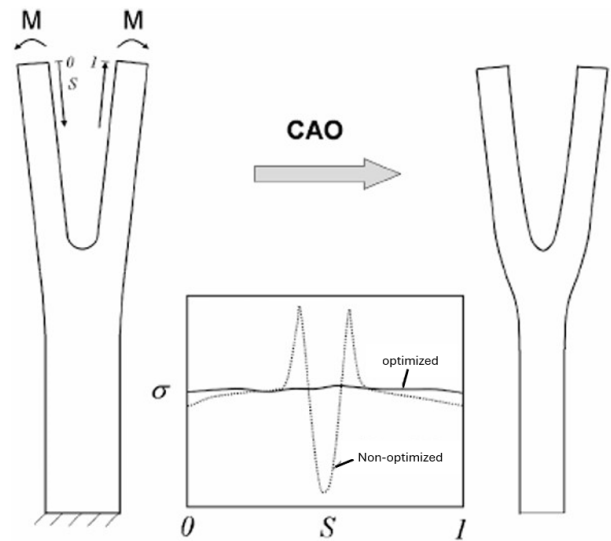


Figure 3.46.: Example of how CAO works on a tree fork. Harzheim Strukturoptimierung [67].

- Shape optimization using shape basis vectors:

This technique involves segmenting the surface of the area with stress concentrations into a grid, assigning a shape basis vector to each grid point, as illustrated in Figure 3.45. The software adjusts these vectors upwards or downwards to find an optimal shape that minimizes stress in that section, a process depicted in [67]. A specialized form of this method is topography optimization.

- Shape optimization through CAO (Computer Aided Optimization):

CAO emulates adaptive biological growth rules, stating that material should be added in high-stress areas and removed from low-stress ones, akin to the BESO method used in TO 3.46. This mimics natural processes observable in numerous examples. An optimization case of a tree fork, affecting both inner and outer contours, demonstrates how local adjustments can entirely eliminate stress concentrations without significantly altering the global structure, aligning with the desired process here [67]. A concrete FEM example of a shape optimization can be found in the appendix A.36.

3.6.2. Moving Components

To extract further material from the design, an approach similar to the MMC (cf. Section 3.2) can be employed by engineers. Desired ribs or the global structure can be shifted to find an optimal position using special functions, such as "sliding planes" in software like Optistruct. This method resembles an MMC approach but allows for limiting the extent of rib movement. Optistruct already incorporates this function, though it requires specific adjustments or preliminary work by trained personnel. However, this step is less daunting than implementing a functioning TO in Optistruct and maintains the assumptions made to meet non-mechanical constraints.

3.6.3. Summary

This methodology facilitates finding highly efficient, functionally deployable, and by architect or client accepted print geometries for reinforcing glass plates. The focus lies on achieving general material savings of 50-70% (depending on the chosen base plate thickness) for the presented application. Pursuing the last grams in structures through a perfect TO design suggestion (which does not exist) is not expedient in this context. The effort to discover a mechanically optimal geometry becomes excessive when considering die stark changing load cases and framework conditions in the BE and that it must be modified or deteriorated to meet non-mechanical requirements. Ignoring non-mechanical demands may result in a geometry that cannot be installed or is rejected for aesthetic reasons. The workflow proposed here for creating optimized panel geometries (cf. Figure 3.44) is recommended.

4. Mechanical tests of AM Glass

4.1. Test methodology for mechanical properties

4.1.1. Test methodology in AM



Figure 4.1.: Example of a "dog-bone" tensile test with aluminium. Photo by Ramasamy.

In the field of AM, so-called "dog-bone" tests have become standard for characterizing the anisotropic tensile strength behavior due to layer orientation [88], especially in FDM and DED processes, as discussed in Section 3.1. Dog-bone tests are standard in classical material testing, most notably for determining the yield and failure limits of metals and polymers. An illustration of this can be found in Figure 4.1. The test specimen is clamped at its wider sections or secured through a bolt. The clamps are pulled apart, applying a constant tensile stress in the thinner midsection.

This principle has been adapted for AM; however, tensile tests in following layer orientations are necessary to characterize AM objects:

- 0° Layer Orientation - Parallel to the loading direction: This orientation assesses the material's strength along the layers, providing insights into tensile strength and material behavior when force is applied parallel to the print layers.
- 90° Layer Orientation - Perpendicular to the loading direction: Tests in this orientation evaluate the adhesion between layers, shedding light on the interlaminar strength, which is typically significantly lower than the strength parallel to the print layers in additive manufacturing.
- 45° Layer Orientation: This orientation is used to assess the material's shear behavior, offering a comparative value to the previous orientations.

A depiction of these layer orientations can be found in Figure 4.2.



Figure 4.2.: Test geometry with a layer orientation of 0°.

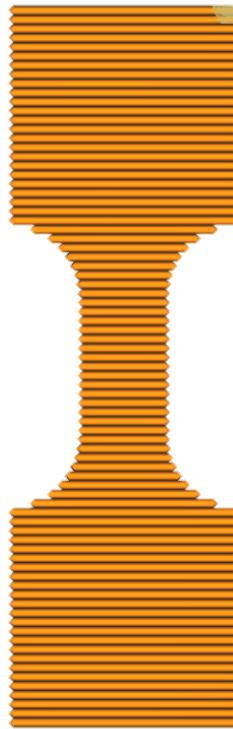


Figure 4.3.: Test geometry with a layer orientation of 90°.



Figure 4.4.: Test geometry with a layer orientation of 45°.

4.1.2. Test methodology for AM Glass

Clamping AM-fabricated components made from polymers or metals can be accomplished with relatively little effort. However, this is not as straightforward with glass or brittle materials due to its extreme sensitivity to stress concentrations, necessitating the avoidance of direct glass-metal contact. One solution could involve casting the ends of the AM glass specimens in silicone or a similar substance and clamping the encapsulated parts. The material used must not be too soft to ensure reliable clamping. Given the complexity and inefficiency of this method for a large number of specimens, as well as eccentricity issues, it is not pursued further here.

Instead, a highly advantageous property of brittle materials is utilized. Due to the non-plastic behavior of brittle materials, the bending tensile strength is identical to the tensile strength. This uniquely allows replacing tensile tests with bending tests, which has both advantages and disadvantages:

Advantages:

- Simple, fast handling
- Samples require only minimal preparation
- Simple experimental setup

Disadvantages:

- Quite local load application via line bearing
- Samples must be very straight/not be twisted in themselves
- Higher stress level at the edge of the samples

In bending tests, there are two prevalent methods: three-point and four-point bending tests. To decide which one to use, the strength behavior of brittle materials, which is significantly determined by surface defects as discussed in detail in Section 3.1, must be considered. In a three-point bending test, the maximum moment or load is applied at a single point (at the load edge), see moment line Figure 4.5a. Thus, only the defects located there are tested under maximum stress. In a four-point bending test, the maximum moment is applied over a greater length (specifically, between the two load edges), allowing a much higher number of defects to be maximally stressed. Therefore, for brittle materials, the four-point bending test typically results in significantly lower variances between test specimens than the three-point bending test. For this reason, a series of test standards for glass and ceramics (see DIN EN 843 [51], DIN EN 1288-3 [33]) prescribes the four-point bending test for evaluating mechanical properties, and it is also used here for testing the mechanical properties of AM glass.

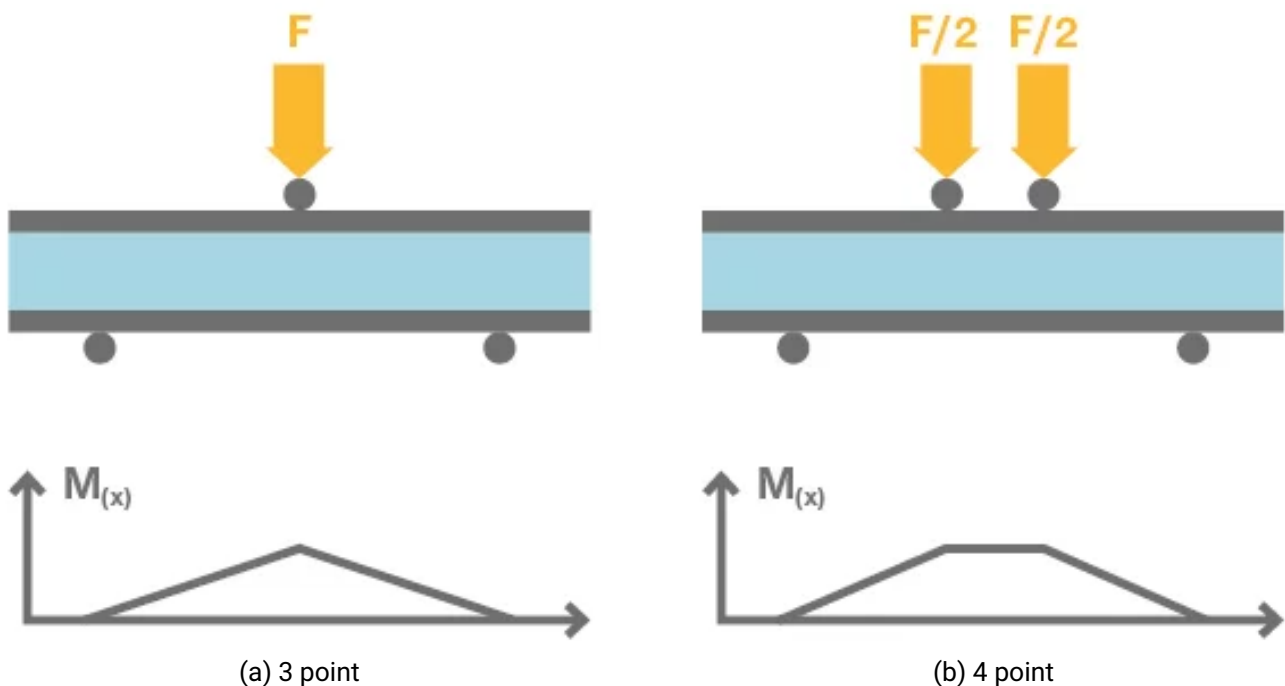


Figure 4.5.: Moment lines 3 point and 4 point bending test. Illustration from Lamilux GmbH.

4.1.3. Requirements for test specimen

For investigating the mechanical properties of AM glass using the four-point bending test, an appropriate specimen geometry is required. The geometry was developed based on four considerations:

1. Printability or manufacturability:

The specimens must be easily producible without requiring significant research effort from the producer or modifications to the printers. This ensures that as many producers/developers as possible can use this test for qualifying their prints.

Therefore, a geometry that can be flatly printed on the print bed and is only one layer high was chosen. This approach prevents issues such as layer misalignment, uneven temperature heating/cooling, warping, etc. It also guarantees that the specimens are not twisted internally, which is crucial for conducting

reliable bending tests. Printing the different layer orientations is also straightforward with a flat geometry parallel to the z-direction (perpendicular to print bed). An additional advantage is that the specimens will have one ribbed side (open layer structure) and one polished side (on the print bed side), allowing for the qualification of layer notch effects. However, a drawback is that the DED process cannot produce these specimens since it can only print on glass plates. Thus, the chosen test geometry is suitable only for FDM and SLA processes.

2. Costs:

AM glass is currently an expensive process. High costs will limit the number of test specimens that can be produced, reducing both acceptance and statistical reliability.

Therefore, a relatively small geometry with dimensions of approximately $150 \times 50 \text{ mm}$ is chosen here. With a test area of $20 \text{ mm} \times 30 \text{ mm}$, sufficiently accurate test results with low variances should be achievable for the material model. However, the size is currently also dominated by printability, as the build volumes of most current printers cannot accommodate large geometries.

3. Reduction/Avoidance of cutting influences

Chhaddeh et al. [18] reported on the significant impact of edge strengths when testing AM glass geometries. This influence is well-known in glass, where the quality of the cut edges significantly affects or weakens the strength of glass, leading to a strong focus on the quality of these cut edges in the production of flat glass. The effect of these cut edges is still a subject of research, so inducing such cut edges in test specimens should be avoided.

Therefore, the chosen test specimen is printed as a whole component and not cut out post-production.

4. Reduction of local stress concentrations at load introductions

As mentioned above, glass is very sensitive to local stress concentrations, which are initially unavoidable in bending tests. Appropriate measures must ensure that the specimens do not fail due to these local stress concentrations, thereby distorting the test results.

Therefore, a dog-bone geometry is chosen here. At the points of load application and supports, significantly more material is provided to absorb the stress concentrations. It is planned for the specimens to fail in the area of the significantly narrower web, before stresses in the load application/support area become large enough to induce failure.

Additionally, adhesive films are applied to the specimens, as prescribed in DIN EN 1288-3 [33]. This not only prevents direct glass-metal contact but also keeps the specimens together upon failure.

A drawing of the selected geometry is provided in 4.6. Corresponding results of the FEM simulation of the geometry through a four-point bending test are given in the Appendix A.37. In the area of cross-sectional tapering, shear forces are inevitably present, as seen in the FEM results. However, as glass predominantly only fails under tension and not under shear load [107], it is estimated that the shear forces will not impact the test results, and failure will not be induced at that location. This assumption will be examined in the tests.

However, this geometry also has disadvantages. It is currently not producible using the DED process. Moreover, laying down layers individually as shown in Fig. 4.2 is not straightforward. For the specimens by Maple Glass Printing Ltd. in the subsequent Section 4.2, achieving good quality was only possible with a continuous layer run. The influence of continuous and non-continuous layer run has to be investigated.

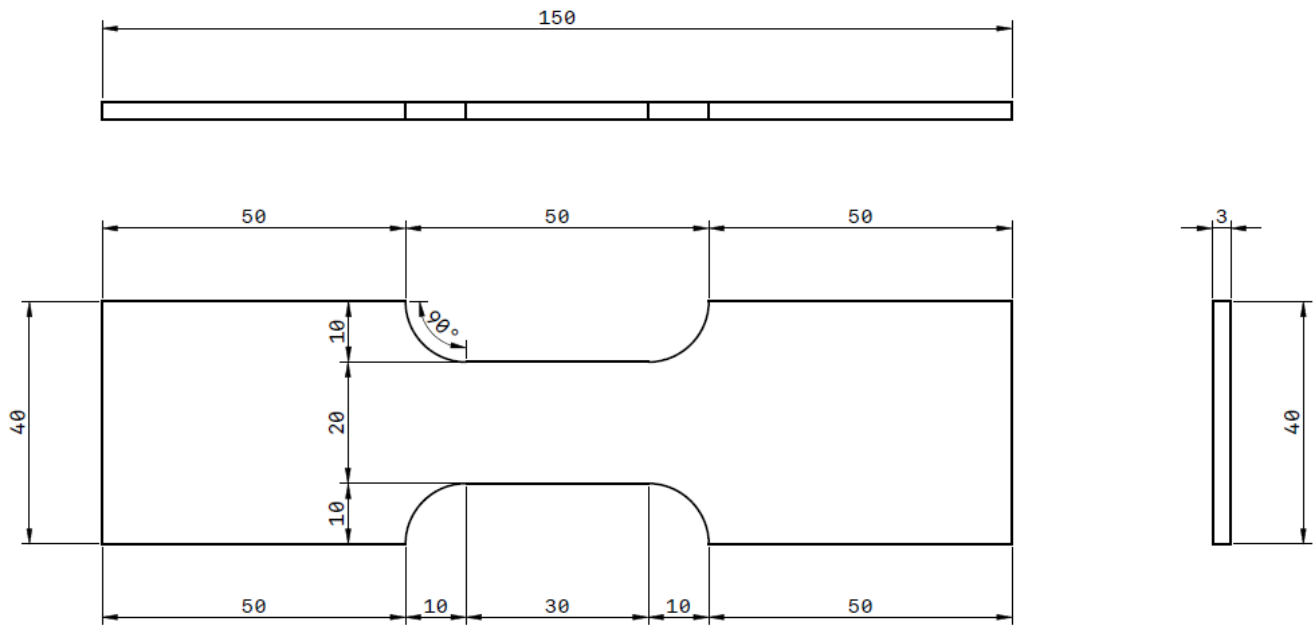


Figure 4.6.: Dimensions of the test geometry in mm. Bottom left the top view of the test geometry with two corresponding projections of the side views.

4.2. Test specimen

Maple Glass Printing Ltd. printed 15 specimens for the experiments according to the specifications in Section 4.1. Of these, five specimens were printed with a layer orientation of 90° , five with 0° , and five with 45° . Images of the different layer orientations are presented in Figures 4.7, 4.8, and 4.9.

The filament used was "001100 Tekta Clear" by Bullseye-Glass Co., formed into filament by the Maple "The Vidri-Glass" machine. The chemical composition of the glass is not available, as it is primarily intended for artistic purposes.

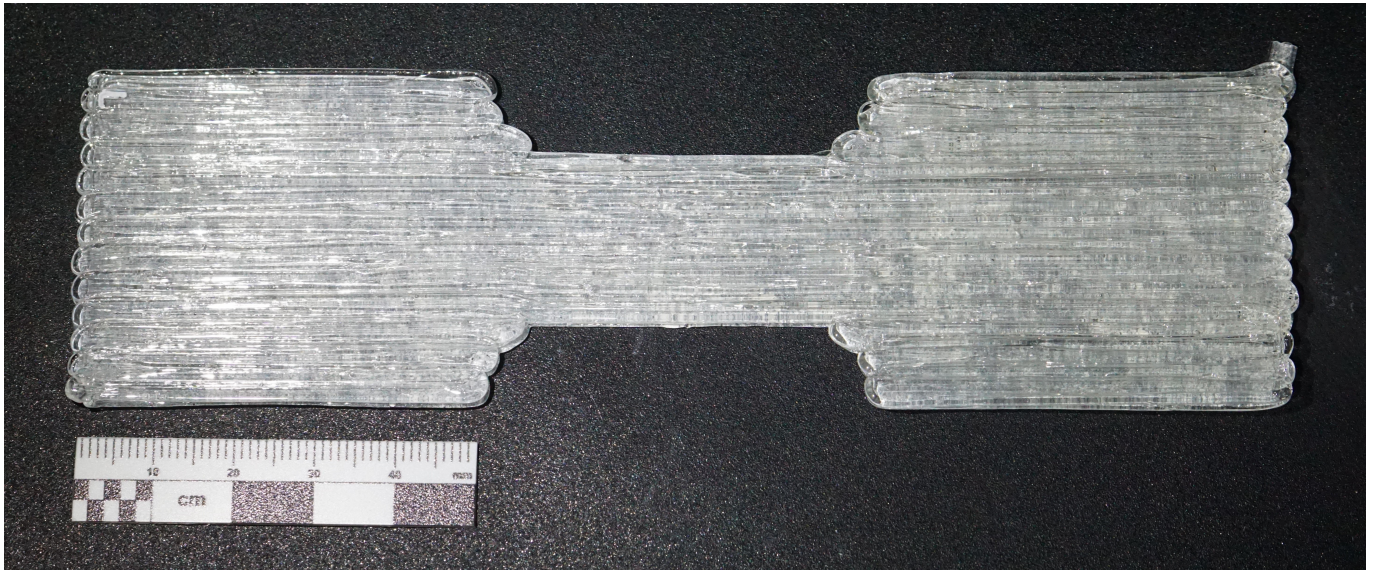


Figure 4.7.: Test specimen 0-1.

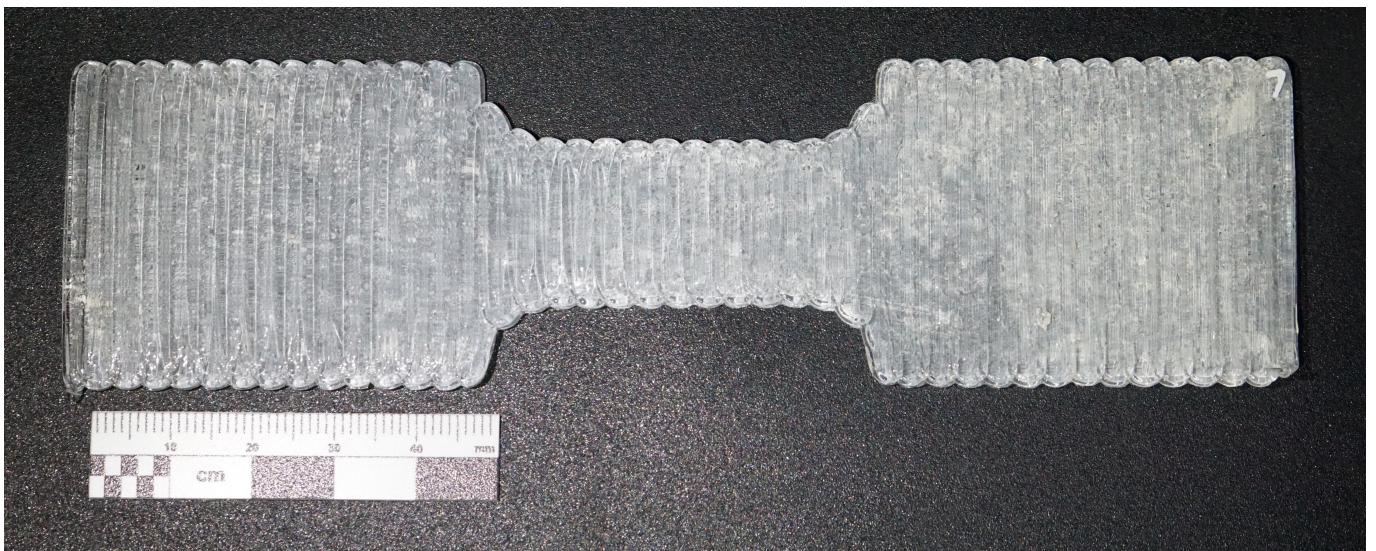


Figure 4.8.: Test specimen 90-1.



Figure 4.9.: Test specimen 45-3.

The specimens were printed by Maple Glass using their "The Maple 4" printer. Process parameters can be found in Table 4.1.

Parameter	Value
Printer	Maple 4
Nozzle Size	1.5 mm
Nozzle Temperature	940°C
Chamber Temperature	500°C
Extrusion Rate	2.26 mm/s for 1 st Layer 4.53 mm/s for 2 nd & 3 rd Layer
1 st Layer	2 mm/s and <1 mm layer height for good bed adhesion
2 nd & 3 rd Layer	4 mm/s and 1 mm layer height
Travel Speed	30 mm/s
Annealing Time	15 min
Cooldown Rate	Decreasing from 30 to 5 K/min over time
Slicer	PrusaSlicer with path-spacing of 1.785 mm. Manual g-code adjustment for the 0°-samples.

Table 4.1.: Printing parameters for the test specimen printed by Maple Glass Ltd.

Additionally, six reference specimens were manually crafted from soda-lime glass rods with a diameter of 4 mm. For three specimens, the glass rods were oriented longitudinally (0°), and for the other three, transversely (90°). Images of the different layer orientations are shown in Figure 4.10 and 4.11. Soda-lime glass rods from Rohe GmbH, intended for laboratory use, were individually cut to shape and heated in a furnace. The rods were heated at a rate of 100 K/h to 900°C, maintained at 900°C for 20 minutes, and cooled down at 350 K/h.

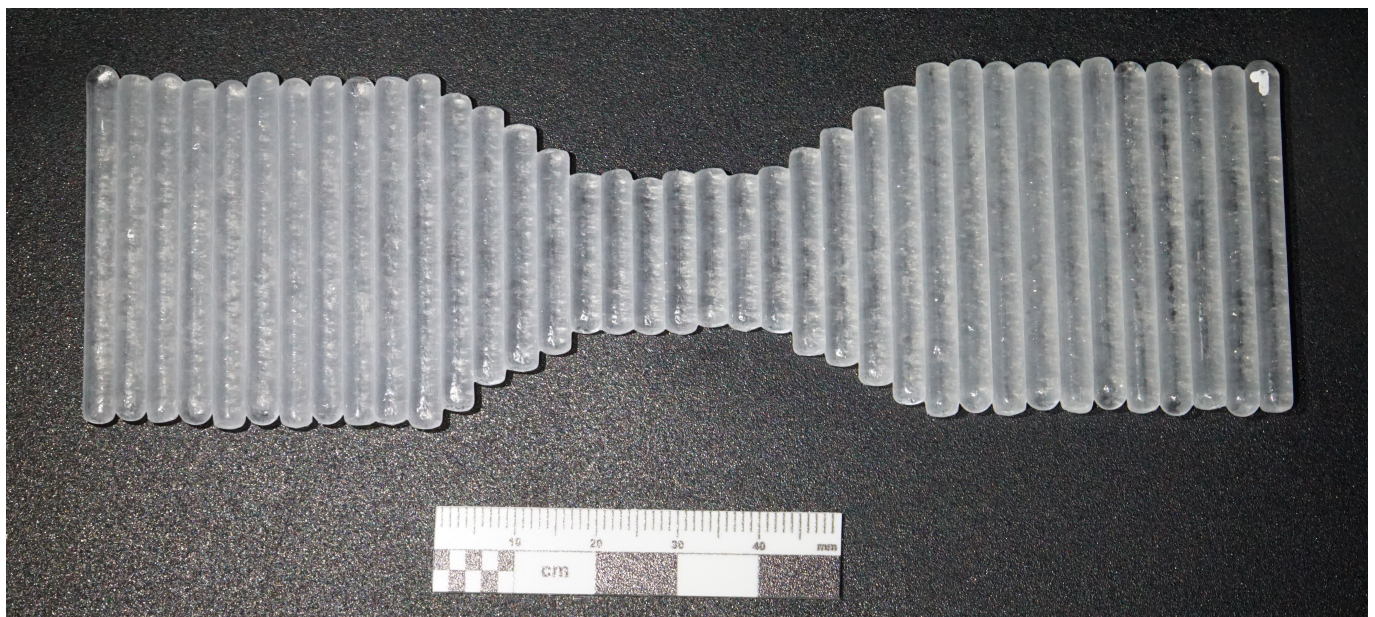


Figure 4.10.: Test specimen N1-90 made by hand.

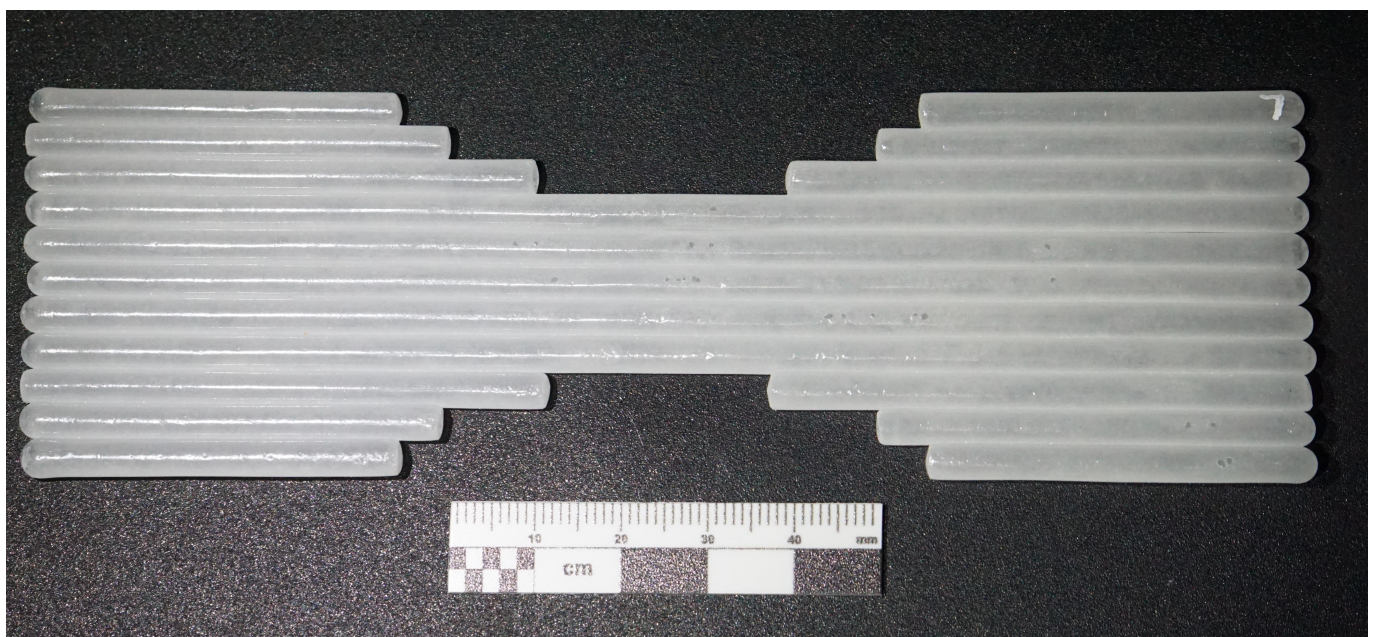


Figure 4.11.: Test specimen N6-0 made by hand.

All 21 specimens were cleaned with isopropyl alcohol and measured at 10 different points using a caliper (linearity ± 0.05 mm), with particular attention paid to capturing thickness variations due to notches. Since the specimens were not completely flat, as expected, a straightedge was used to record the irregularities/elevations. Additionally, the specimens were weighed on a scale with a linearity of ± 1 g. The measurement data can be found in Appendix A.4.

The specimens were examined for residual stresses using polarized light and a polarizing filter, with no

residual stresses detected in any of the specimens.

Subsequently, both sides of the specimens were covered with a transparent PVC adhesive film as prescribed in DIN EN 1288-3 [34] to hold the fragments together. The adhesive film thickness is 100 μ m.

4.3. Setup

4.3.1. Test setup

The machines and components used for this test can be found in Table 4.2.

Component	Description
Testing Machine	ZwickRoell Z050
Load Cell	ZwickRoell Performance P (within the range of 5 N-150 kN linearity of $\pm 1\%$)
Displacement Transducer	Laser displacement sensor Keyence IL-030 (in the range of 20-45mm linearity of $\pm 0.1\%$).
Blades	Made of stainless steel with a radius of 6 mm, length 100 mm
Elastomer on Blades	3 mm thick EPDM conforming to ISO 48 (IRHD: 40 $\pm$ 10)
Testing Software	ZwickRoell testXpert III

Table 4.2.: Machines and components used for the four-point bending test

The experimental setup is illustrated in Figure 4.12 and follows the guidelines of DIN EN 1288-3 [34]. The dimensions are as follows:

- Support span $L_s = 130$ mm
- Load application span $L_b = 70$ mm
- Lever arm (distance between support and load application) $L_w = 30$ mm

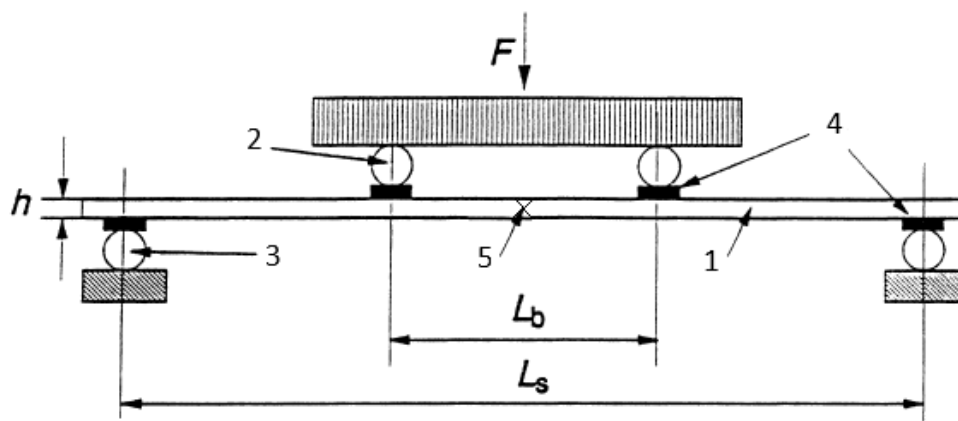


Figure 4.12.: Test setup based on DIN EN 1288-3 [34]. (1) represents the test specimen, (2) the load blades, (3) the bearing blades, (4) the elastomer on blades and (5) the point for measuring the deflection.

This setup deviates from DIN EN 1288-3 [34] in terms of dimensions and does not use load and support edges that are freely rotatable along the longitudinal axis of the blades. The dimensions conform to DIN 843-1 [51] for four-point testing of small ceramics, which specifies that the edges must be rotatable up to 15° parallel to the longitudinal axis of the specimen. In this setup, the support edges allow rotation of $\pm 10^\circ$, while the load edges permit coupled rotation of $\pm 1^\circ$ around the specimen's longitudinal axis (see Figure 4.13). The plate with the load edges is pivotally mounted at the point of force application, allowing the edges to align towards the specimen. The deflection of the specimen at its center of gravity was recorded using a laser displacement sensor.

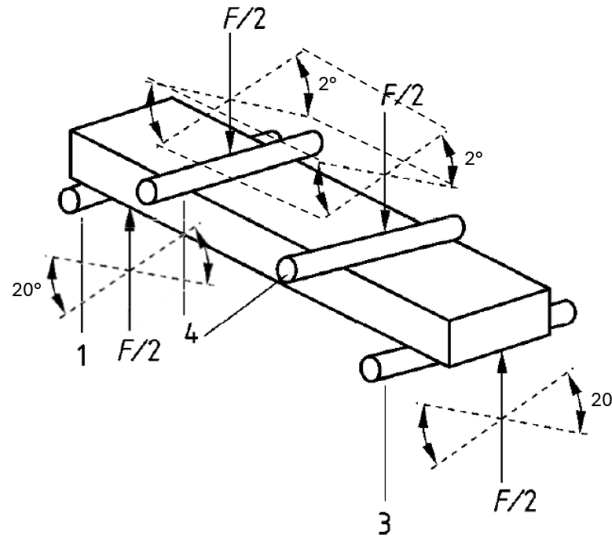


Figure 4.13.: Illustration of the freedom of rotation of the load and bearing blades with a clamped cubic test specimen.

A picture of the finished experimental setup can be found in Figure 4.14.

4.3.2. Execution

The experiment was conducted at a temperature of 22°C and a relative humidity of 44%. Due to the very low forces encountered, the load application rate prescribed in DIN EN 1288-3 [34] was reduced from 2 MPa/s to 1 MPa/s (equivalent to 1.5 N/s). Measurements were taken every 0.1 s using the testXpert III software.

Specimens were centrally placed and aligned in the setup, with the print bed side facing upwards (into the compression zone) so that the typical AM surface was in the tension zone. A preload of 3-5 N was applied to ensure the blades aligned properly with the specimen and made uniform contact everywhere.

When the test commenced, load, specimen's deflection, and crosshead displacement were recorded until failure. Upon fracture, the testing machine rapidly retracted to prevent further loading on the break or inducing additional fractures.



Figure 4.14.: Picture of the finished test setup.

4.4. Evaluation

4.4.1. Fracture stress calculation

The fracture stress (σ_u) is calculated using the equation assuming a rectangular fracture surface:

$$\sigma_u = \frac{M}{W_y} = \frac{\frac{F}{2} \cdot L_w}{\frac{l_a^2 \cdot l_b}{6}} = \frac{3 \cdot F \cdot L_w}{l_a^2 \cdot l_b} \quad (4.1)$$

where M is the moment between the two load edges, W_y is the sectional modulus in the y-direction, l_a is the height of the fracture area (cf. Figure 4.15), l_b is the width of the fracture area (cf. Figure 4.15), F is the fracture load, and L_w is the lever arm, set at 30 mm (4.3).

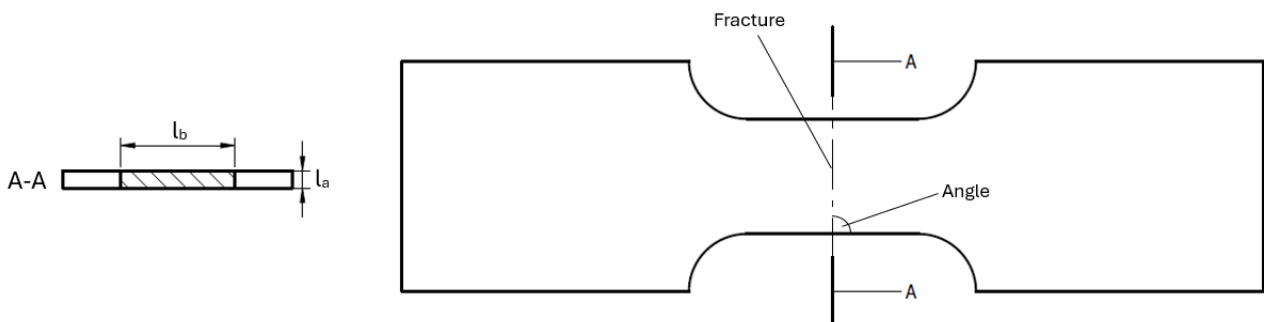


Figure 4.15.: View of the fracture surface as it is also examined in microscopy. l_a represents the height and l_b the width of the fracture area.

Calculating fracture stress introduces uncertainties that significantly affect stress values. The dimensions l_a and l_b are determined through microscopy (see Figure 4.19) with an accuracy of approximately ± 0.1 mm. Along with the uncertainties related to force measurement and the length of the lever arm (see Section 4.3), the fracture stress values are subject to an uncertainty of up to ± 4 MPa. Other influences such as uneven load application, twisting of the test specimens, etc. can contribute to further uncertainties.

The fracture stresses for individual test specimens are presented in Table 4.3. The mean value and standard deviation of the individual series is given in Table 4.4.

Table 4.3.: Fracture stress of the 21 tested specimen. The values for σ_u should be considered with an approximate uncertainty of up to ± 4 MPa, attributable to measurement inaccuracies in the fracture sides, the fracture load and length of lever arm.

#	Side A mm	Side B mm	W_y mm ³	Fracture load N	σ_u N/mm ²
0-1	2.7	23.4	28.43	81.77	43
0-2	2.3	21.9	19.31	54.49	42
0-3	2.3	29	25.57	62.23	36
0-4	2	24.1	16.07	42.53	40
0-5	2.2	22	17.75	45.12	38
90-1	2.9	21.1	29.58	92.53	47
90-2	3.2	22	37.55	142.36	57
90-3	2.6	19.9	22.42	81.25	54
90-4	2.6	23	25.91	101.85	59
90-5	2.8	24.1	31.49	127.96	61
45-1	2.9	21	29.44	51.09	26
45-2	2.2	20.4	16.46	66.28	60
45-3	2.8	20.5	26.79	61.63	35
45-4	2.8	22.5	29.40	76.09	39
45-5	2.5	21.8	22.71	55.3	37
N1-90	1.7	20.6	9.92	17.36	26
N2-90	1.7	20.4	9.83	15.67	24
N3-90	1.7	20.8	10.02	31.57	47
N4-0			29.80	92.94	47
N5-0			29.80	71.72	36
N6-0			29.80	75.31	38

4.4.2. Statistical analysis of results

The correlation between angle orientation (0° , 90° , 45°) and fracture stress was statistically analyzed across all 15 specimens tested by Maple Glass Ltd. (Series 0-1 to 0-5, 90-1 to 90-5, and 45-1 to 45-5), yielding the following metrics:

- Pearson's $r = 0.608$
- Pearson's p -value = 0.01605
- Spearman's $\rho = 0.539$

Table 4.4.: Mean value and standard deviation of each series.

Series	Mean value N/mm^2	Standard deviation N/mm^2
0°	40	3
90°	56	5
45°	39	13
N-90	34	13
N-0	40	6

- Spearman's p-value = 0.03811

Assuming a significance level of 0.05, both tests reveal statistically significant relationships, with Pearson highlighting a linear and Spearman a monotonic relationship.

Notable outliers in the 45° series impacted the results' variance. Therefore, a focused analysis on the 0° and 90° series found:

- Pearson's $r = 0.897$
- Pearson's p-value = 0.000441
- Spearman's $\rho = 0.870$
- Spearman's p-value = 0.001053

These significantly low p-values (<0.001) indicate a very strong statistical significance. The cause of outliers at 45° is discussed in Section 4.4.6.

Despite the small sample size of 15 specimens, potential high variability did not manifest. However, the limited sample size resulted in wide confidence intervals, affecting generalizability.

4.4.3. Fracture behavior and fracture mirror

All fractures occurred as intended within the narrow web, aligning with the chosen geometry (cf. Section 4.1), except for one specimen (0-3) where the fracture extended from the narrow web into the broader area.

Seven specimens (0-1, 0-2, 0-4, 45-1, 45-3, 45-4, 45-5) exhibited a completely straight crack perpendicular to the longitudinal axis (90°, see Figure 4.15), indicating effective interlayer adhesion that did not follow individual layer deposition directions unlike the control specimens (N4-0, N5-0, N6-0). This straight fracture path also suggests uniform load introduction. The fractured state of Specimen 0-1 is shown in Figure 4.16.

All specimens in the 90° series had at least 3 cracks (typically originating from the same point) that did not always follow a straight path but sometimes angled through the thin web. Compared to handmade specimens (N1-90, N2-90, N3-90), which break along the layer junctions, a good interlayer bond is evident. Specimen 90-2 showed 6 cracks, indicating significant energy release upon failure, consistent with the high fracture stresses observed in the 90° series. Figure 4.17 shows Specimen 90-1 with 3 occurring cracks.

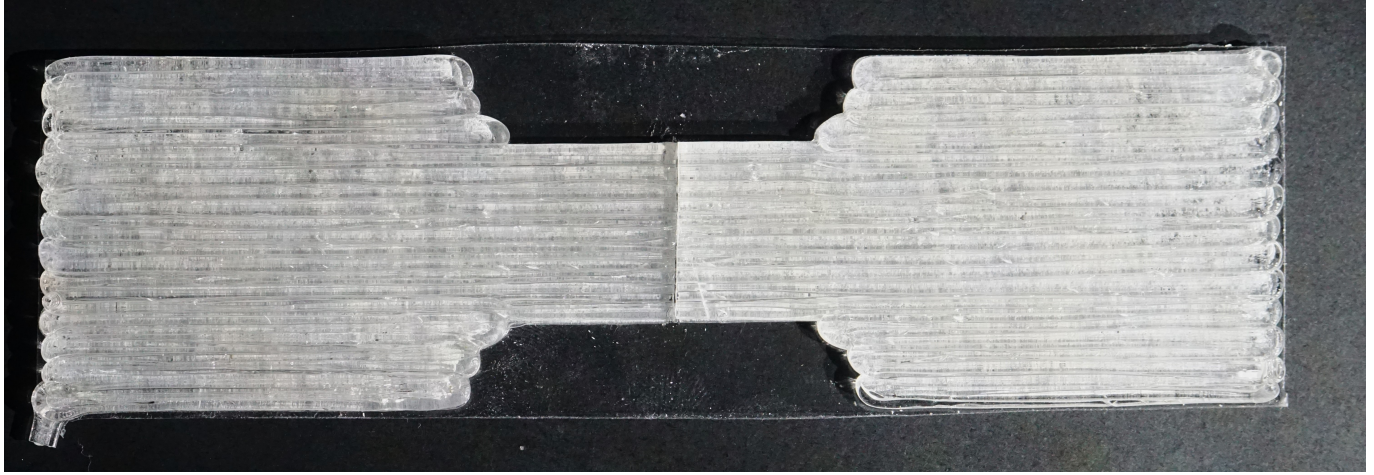


Figure 4.16.: Specimen 0-1 in the fractured state. The crack is perpendicular to the longitudinal axis of the specimen.



Figure 4.17.: Specimen 90-1 in the fractured state. The specimen is broken into 4 pieces from one fracture origin.



Figure 4.18.: Specimen 45-2 in the fractured state. The crack runs perpendicular to the longitudinal axis of the specimen and then splits into 2 angled cracks.

Fractography typically aims to identify both the origin and mirror of a fracture to infer the cause of failure and deduce material properties. The fracture mirror radius r_m is calculated as:

$$r_m = \left(\frac{A_m}{\sigma_u} \right)^2 \quad (4.2)$$

with $A_m = 1.8 - 1.9 \frac{\text{N}}{\text{mm}^2} \sqrt{\text{m}}$ for soda-lime glass [110].

For specimen 90-5, with the highest fracture stress, a fracture mirror radius $r_m \approx 1$ mm was determined. For the weakest, 45-1, $r_m \approx 5$ mm. Thus, individual fracture mirrors might be observable under a microscope, especially for specimens with high fracture stress and few defects.

Wallner lines, which can help trace the fracture origin, were observed in some specimens (cf. Figure 4.22), allowing inferences about the fracture origins.

4.4.4. Microscopy

The microscope Dino-Light Edge Plus was employed for microscopic examinations, utilizing polarized light and multiple polarizing filters to achieve high-contrast and informative images. The small and often non-flat fracture surface, combined with significant reflections due to the surface structure, made imaging challenging. Alternative microscopy methods or equipment may be necessary for sharper, higher-quality images.

Microscopy images presented include the strongest and weakest specimens from each series, with the pressurized side (also the print bed side) oriented upwards. Blue lines highlight individual layer boundaries, a yellow circle indicates the presumed fracture origin, and red circles mark voids. Green traces Wallner lines, visible in some specimens. The fracture mirror could not be detected with the technology used here.

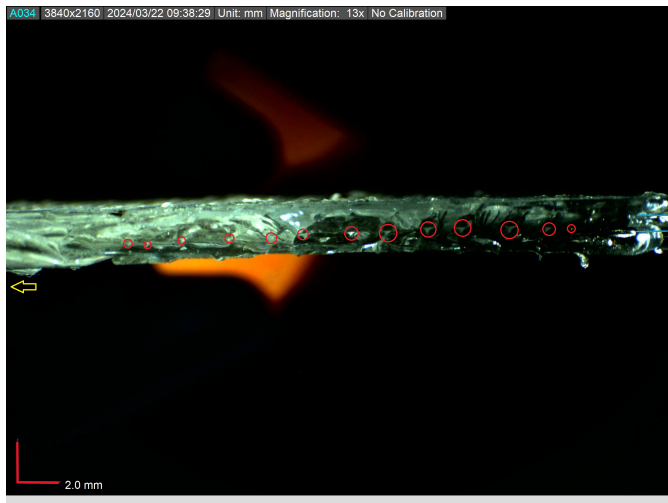


Figure 4.19.: Microscopy of the fracture area of specimen 0-3. Voids are marked in red, the individual layers with blue lines and the suspected fracture origin in yellow. Side under compression load in testing is facing upwards.

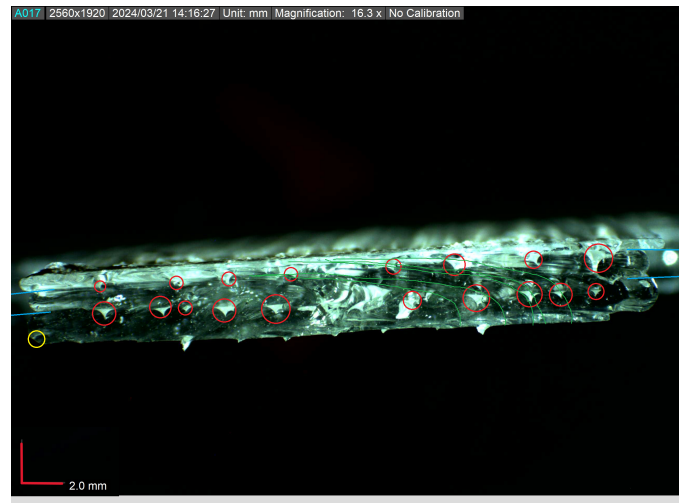


Figure 4.20.: Microscopy of the fracture area of specimen 0-1. Voids are marked in red, the individual layers with blue lines, Wallner lines with green lines, and the suspected fracture origin in yellow.

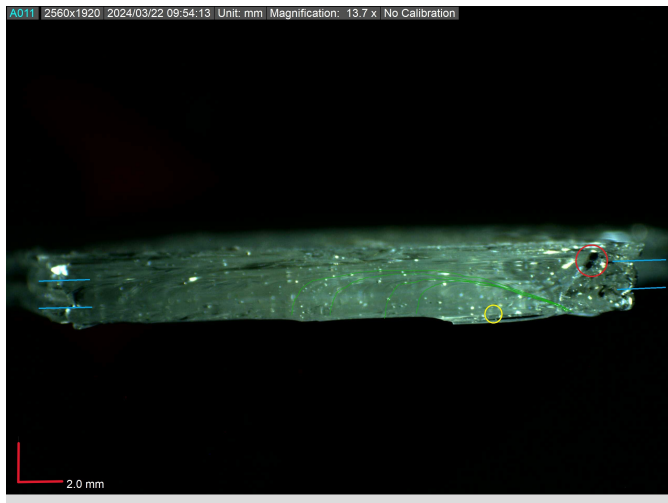


Figure 4.21.: Microscopy of the fracture area of specimen 90-1. Void is marked in red, the individual layers with blue lines, Wallner lines with green lines, and the suspected fracture origin in yellow.

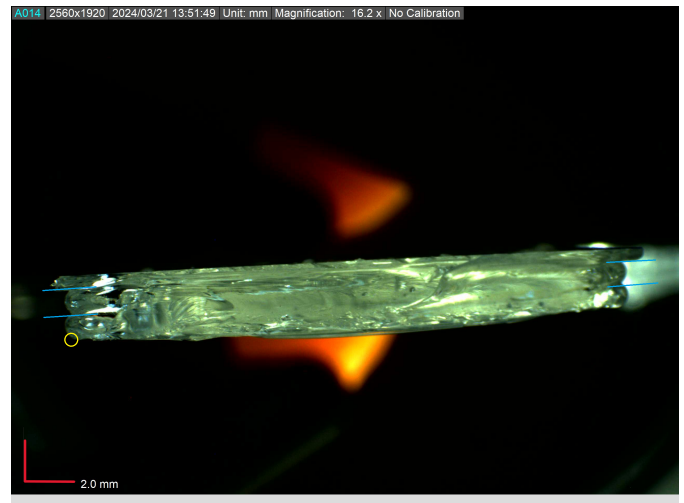


Figure 4.22.: Microscopy of the fracture area of specimen 90-5. The individual layers are marked with blue lines, and the suspected fracture origin in yellow.

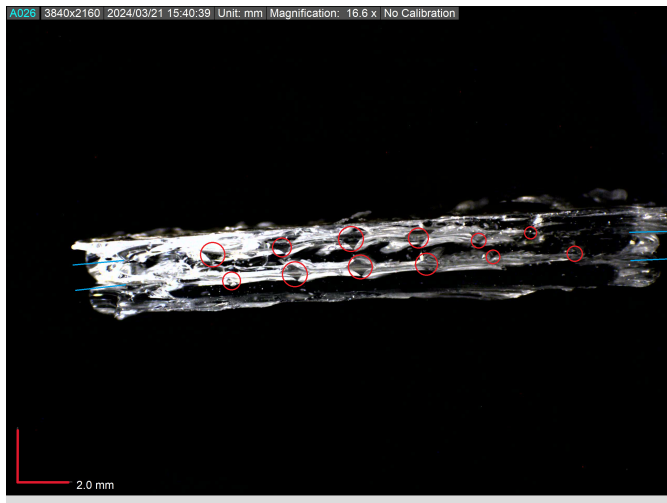


Figure 4.23.: Microscopy of the fracture area of specimen 45-1. Voids are marked in red and the individual layers with blue lines.

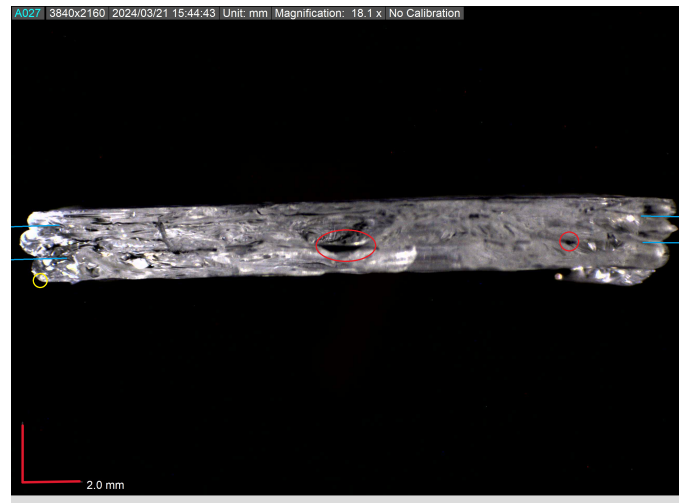


Figure 4.24.: Microscopy of the fracture area of specimen 45-2. Voids are marked in red, the individual layers with blue lines, and the suspected fracture origin in yellow.

As indicated by the red circles, numerous voids were observed within the fracture surfaces. A correlation between the number and size of these voids and the fracture stress was identified. While the highest-performing specimens (90° series) exhibited few or no voids (see Figures 4.21 and 4.22), specimens from the 45° (see Figure 4.23) and 0° (see Figures 4.19 and 4.20) series showed many such voids. Notably, the strongest specimen of the 45° series (45-2, see Figure 4.24) had a low number of voids, aligning with this observation.

Table 4.5.: Number of voids observed by microscopy.

Test specimen	Number of voids
0-3	14
0-1	19
90-1	1
90-5	0
45-1	14
45-2	2

These observations were made solely on the fracture surface. To robustly support this hypothesis, further sectional analysis of the specimens, both longitudinally and transversely, would be necessary.

4.4.5. Manufacturing process

Efforts were made to maintain consistent parameters during specimen production, except for the toolpaths, which varied significantly across series to create different layer orientations. These variations in toolpaths, especially in terms of thermal management, significantly impacted the manufactured specimens and their ultimate performance.

The toolpaths are described as follows:

- For the 90° series, paths were short and rapidly repeated, allowing previously printed layers to retain heat, with nozzle radiation continuously warming the contact surfaces.
- In the 45° series, paths were approximately 50% longer than those of the 90° series. The nozzle was paused twice during the printing of the web to complete external corners, moving slower at the corners of layer lines than in the 90° series.
- The 0° series involved extremely long paths, with the nozzle printing over distances exceeding 300 mm to reach certain contact points. Outer contours were printed first, resulting in subsequently printed internal lines encountering cooler contact points.

A comparison of the three toolpaths at 50% printing time of the first layer is provided in Figure 4.25.

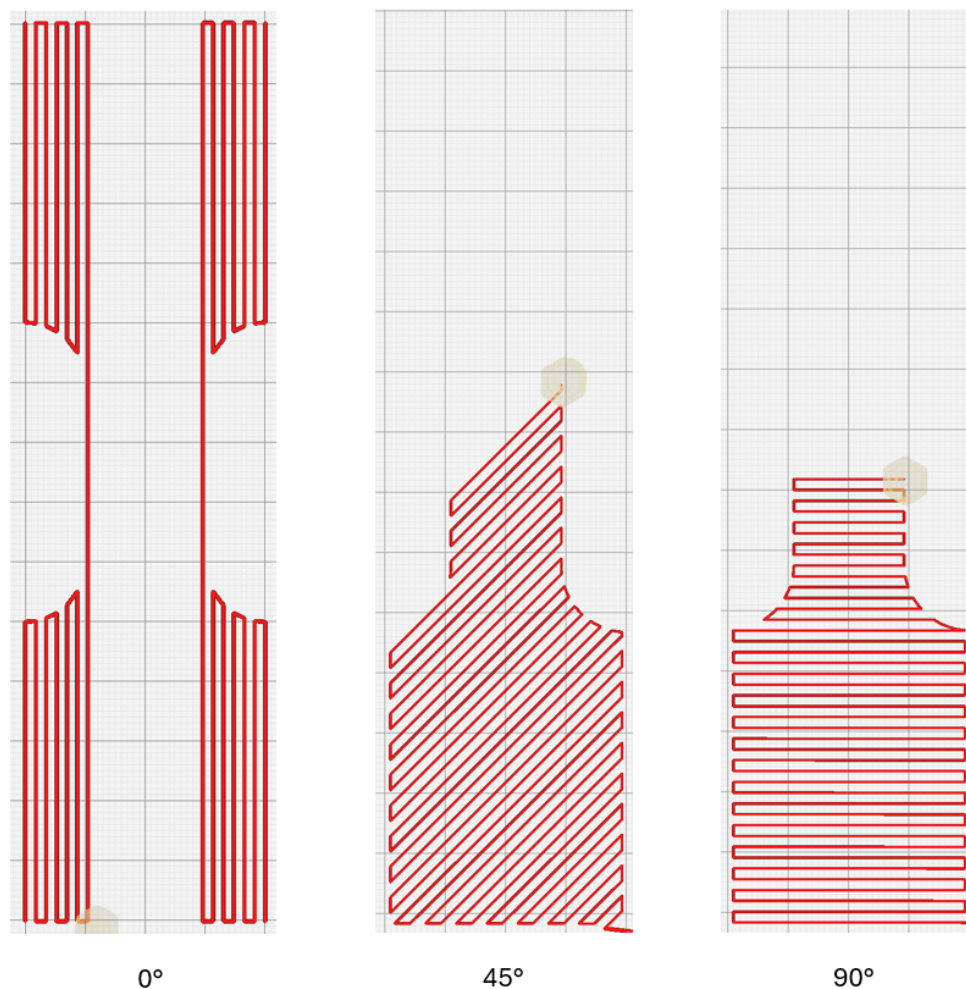


Figure 4.25.: Toolpaths of the different layer orientations at 50% of the first layer.

4.4.6. Interpretation of experimental results

Despite the limited number of specimens, the results are statistically significant, indicating the 90° series exhibits the highest fracture stress. A correlation between void presence and fracture stress suggests that

process parameters associated with different toolpaths, rather than the intended surface texture of the series, are critical for fracture stress.

Specimen 45-1 is identified as an outlier, possibly due to its significant warping/non-planarity of approximately 3mm, probably leading to uneven load introduction not accommodated by the experimental setup.

Specimen 45-2, which also deviates significantly, showed few voids in microscopic examination. The reason for 45-2 having fewer process-induced voids compared to other specimens in the 45° series remains unclear.

The fracture stresses of handmade samples are significantly exceeded by the 90° series, while the fracture stresses of the 45° and 0° series are comparable to those of the N0 series.

5. Discussion

5.1. Assessment of optimized plates

5.1.1. Manufacturability

The optimizations in Chapter 3 ensured the manufacturability of glass plate structures from the outset. Adhering strictly to a 0° overhang restriction and a minimum element size of 10 mm, the optimized plate structures are manufacturable with current technology, except for a limitation on the building chamber size. Solutions to this issue are discussed in the following section.

However, beyond mechanical aspects, optimizations in Chapter 3 also considered optical quality requirements and cleaning feasibility. Both criteria necessitate a uniformly smooth surface as depicted in design illustrations, contrasting with the uneven surfaces of AM Glass described in Chapters 1.4 and 2.2. Retaining this inherent surface texture may be feasible, but fails to meet the specified non-mechanical demands for optimized glass plates reinforced with AM. Test specimens produced by Maple Glass Printing Ltd. (cf. Section 4.2) exhibit a remarkably smooth surface (height variation < 0.1 mm), which is primarily sufficient for cleaning. Nevertheless, achieving the desired optical quality requires post-processing, as detailed in the following section.

5.1.2. Economics

In construction, glass plates are typically installed with 2-sided or 4-sided support (see Section 1.4). A 4-sided support requires more material for framing, but allows for significantly thinner glass plates. A comparison in Figure 5.1 for the assumed load case in this thesis shows that from both an economic and ecological perspective, 4-sided support for conventional glass plates is advantageous.

Stiffening of glass plates with AM minimizes the difference between 2-sided and 4-sided support. Variant 1d (cf. Figure 3.21), with dimensions of 3 m x 3 m, weighs 164 kg, while variant 2f (cf. Figure 3.42) weighs 138 kg, which results in a difference of 26 kg. For conventional glass plates, the weight difference for this load case and dimensions is 225 kg. Therefore, a 4-sided support is not necessarily required as the reinforced geometry of Geometry 1d (cf. Figure 3.21) activates the plate's membrane effects, assuming the support of the remaining two sides.

This fact allows for the elimination of entire substructures, saving material and costs. For plate dimensions larger than 2 m x 2 m, it may be sensible to mount the glass directly between floor slabs, avoiding entire facade constructions and associated installation costs.

In addition, the low deflection of the panels can counteract sealing problems, which are often a reason for complaints in the BE.

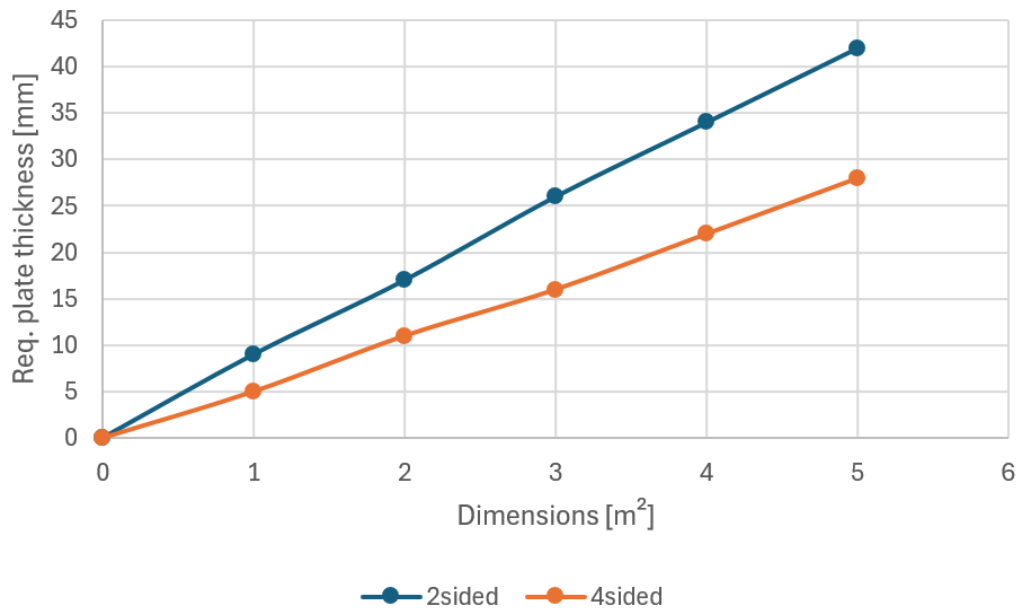


Figure 5.1.: Required plate thickness for square glass panels under support on two or four sides, subject to the load case specified in Section 2.6.

However, the cost of the AM process cannot be overlooked. As detailed in Chapter 2.3, the market price (including development, process, material costs, design, profit, and tax) of Evenline’s AM-printed Soda-Lime-Glass is 200 US-\$/kg. The AM mass for variant 2f (cf. Figure 3.42) is 48 kg, translating to a direct cost of 9,600 US-\$. Limiting the calculation to process, equipment purchase, and material costs, rough estimates place the price at about 2,000-3,000 US-\$ for this construction. With higher production volumes and integration into existing processes, as described in the following section, costs could be significantly reduced.

While undeniably costly, this is primarily due to the fact that the industry depressed the prices of conventional glass plates due to high production volumes. With rising CO₂ taxes, energy costs, and a push for sustainability (cf. Sections 1.4 and 1.1), such plate constructions could become a viable alternative with competitive pricing in the future.

5.1.3. Ecologics

Today the question of the carbon footprint or Global Warming Potential (GWP) is always pertinent. A study by the US-based Glass Packaging Institute (GPI) indicates a GWP of 1.25 kg CO₂ eq./kg of glass [11]. Even the significantly carbon footprint-reduced window glass, Oraé by Saint-Gobain-Glass [117], registers at 0.7 kg CO₂ eq./kg of glass in production. Considering variant 1d (cf. Figure 3.21) with dimensions of 3 m x 3 m, which saves 421 kg of glass compared to a conventional glass plate, and a GWP of 1.25 kg CO₂/kg glass, this equates to an approximate production-side savings of 526 kg CO₂ eq. per 3 m x 3 m glass plate.

The carbon footprint of the AM glass process is currently indeterminable. Reports from Maple Glass Printing Ltd. [2] suggest that the most significant energy consumption occurs in heating the build space, whereas the energy used for the nozzle and other components is relatively minor. The following section will introduce ideas for minimizing building chamber heating, thus avoiding additional heating and cooling steps for the glass plates.

Based on the results of this thesis, full-glass facades produced with AM-Glass geometries promise weight reductions of 50-60%. For skyscrapers or tall buildings, this weight reduction also implies a decrease in dead-loads, reducing the need for steel and concrete to support these loads.

However, CO₂ savings coupled with the issue of "green washing" are highly sensitive topics that cannot be adequately addressed here to make reliable claims. It can be noted, though, that general material savings, especially if the AM-Glass process maintains a reasonable carbon footprint, present a potential for CO₂ reduction urgently needed in the glass industry (cf. Section 1.4).

5.1.4. Safety requirements

In Section 2.1, the requirements set by legislation/standards for safety concepts of overhead glazing were thoroughly discussed. As this was subsequently overlooked in the thesis, it is briefly revisited here, focusing not on additional impacts (such as shock impacts) but on the safety of individuals in the event of failure.

This safety can preferably be ensured through LSG for the selected application, as detailed in Section 1.4.4. This approach is feasible because, as planned, printing on one side of the glass plate allows the other side to be used for lamination purposes, leading to two sensible scenarios:

1. Laminating two identical AM-Glass-reinforced plate geometries with the AM geometry on the outer sides. However, having an AM-Glass geometry on the exterior introduces challenges such as increased cleaning effort, additional wind loads, etc. (see Section 1.6).
2. Laminating a conventional glass plate with an AM-Glass-reinforced plate. This takes advantage of the fact that failure represents an unusual load, allowing reduced loads to be considered. Thus, a relatively thin conventional glass plate can be chosen, primarily to catch and secure the weight of a broken AM-Glass-reinforced plate, preventing it from falling. Adjusting the various stiffness ratios within an LSG composite will present a challenge.

Alternative methods to meet safety requirements may include thermal tempering and other structural measures.

5.1.5. Other requirements

Beyond the neglected requirements in Section 2.4, the geometries generated herein introduce new requirements/questions that need exploration, including:

- The emergence of shear stresses, previously negligible in classic plate geometries. As discussed in Section 3.5 these may pose a failure risk if the interface's shear strength is insufficient.
- New wind load considerations. Especially for geometries on the building's exterior, as well as for geometries on the buildings's interior, new surfaces susceptible to wind forces require examination.
- Stability studies. Conventional glass plates did not previously face the risk of stability failure due to buckling, etc.

5.2. Ideas for improvement in manufacturing

5.2.1. Integration into existing processes

To avoid economic and ecological disadvantages, reheating a glass plate along with its build space should be avoided. Two solutions are proposed:

- Integration into the Float process: An approach is to construct mobile 3D printers that accompany the cooling process of flat glass sheets over 300-1000 m and apply additive glass in the appropriate temperature range of 550-800°C (for SLG). Alternatively, interrupting the cooling process of flat glass sheets before they drop below the glass transition temperature (T_g) and transferring still-hot plates to 3D printers is another. An illustration of float-glass lines is shown in Figure 1.14.
- Integration into the heat-strengthening process (cf. Section 1.4): For the production of FTG or HSG, the glass plates must be heated above T_g . This process could be combined with 3D printing, where plates are heated, additive glass is applied, and then quickly cooled to induce the desired pre-stress.

Figure 5.2 depicts a conceptual life cycle for flat glass in the building industry where the AM process is integrated into the float line process.

5.2.2. Strengthening of AM Glass through thermal or chemical treatment

Incorporating the heat-strengthening process into AM of glass offers both economic and ecological benefits by combining two processes, and significantly increases the strength of AM glass. This enhancement in strength can also be achieved through chemical treatment of the glass (cf. Section 1.4).

Enhancing the strength of AM glass presents additional optimization potential, allowing for increased material load capacity. If thermal treatment, similar to that used in HSG as mentioned in Section 1.4, doubles or triples the characteristic strength, it would result in significant material savings in the optimization process. Increased strength, applied to the geometries discussed here, would lead to steeper contours in the z-direction, thinner webs, and fewer stress concentrations that need elimination.

5.2.3. Optimization with consideration of compressive strength

The significant difference between the compressive and tensile strength of glass, as mentioned in Section 1.4, was only considered during the manual post-optimization phase of the optimization process. However, this characteristic has the potential, similar to thermal treatment, to assume a significantly higher strength under specific load conditions. For the load case of wind load + self-weight discussed in this thesis (cf. Section 2.6) for vertical glass, this property was only partially relevant as the pressure and suction of the wind did not vary significantly. In applications, especially in horizontal glazing (cf. Section 2.1.4), where loads due to gravity are always directed in one direction, it is recommended to take advantage of the high compressive strength of glass.

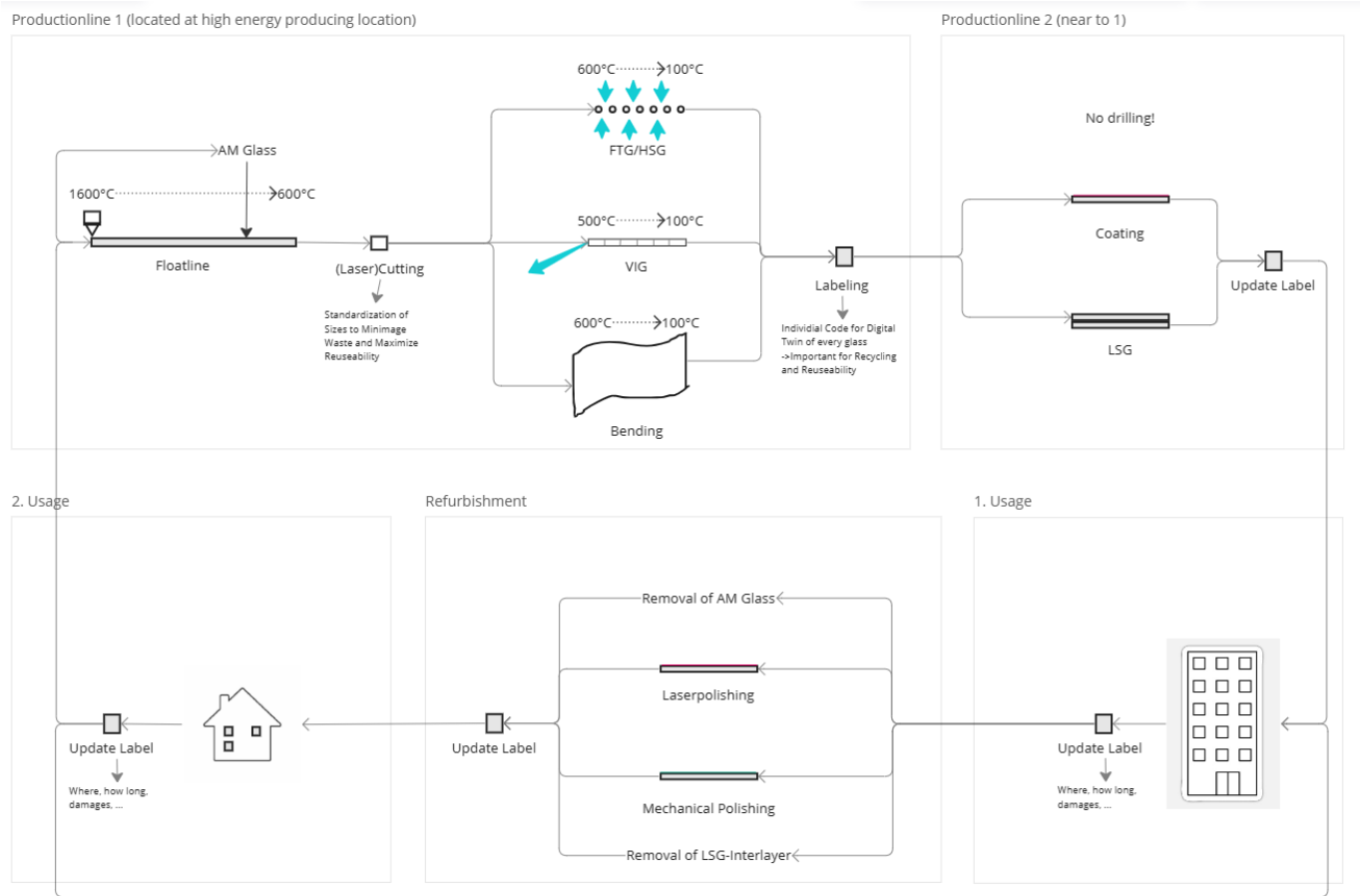


Figure 5.2.: Concept of circularity of glass in the BE. The initial production phase aims to consolidate all energy-intensive processes to avoid unnecessary heating of glass panels, including the AM Glass process. Production line 2 combines less energy-intensive processes. Through standardized labeling, production, usage, and damages can be documented, thereby simplifying the reuse, refurbishment, and recycling processes.

5.2.4. Suitable process settings

Specimens from Maple Glass Printing Ltd., tested in Chapter 4, were printed with a nozzle diameter of 1.5 mm and a layer height of 1 mm. While suitable for fine geometries (e.g., Figure 2.17a), this setup would be time-intensive for the 48 kg of AM print mass required by Geometry 2f (cf. Figure 3.40). Hence, a 10-mm nozzle diameter is recommended for these geometries to print the wall structures in a single line. Experimentation with rectangular nozzles could yield more uniform, yet angular geometries at a 10-mm nozzle diameter.

A layer height of approximately 1 mm is suggested to minimize the stair-step effect typical in 3D printing and achieve a consistent exterior wall/surface. The print process for Geometry 2f (3.40), measuring 3 m x 3 m, would take about 50-55 minutes for a maximum defined build height of 200 mm at a print speed of 100 mm/s, including movement times.

5.2.5. Postprocessing

Postprocessing is a critical next step for AM Glass using DED and FDM, as glass is inherently associated with high transparency. This demand for a smooth surface, both important aesthetically and for ease of cleaning, does not necessarily impact the mechanical quality of the glass, as Chapter 4 suggests.

Three postprocessing ideas are introduced:

- Flame Polishing: Using gas flames (hydrogen, etc.) to locally heat the surface of hot AM parts, making it flow into a smooth finish.
- Laser Polishing: Applying lasers to polish the surface of cold AM parts, with the caveat that the notches of the part should not be excessively large. The Fraunhofer Institute for Laser Technology, for instance, provides suitable solutions [83].
- Mechanical Polishing: Treating the surface of cold AM parts with traditional mechanical polishing tools, either by hand or machine. However, it's suspected that mechanical polishing might adversely affect the glass's strength.

5.3. Assessment of mechanical tests

The test developed for generating material models of AM Glass within this thesis proved reliable and functional. Despite a small sample size (here 5 per Series), the outcomes are statistically significant with minimal variance particularly for glass, successfully eliminating local effects of loading blades and glass edges through chosen geometry.

The tests revealed that the dependence of the specimen strength on the various layer orientations is production related. The reason for this is that the test specimen experienced different thermal profiles during printing due to the different toolpaths of the layer orientations, which significantly influenced the bond between the layers. An influence of the general layer orientation or surface geometry is not suspected or considered minimal.

The hypothesized anisotropy or transversal isotropy through surface effects in FDM-manufactured glass components, as discussed in Chapter 3, was not supported by mechanical tests in Chapter 4, diverging from Klein et al. [77] and experiences with additive manufacturing in polymers or metals (cf. Section 3.1). It is speculated that, under strict process control, isotropically behaving specimens or components can be produced using the method employed here.

However, to draw statistically reliable conclusions, a larger number of test objects is required. An initial reliable assessment would necessitate approximately 15-30 test objects for each layer orientation depending on the coefficient of variation, totaling up to 90 specimens. In addition, specimens should be produced with consistent quality and minimal inclusions of air or other substances to draw reliable conclusions about the influences of surface geometry.

Reliable comparative values are lacking, as they cannot be ensured through handmade samples. Such a benchmark could be obtained by testing individual filament strings that are used as raw material for the specimens. The experimental setup developed for this thesis can also be employed for this purpose.

A comparison with the strength of untreated float glass from SLG is feasible to ascertain a specific strength magnitude. Lindqvist [86] conducted experiments on a series of 4 mm thick SLG specimens with similar dimensions (area under constant moment load: 40 mm x 10 mm) as those used in the current study, utilizing

four-point bending tests to highlight differences attributable to edge finishing. The mean fracture strengths observed range from 50-95 MPa for untreated, arised, and ground edges, showing a similar or slightly higher deviation as in the conducted tests in Chapter 4. Specifically, the 90-degree series exhibited a mean strength of 56 MPa, positioning it at the lower boundary, yet within the range of fracture strengths reported by Lindqvist. This suggests that the specimens from the 90-degree series demonstrate marginally lower, yet still adequately high strengths compared to standard float glass. Nevertheless, a reliable comparison can only be achieved through the aforementioned tests of the raw material.

The assumed strength for the material used in optimization in the XX- and YY-directions, as described in Section 3.1, aligns well with the results of the 90° series. Assuming untreated float glass, a maximum strength of $R_{d,x,y} \approx 17.5$ MPa could be expected. The strength used for optimization, $R_{d,x,y} \approx 15$ MPa, is slightly lower than that of float glass, consistent with the behavior of the test specimen. However, the 50% lower strength assumed for the ZZ-direction in Section 3.1 does not match the experimental findings, as the estimated lower strength of the layer bond (90°-Specimen) could not be determined.

This assessment currently applies only to FDM processes that use the Maple 4 glass printer with specific settings. It's conceivable that minor process adjustments could significantly alter component behavior. Further testing with other FDM glass printers, especially those with larger nozzle diameters (and thus larger surface effects), such as Evenline's or TU Darmstadt's, is necessary.

Section 2.5 left open whether such a test could be eligible for load-bearing proof in approvals. Currently, approval is only possible through component testing of products as they will be installed, which misses the objective of individual AM components that rarely share the same geometry. Material model tests from printers represent the preferred approach, suggesting that in future computer-controlled processes instead of individual components were approved. The here developed test, noted for its reliability, efficiency, and ability to negate extraneous influences, presents a promising avenue for qualifying AM Glass processes, advocating its use as evidence in regulatory approvals.

5.4. Ideas for improvement in testing

No suggestions for further improvement of the test execution conducted here are available. All objectives and requirements set forth in Section 4.1 have been met. There were no observed effects from load application/-support nor reduced strength due to cutting edges. The test was cost-effective, effort-efficient, and proved to be user-friendly for the test subject.

To better understand the correlation involving voids, more comprehensive investigations are required, utilizing the following approaches:

- Enhanced microscopy in conjunction with grinded surface pattern.
- Cross-sectional cuts of the specimens away from the fracture surfaces.
- CT scans, although costly.
- Density displacement tests.

Additionally, modeling the impact of voids on fracture stress using FEA should be considered for a deeper understanding.

A chemical analysis of the printed glass is recommended, as sheet glass used for artistic purposes often differs slightly from float glass and thus may have slightly different physical properties (cf. Section 3.1).

Expanding this test to the DED process is desirable. One idea is to print the test geometry onto thin base glass plates (1-2 mm thickness). Alternatively, incorporating a glass part in which the specimen is "welded" on the side and later detached could be explored. Conducting the test with SLA specimens should be feasible, offering reliable tensile strength determination even without expecting anisotropic behavior.

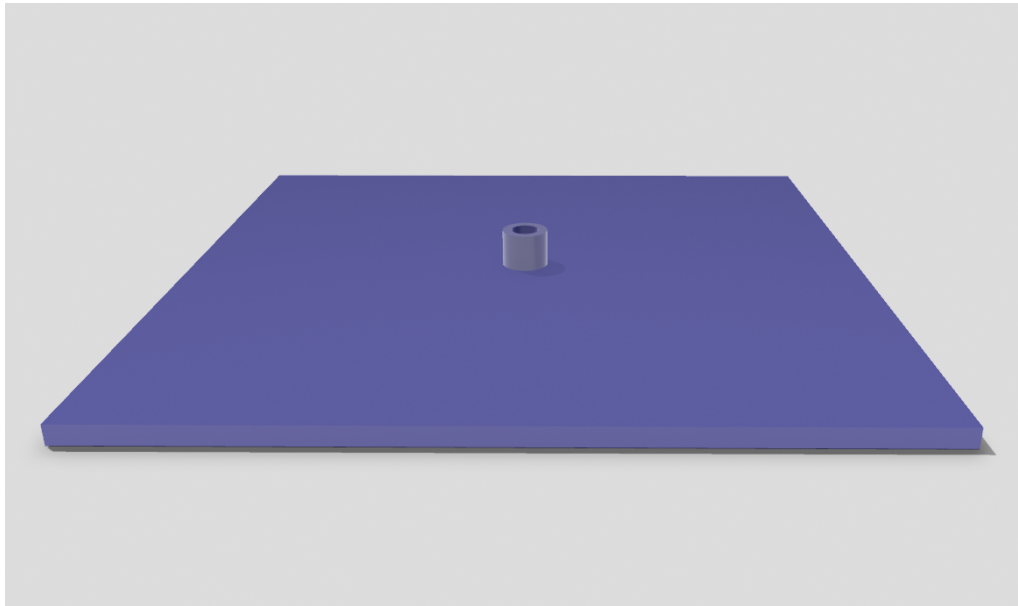


Figure 5.3.: Developed specimen geometry for classifying the bond strength between flat glass and printed additive manufactured glass using a double ring bending test. The base plate is 150 mm x 150 mm x 4 mm, with the print being 8 mm high and 10 mm in diameter.

For standalone AM glass components, no further test setup is necessary. Beyond the tests conducted here, the behavior of 3D-printed glass components in larger dimensions and with greater thickness (more layers) is of interest. These can also be examined using a four-point bending test with bone geometry. Based on these tests, which have proven reliable in Chapter 4, reliable material models for the respective processes can be established. Shear tests, or tests aimed at inducing failure in glass under Mode II or mixed-mode strain (cf. Section 3.1), appear to be irrelevant for standalone AM Glass applications (cf. Section 1.6).

The conducted test does not provide insights into the bond with an existing glass plate, which is of particular interest in this thesis. To classify the composite action between the base plate and AM glass at the interface, double ring bending tests on printed circular geometries on flat glass were considered (see Figure 5.3) but not completed in time. These are essential for future studies to determine if the optimization of glass plate structures should account for three materials (different strengths of the base plate, interface, and AM Glass), two materials (combined strengths of interface and AM Glass, different base plate strength), or a single homogeneous and isotropic material (where the strengths of the base plate, interface, and AM Glass are equal).

6. Summary and outlook

6.1. Summary

The thesis titled "Optimization of Glass Plate Structures with Additive Manufacturing" focused on optimizing glass plate structures subjected to bending loads in the built environment. This is achieved by employing a stiffening construction produced through additive glass manufacturing. The objective is to create a concept that allows the use of thinner glass plate structures, thus enhancing the resource efficiency of glass material utilization.

For this, the thesis highlighted at the beginning of Chapter 1 the critical need to reduce the environmental footprint of glass production by leveraging AM to selectively reinforce glass plate structures, thus minimizing material use while maintaining or improving structural integrity. The chapter delved into the state of the art in glass in BE, in AM technologies in BE and in AM Glass, assessing their potential applications of adopting such technologies in glass and facade engineering.

A significant contribution of this thesis is the detailed examination of the mechanical, optical, and economic requirements for glass in building structures in Chapter 2. This examination considers all glass panels in the BE that are subjected to bending loads, including facades, barriers, horizontal and interior glazing. Alongside legal requirements have been investigated in order to take these into account in the conceptual phase and to quickly legalize glass panels reinforced with AM into the BE. Through this comprehensive review of existing glass types and their applications, this thesis sets the stage for exploring how AM can revolutionize the design and construction of glass structures.

The core of the thesis is the experimental and theoretical optimization of glass plate structures in Chapter 3. It presents a methodical approach to TO, evaluating different algorithms, software tools, and optimization methods. For this purpose, the physical properties, material model and fracture mechanical behavior of 3D-printed SLG were discussed, providing a foundation for the optimization process. While facing challenges in this unusual TO problem, a working workflow was developed. With this, it is possible to develop appropriate geometries for corresponding applications and framework conditions, taking into account mechanical, optical, structural, aesthetic, and other requirements. By creating different optimized geometries for a defined load case, it shows the potential to improve the structural efficiency of glass plates with material savings of up to 70%.

During the development of various optimized geometries, it was observed that the specific stiffening geometry does not significantly influence overall performance, indicating the existence of multiple functionally equivalent geometries with similar mechanical performance. This finding allows for considerable design flexibility and individuality in the corresponding glass plate structures. Additionally, methods were identified that modify proposed geometries through local shape optimizations or minor displacements to meet stress requirements effectively.

The development of geometries was conducted for both two-sided and four-sided support configurations. In the case of conventional glass plates for the assumed application, a weight difference of 225 kg occurs between two-sided and four-sided supports. However, for optimized glass plates with dimensions of 3 m x 3 m, the difference is reduced to approximately 26 kg. These results suggest that entire substructures could be omitted for AM-reinforced glass plates with only a slight increase in material usage for the stiffening geometry. However, a two-sided support configuration for reinforced glass plates offers less design flexibility compared to a four-sided configuration.

Mechanical tests on AM glass in Chapter 4 further underscore the practical aspects of this research, offering insights into the material properties and the performance of optimized glass structures. A reliable testing procedure has been developed to quantify the material behavior and processes. Apart from many aspects that need further investigation and testing, the test specimens have shown that AM glass can be used mechanically to stiffen glass plates.

The thesis concludes in Chapter 5 with a critical evaluation of the optimized plates, discussing their manufacturability, economic viability, ecological benefits, and compliance with safety standards. The thesis proposes avenues for future research and potential improvements in manufacturing processes, highlighting the role of mock-ups and visualizations for the entry of this technology into the BE.

This thesis not only contributes to the academic discourse on sustainable glass constructions but also presents a viable path forward for the glass manufacturing industry to reduce its environmental impact. The thesis' findings demonstrate the feasibility of using AM to create optimized glass structures that meet the stringent requirements of modern construction while advancing the goals of aesthetics, sustainability and innovation in architectural design.

6.2. Outlook



Figure 6.1.: Transparent mock-up at a trade fair [93].

The beginning of this thesis stated: "The aim is to inspire the construction of a mock-up, facilitating the technology's entry into the built environment" (see Section 1.7). This thesis lays a foundational basis for the informed and scientifically grounded development of mock-ups to demonstrate the potential of AM Glass applications discussed herein, especially highlighted by the significant savings potential of specific geometries in Chapter 3 and the validation of AM Glass's load-bearing capacity in Chapter 4.

The construction of such mock-ups aims to generate future interest and attention. While scaling up the build chambers of glass 3D printers is necessary for full-scale models, further research is crucial for the deployment of such glass plate structures in construction environment. Future research must investigate into the reliability and manufacturability of glass plates reinforced with AM Glass, a scope that extends beyond the confines of a single thesis.

The test developed here can be used for such further research, as well in combination with other tests. From the author's perspective, this test could serve to classify various FDM/SLA or possibly DED processes and establish a type of benchmark. Such a benchmark test can help determine the suitable process for the specific application area of AM glass and contribute to the improvement of individual AM glass processes, especially in the BE.

6.3. Beautiful side of non-flat glass in architecture

For initial visualization attempts, this section presents a series of general concepts (see Figures 6.2-6.8) for the use of non-flat glass in architecture. In addition to stiffening flat glass through AM, local bending of glass panels to increase stiffness is also possible, representing the two most promising approaches for the efficient use of glass panels currently. The dissemination of these concepts and the renderings of the geometries in Chapter 3 are encouraged to highlight the beautiful and unusual aspects of non-flat glass in architecture and to bring them into reality.



Figure 6.2.: Visualization of a locally curved glass to increase the moment of inertia [93].



Figure 6.3.: Visualization of a glass facade of an inner city building, which was stiffened by local bending or AM imprint in cross shape [93].



Figure 6.4.: Visualization of a locally curved glass to increase the moment of inertia [93].



Figure 6.5.: Visualization of a fully glass facade, which was stiffened by local bending or AM imprint in cross shape [93].



Figure 6.6.: Visualization of a non-planar glass balustrade [93].

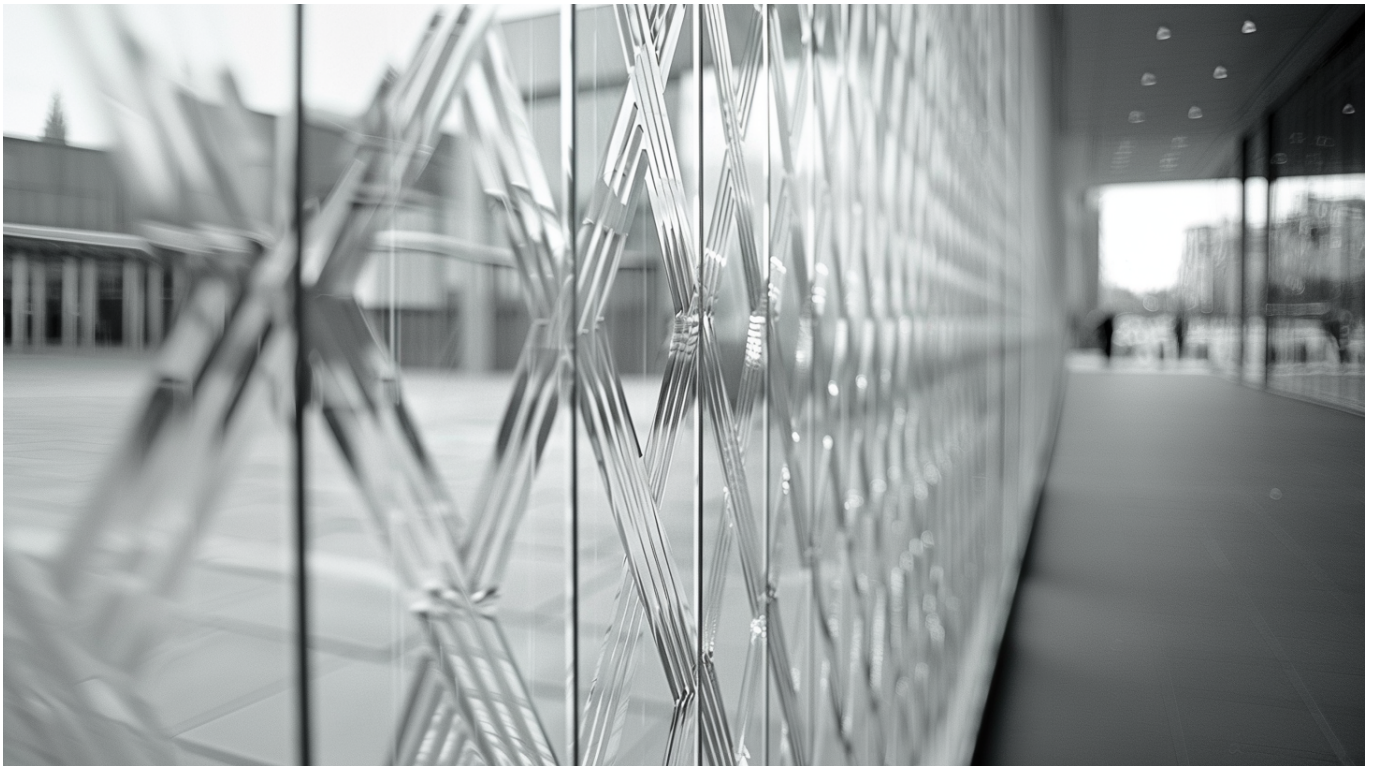


Figure 6.7.: Visualization of glass panels, which were provided with a thin line pattern via AM [93].



Figure 6.8.: Visualization of a locally curved glass to increase the moment of inertia [93].

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A. Appendix

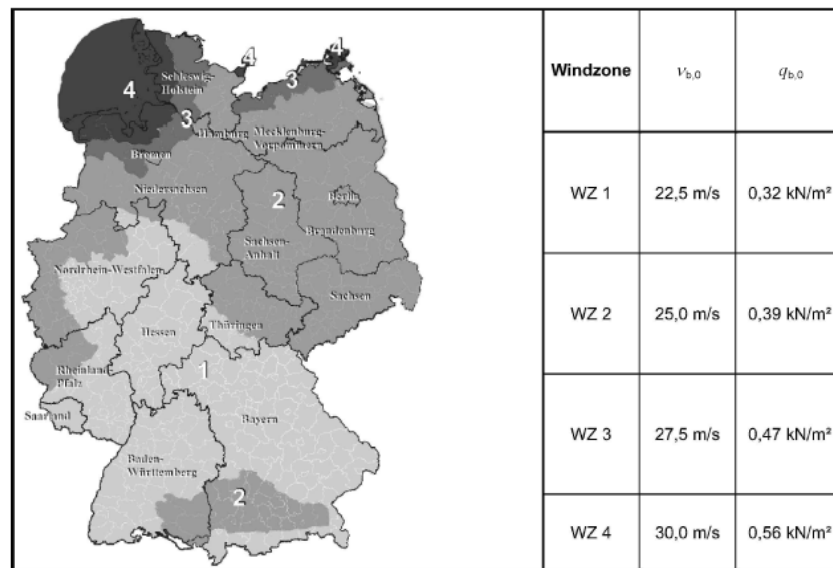


Bild NA.A.1 — Windzonenkarte für das Gebiet der Bundesrepublik Deutschland

Figure A.1.: Geographic wind zones in Germany according to DIN EN 1991-1-4 [45].

Table A.1.: Calculation for mean wind speed according to DIN EN 1991-1-4 [45].

Tabelle NA.B.2 — Profile der mittleren Windgeschwindigkeit, der Turbulenzintensität, des Böengeschwindigkeitsdrucks und der Böengeschwindigkeit in ebenem Gelände für 4 Geländekategorien

Geländekategorie	I	II	III	IV
Mindesthöhe $z_{\min}$	2,00 m	4,00 m	8,00 m	16,00 m
Mittlere Windgeschwindigkeit v_m für $z > z_{\min}$	$1,18 \times v_b (z/10)^{0,12}$	$1,00 \times v_b (z/10)^{0,16}$	$0,77 \times v_b (z/10)^{0,22}$	$0,56 \times v_b (z/10)^{0,30}$
v_m/v_b für $z < z_{\min}$	0,97	0,86	0,73	0,64
Turbulenzintensität I_v für $z > z_{\min}$	$0,14 \times (z/10)^{-0,12}$	$0,19 \times (z/10)^{-0,16}$	$0,28 \times (z/10)^{-0,22}$	$0,43 \times (z/10)^{-0,30}$
I_v für $z < z_{\min}$	0,17	0,22	0,29	0,37
Böengeschwindigkeitsdruck q_p für $z > z_{\min}$	$2,6 \times q_b (z/10)^{0,19}$	$2,1 \times q_b (z/10)^{0,24}$	$1,6 \times q_b (z/10)^{0,31}$	$1,1 \times q_b (z/10)^{0,40}$
q_p/q_b für $z < z_{\min}$	1,9	1,7	1,5	1,3
Böengeschwindigkeit v_p für $z > z_{\min}$	$1,61 \times v_b (z/10)^{0,095}$	$1,45 \times v_b (z/10)^{0,120}$	$1,27 \times v_b (z/10)^{0,155}$	$1,05 \times v_b (z/10)^{0,200}$
v_p/v_b für $z < z_{\min}$	1,38	1,30	1,23	1,15

Table A.2.: Wind load calculations for Section 2.6

Parameter	Value	Reference
Wind Zone	1	Wind zone map A.1
Base Wind Velocity, $v_{(b,0)}$	22.5m/s	Formula 2.3
Terrain Category	IV	Terrain categories 2.4
Average Wind Velocity, v_m	25.14m/s for $z = 100m$	
Velocity Pressure, q_b	$0.32kN/m^2$	Figure A.1
Pressure at Height, $q_p(z)$	$0.88kN/m^2$	Table A.2
Coefficient $c_{pe,10}$	0.8	Table 2.1
Coefficient $c_{pe,1}$	1.0	Table 2.1
Coefficient $c_{pe,4}$	0.933	Table 2.1
Coefficient $c_{pe,9}$	0.822	Table 2.1
Suction Coefficient for $c_{pe,4}$ and $c_{pe,10}$	0.7	Table 2.1
Wind Pressure $w_{1,4m^2}$	$0.82kN/m^2$	Formula 2.7
Wind Pressure $w_{1,9m^2}$	$0.72kN/m^2$	Formula 2.7
Suction Load w_2	$-0.62kN/m^2$	Formula 2.7

Table A.3.: FEA results: AM cross section under constant momentum load.

ID	w(mm)	h(mm)	r_1 (mm)	r_2 (mm)	$\sigma_{\max}$ h(MPa)	$\sigma_{\max}$ r_1 (MPa)	$\sigma_{\max}$ r_2 (MPa)	def(mm)
1	50	4	0.1	0.1	26.54	29.87	24.20	0.0055
2	39	5	0.1	4.83	27.54	30.63	29.66	0.0055
3	40	5	0.1	0.1	27.27	30.24	21.40	0.0054
4	33	6	0.1	3.05	27.89	30.71	18.74	0.0054
5	28	7	0.1	4.32	28.39	30.70	20.93	0.0053
6	24	8	0.1	6.11	28.74	30.86	25.30	0.0052
8	21	9	0.1	7.16	29.30	31.29	26.51	0.0052
9	22	9	0.1	3.05	28.39	30.34	10.47	0.0051
10	18	10	0.1	9.65	30.04	31.31	30.24	0.0052
11	19	10	0.1	6.83	29.14	30.72	21.12	0.0051
13	16	11	0.1	10.58	30.70	32.18	31.01	0.0052
14	17	11	0.1	7.78	29.55	30.80	23.04	0.0051
15	18	11	0.1	3.05	28.36	29.91	7.69	0.0049
16	15	12	0.1	9.65	30.59	31.84	26.95	0.0051
17	16	12	0.1	6.11	29.09	30.58	14.51	0.0049
18	13	13	0.1	12.02	32.04	33.27	30.87	0.0053
19	14	13	0.1	9.16	30.58	31.73	22.26	0.0051
20	15	13	0.1	4.83	28.66	29.85	9.79	0.0048
21	12	14	0.1	12.21	32.58	34.07	30.73	0.0054
22	13	14	0.1	9.16	30.66	31.79	20.14	0.0050
23	14	14	0.1	4.32	28.60	29.58	7.61	0.0047
24	11	15	0.1	12.77	33.57	34.49	29.78	0.0055
25	12	15	0.1	9.65	31.09	32.37	20.56	0.0051
26	13	15	0.1	4.83	28.64	29.67	7.98	0.0047
27	10	16	0.1	13.65	35.29	36.05	31.47	0.0057
28	11	16	0.1	10.58	32.22	33.09	21.31	0.0052
29	12	16	0.1	6.11	29.11	30.26	10.36	0.0048
30	9	17	0.1	14.80	37.80	38.59	33.67	0.0061
31	10	17	0.1	11.82	34.13	34.85	23.85	0.0055
32	11	17	0.1	7.78	30.44	31.25	13.02	0.0049
33	8	18	0.1	16.15	41.64	42.38	38.22	0.0067
34	9	18	0.1	13.31	36.93	38.12	27.69	0.0059
35	10	18	0.1	9.65	32.46	33.25	16.80	0.0052
37	7	19	0.1	17.67	47.58	48.33	45.11	0.0077
38	8	19	0.1	14.96	41.26	41.97	33.25	0.0067
39	9	19	0.1	11.63	35.56	36.22	21.49	0.0057
40	10	19	0.1	6.83	30.57	31.27	9.59	0.0049
41	6	20	0.1	19.31	57.35	58.27	56.20	0.0093
42	7	20	0.1	16.72	48.20	48.91	41.61	0.0078
43	8	20	0.1	13.65	40.34	41.00	27.71	0.0065
44	9	20	0.1	9.65	33.85	34.50	15.50	0.0054
46	6	21	0.1	18.57	60.12	62.16	55.49	0.0098
47	7	21	0.1	15.72	48.20	48.85	36.92	0.0078

Table A.3 continued from previous page

ID	w(mm)	h(mm)	r_1 (mm)	r_2 (mm)	$\sigma_{\max}$ h(MPa)	$\sigma_{\max}$ r_1 (MPa)	$\sigma_{\max}$ r_2 (MPa)	def(mm)
48	8	21	0.1	12.21	39.03	39.62	22.35	0.0063
51	6	22	0.1	17.80	62.40	64.07	52.88	0.0102
52	7	22	0.1	14.64	47.63	48.61	32.05	0.0077
53	8	22	0.1	10.58	37.39	37.96	17.23	0.0060
57	6	23	0.1	17.00	64.04	64.84	49.21	0.0105
58	7	23	0.1	13.48	46.61	47.58	27.31	0.0075
62	6	24	0.1	16.15	65.07	65.81	45.25	0.0106
63	7	24	0.1	12.21	45.21	46.09	22.72	0.0073
68	6	25	0.1	15.26	65.47	66.14	41.13	0.0106
74	6	26	0.1	14.32	65.27	65.92	36.96	0.0106

```

1 clear
2 clc
3
4 syms x c_1 c_2
5
6 p = 0.00132; % Flächenlast in N/mm^2
7 L = 2000; % Plattenlänge in mm
8 E = 70000; % E-Modul
9 t_1 = 18; % Plattendicke in mm
10 t_2 = 0;
11
12 w_strich_strich = 6 * p * (x^2 - L * x) / (E * (t_1 - 4 * t_2 / L^2 * x^2 + 4 * t_2 / L * x)^3);
13
14 w_strich = int(w_strich_strich, x);
15
16 w = int(w_strich, x);
17
18 w_1 = w + c_1; % w(0)=0 und w(L)=0
19
20 % Bestimmen von c_1 über Randbedingung w(0)=0
21 c_1_value = solve(subs(w_1, x, 0) == 0, c_1);
22
23 w_with_c_1 = simplify(w + c_1_value + c_2 * x);
24
25 a = L;
26 b = 0;
27
28 % Bestimmen von c_2 über Randbedingung w(L)=0
29 c_2_value = solve(subs(w_with_c_1, x, a) == b, c_2);
30
31 w_with_c_2 = simplify(w + c_1_value + c_2_value * x);
32
33 max_w = double(subs(w_with_c_2, x, L/2));
34
35 syms x c_1 c_2 t_2 w_new
36
37 t_1_new=4.03;%neue Plattendicke in mm
38 %t_2=4;%AM-Dicke in mm
39 %w_max=1/200*L %5mm bei L=10000
40
41 w_strich_strich=6*p*(x^2-L*x)/(E*(t_1_new-4*t_2/L^2*x^2+4*t_2/L*x)^3);
42
43 w_strich=int(w_strich_strich,x);
44
45 w=int(w_strich,x);
46
47 %assume(c, 'real');
48 %c=1;
49
50 w_1=w+c_1; %w(0)=0 und w(L)=0
51 %Bestimmen von c über Randbedingung w(L)=0
52 c_1_value=solve(subs(w_1,x,0)==0,c_1);
53 w_with_c_1 = simplify(w + c_1_value + c_2*x);
54 a=L;
55 b=0;
56 c_2_value=solve(subs(w_with_c_1,x,a)==b,c_2);
57 w_with_c_2 = simplify(w + c_1_value + c_2_value*x);
58
59 w_value = max_w; %max. Druchbiegung in mm
60 w_max = subs(w_with_c_2, x, L/2);
61 %numerische Annäherung (keine explizite Lösung)
62 num_steps = 500;
63 t_min = 0.1;
64 t_max = 20;
65 t_best_value = 200;
66 t_best = NaN;
67
68 for i = 1:num_steps
69     t_value = t_min + (t_max - t_min) * (i - 1) / (num_steps - 1);
70     y = subs(w_max, t_2, t_value);
71     % Überprüfen, ob dieser Wert näher am gewünschten Wert ist
72     if abs(y - w_value) < abs(t_best_value - w_value)
73         t_best_value = y;
74         t_best = t_value;
75     end
76 end
77
78 volume_opt = 2/3*L*t_best;
79 volume_no_opt = L*(t_1-t_1_new);
80 difference_am = (volume_no_opt-volume_opt)/volume_no_opt*100;
81 difference = (L*t_1-(volume_opt+L*t_1_new))/(L*t_1)*100;
82 fprintf('Es wurde %2f Prozent an Material gespart im Bereich AM.\n', difference_am);
83 fprintf('Es wurde %2f Prozent an Material gesamt gespart.\n', difference);

```

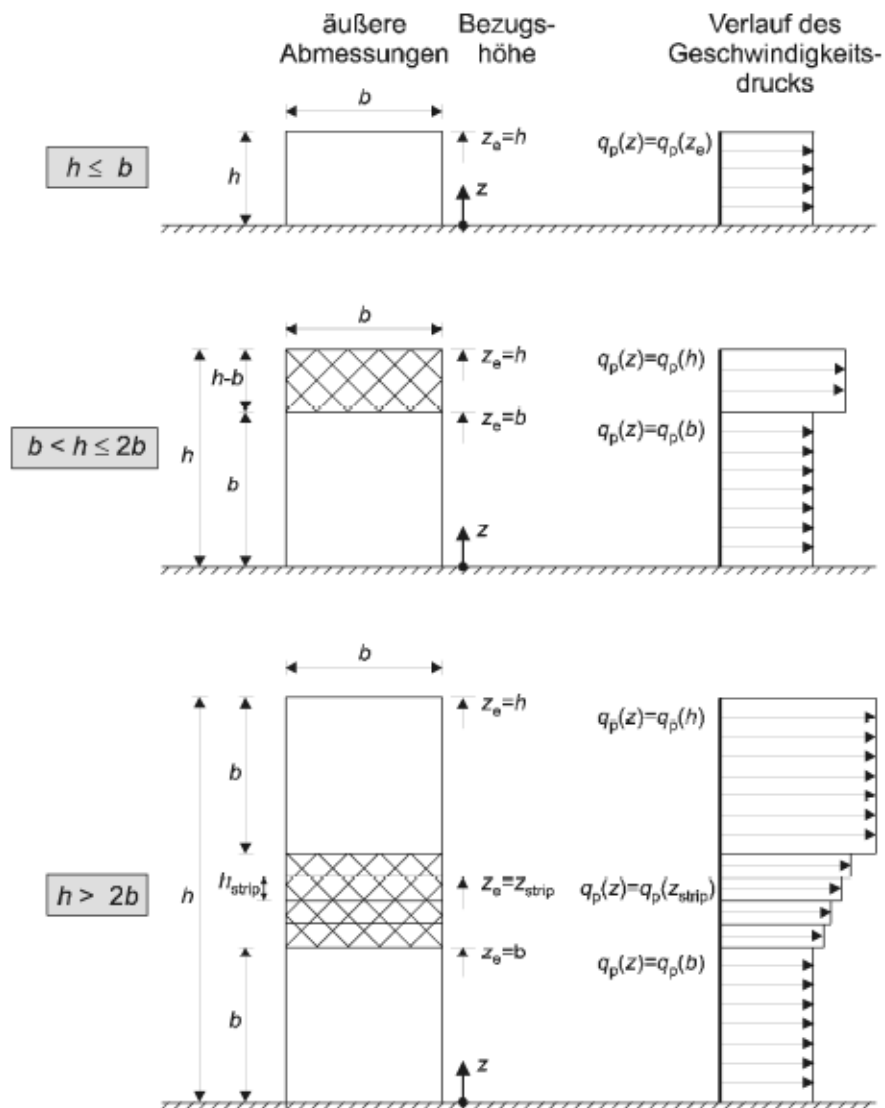
Listing A.1: Matlabcode 1 - Analytical investigation of variable plate thickness of a plate supported on 2 sides

```

1 clear
2 clc
3
4 syms x c_1 c_2
5 % Konstanten
6 p = 0.00132; % Flächenlast in N/mm^2
7 L = 2000; % Plattenlänge in mm
8 E = 70000; % E-Modul
9 t_1 = 18; % Bestehende Plattendicke in mm
10 t_2 = 0;
11 num_t1_new = 40; % Anzahl der Schritte für t_1_new
12 t_1_new_values = linspace(0.1, 17.9, num_t1_new); % t_1_new von 0.1 bis 17.9
13 difference_values = zeros(1, num_t1_new); % Initialisiere Array für Materialersparnis
14
15 w_strich_strich = 6 * p * (x^2 - L * x) / (E * (t_1 - 4 * t_2 / L^2 * x^2 + 4 * t_2 / L * x)^3);
16
17 w_strich = int(w_strich_strich, x);
18
19 w = int(w_strich, x);
20
21 w_1 = w + c_1; % w(0)=0 und w(L)=0
22
23 % Bestimmen von c_1 über Randbedingung w(0)=0
24 c_1_value = solve(subs(w_1, x, 0) == 0, c_1);
25
26 w_with_c_1 = simplify(w + c_1_value + c_2 * x);
27
28 a = L;
29 b = 0;
30
31 % Bestimmen von c_2 über Randbedingung w(L)=0
32 c_2_value = solve(subs(w_with_c_1, x, a) == b, c_2);
33
34 w_with_c_2 = simplify(w + c_1_value + c_2_value * x);
35
36 max_w = double(subs(w_with_c_2, x, L/2));
37
38 for i = 1:num_t1_new
39     t_1_new = t_1_new_values(i);
40     w_strich_strich = 6*p*(x^2-L*x)/(E*(t_1_new-4*t_2/L^2*x^2+4*t_2/L*x)^3);
41
42     w_strich = int(w_strich_strich, x);
43
44     w = int(w_strich, x);
45     w_1 = w + c_1; % w(0)=0 und w(L)=0
46     % Bestimmen von c über Randbedingung w(L)=0
47     c_1_value = solve(subs(w_1, x, 0) == 0, c_1);
48     w_with_c_1 = simplify(w + c_1_value + c_2 * x);
49     a = L;
50     b = 0;
51     c_2_value = solve(subs(w_with_c_1, x, a) == b, c_2);
52     w_with_c_2 = simplify(w + c_1_value + c_2_value * x);
53
54     w_value = max(w); % max. Durchbiegung in mm
55     w_max = subs(w_with_c_2, x, L/2);
56
57     num_steps = 500;
58     t_min = 0.1;
59     t_max = 30;
60     t_best_value = 200;
61     t_best = NaN;
62
63     for j = 1:num_steps
64         t_value = t_min + (t_max - t_min) * (j - 1) / (num_steps - 1);
65         y = subs(w_max, t_2, t_value);
66         % Überprüfen, ob dieser Wert näher am gewünschten Wert ist
67         if abs(y - w_value) < abs(t_best_value - w_value)
68             t_best_value = y;
69             t_best = t_value;
70         end
71     end
72     volume_opt = 2/3*L*t_best; % Optimiertes Volumen
73     difference = (L*t_1 - (volume_opt + L*t_1_new)) / (L*t_1) * 100; % Berechnung der prozentualen Materialersparnis
74     difference_values(i) = difference; % Speichern der Differenz im Array
75 end
76
77 % Plotten der Materialersparnis in Abhängigkeit von t_1_new
78 plot(t_1_new_values, difference_values, 'LineWidth', 2);
79 title('Materialersparnis (%) in Abhängigkeit von t_1_{new}');
80 xlabel('t_1_{new} (mm)');
81 ylabel('Materialersparnis (%)');
82 grid on;

```

Listing A.2: Matlabcode 2- Analytical investigation of variable plate thickness of a plate supported on 2 sides



ERKÜNG: Der Geschwindigkeitsdruck ist für jeden horizontalen Streifen gleichmäßig verteilt anzunehmen.

Bild 7.4 — Bezugshöhe z_e in Abhängigkeit von h und b und Winddruckverteilung

Figure A.2.: Calculation of $q_p(z)$ regarding building height according to DIN EN 1991-1-4 [45].

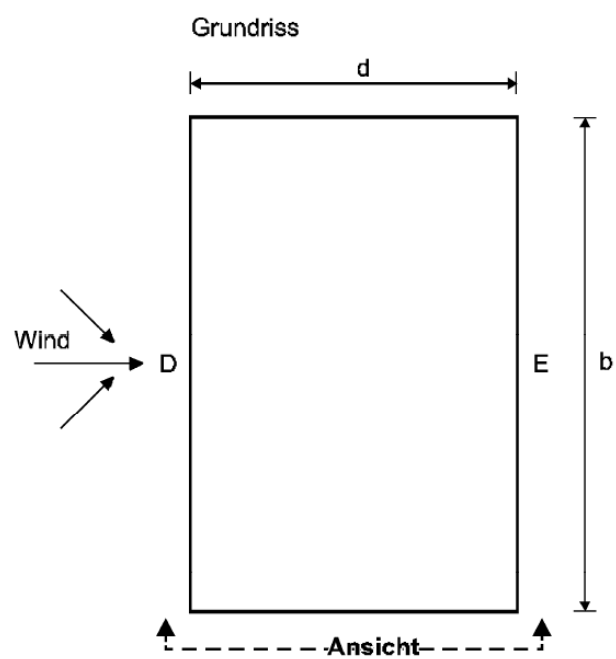
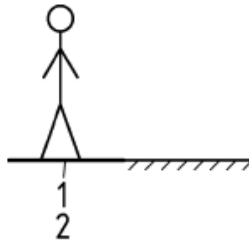
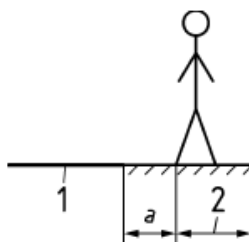


Figure A.3.: Wind load areas of a building according to DIN EN 1991-1-4 [45].

Verglasung auf dem gleichen Niveau wie Arbeitsfläche oder Verkehrsweg:

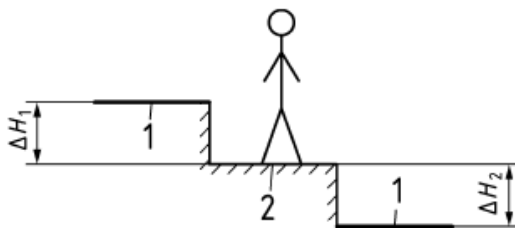


betretbar



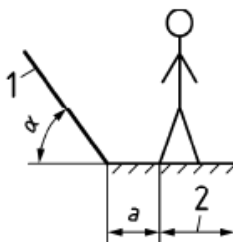
- für $a < 2,0 \text{ m}$ durchsturzsicher
- für $a \geq 2,0 \text{ m}$ keine Anforderungen

Verglasung auf höherem oder niedrigerem Niveau als Arbeitsfläche oder Verkehrsweg:



- für $\Delta H_1 < 0,9 \text{ m}$ durchsturzsicher
- für $\Delta H_1 \geq 0,9 \text{ m}$ keine Anforderungen
- für $\Delta H_2 \leq 0,3 \text{ m}$ durchsturzsicher
- für $\Delta H_2 > 0,3 \text{ m}$ nicht Gegenstand der Norm

Geneigte Verglasungen neben Arbeitsfläche oder Verkehrsweg:



- für $a < 2,0 \text{ m}$ durchsturzsicher für $0^\circ < \alpha \leq 100^\circ$
- für $a \geq 2,0 \text{ m}$ keine Anforderungen

Figure A.4.: Distinction between fall-through protective and non-specified requirement glass panes according to DIN 18008-6 [42].

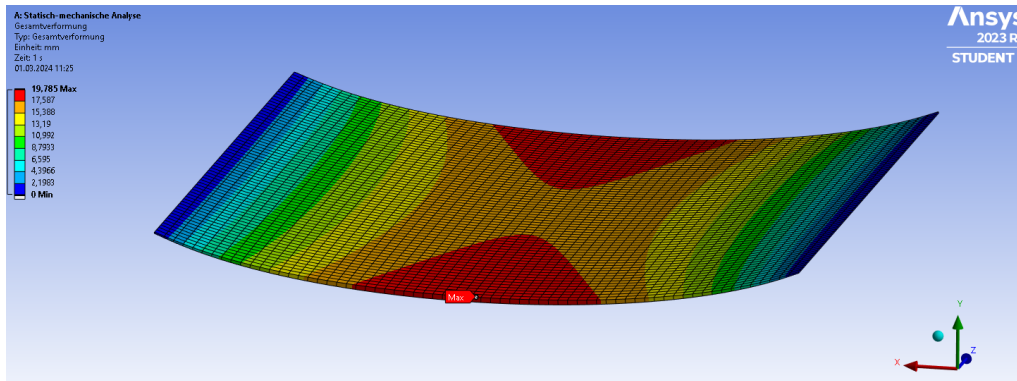


Figure A.5.: Deformation of 2D TO geometry by Matlab Code by Felix Rutsch under pressure load. Associated maximum first principal stress is 16.4 MPa [7].

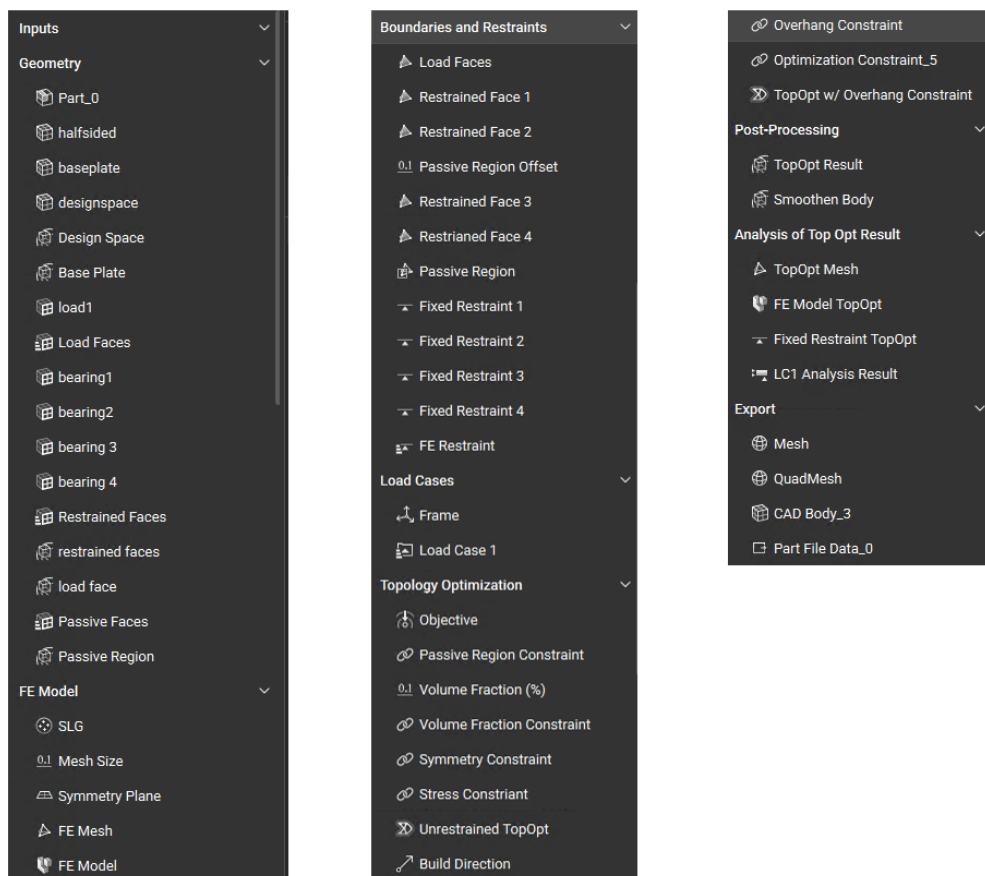


Figure A.6.: Program blocks and associated structure of the program code for topology optimization with nTop®.

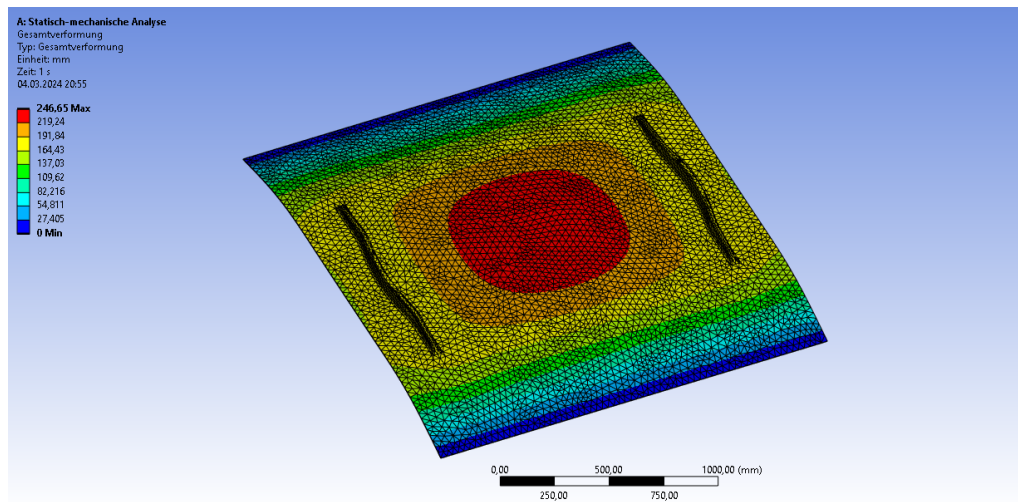


Figure A.7.: Deformation of geometry 1a under pressure load [7].

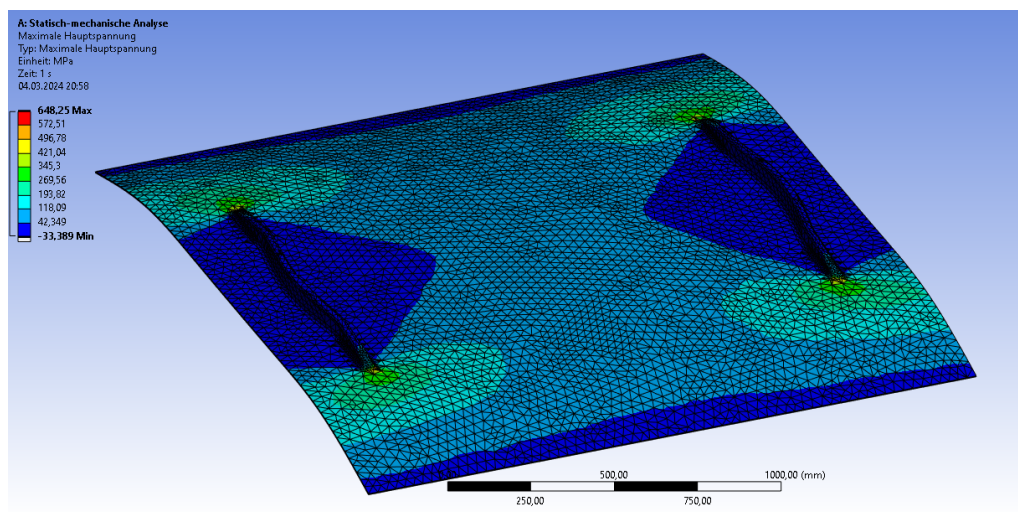


Figure A.8.: First principal stress of geometry 1a under pressure load [7].

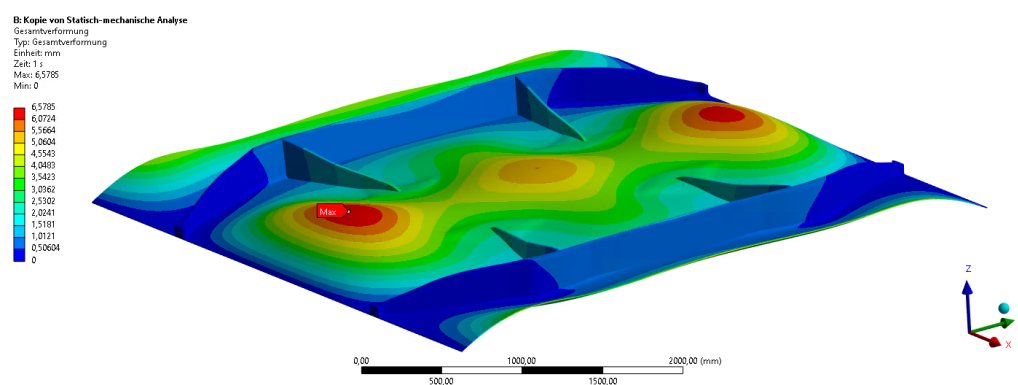


Figure A.9.: Deformation of geometry 1d under pressure load [7].

B: Kopie von Statisch-mechanische Analyse

Maximale Hauptspannung
Typ: Maximale Hauptspannung
Einheit: MPa
Zeit: 1 s
Max: 14,98
Min: -3,5392

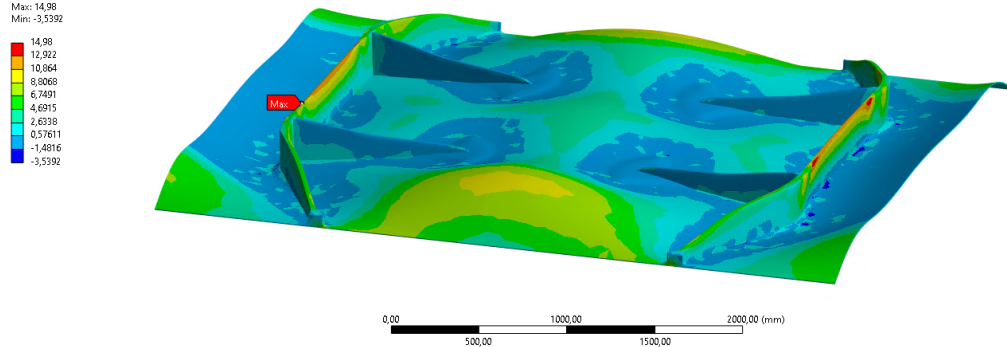


Figure A.10.: First principal stress of geometry 1d under pressure load [7].

A: Statisch-mechanische Analyse

Schubspannung
Typ: Schubspannung(XY-Komponente)
Einheit: MPa
Globales Koordinatensystem
Zeit: 1 s
Max: 8,6135
Min: -8,3798

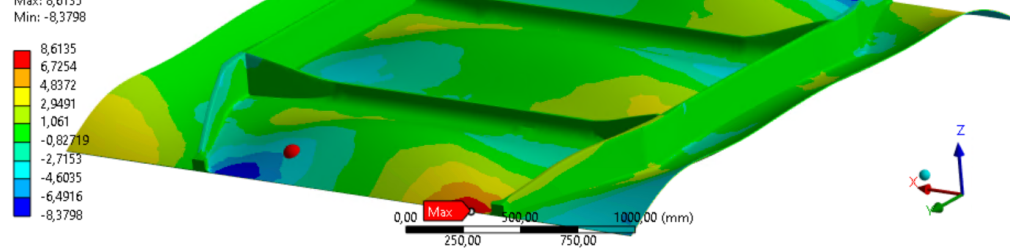


Figure A.11.: Maximum shear stress of geometry 1d under pressure load [7].

B: Kopie von Statisch-mechanische Analyse

Normalspannung
Typ: Normalspannung(Z-Achse)
Einheit: MPa
Globales Koordinatensystem
Zeit: 1 s
Max: 5,9865
Min: -11,834

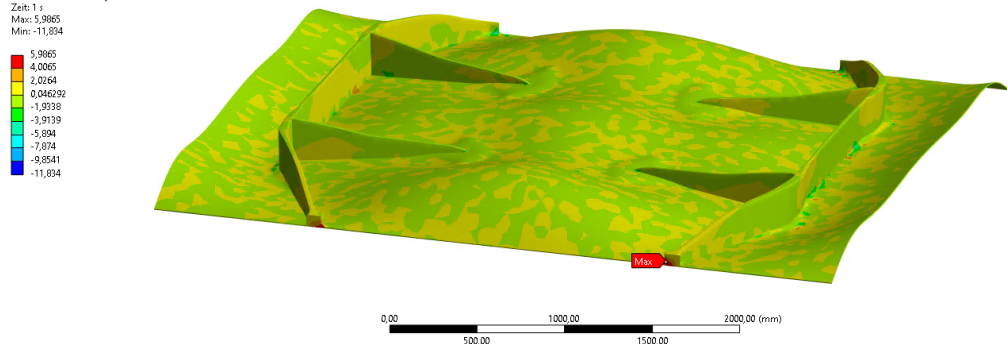


Figure A.12.: Normal stress in z-direction of geometry 1d under pressure load [7].

A: Statisch-mechanische Analyse

Gesamtverformung

Typ: Gesamtverformung

Einheit: mm

Zeit: 1 s

Max: 6,1597

Min: 0

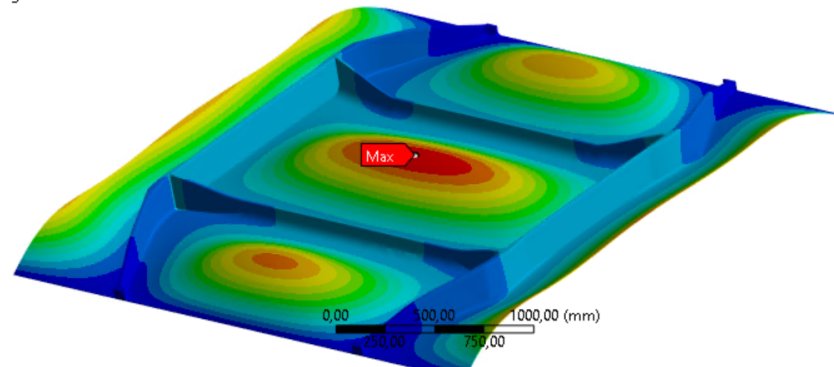
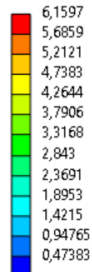


Figure A.13.: Deformation of geometry 1e under pressure load [7].

A: Statisch-mechanische Analyse

Maximale Hauptspannung

Typ: Maximale Hauptspannung

Einheit: MPa

Zeit: 1 s

Max: 13,35

Min: -3,998

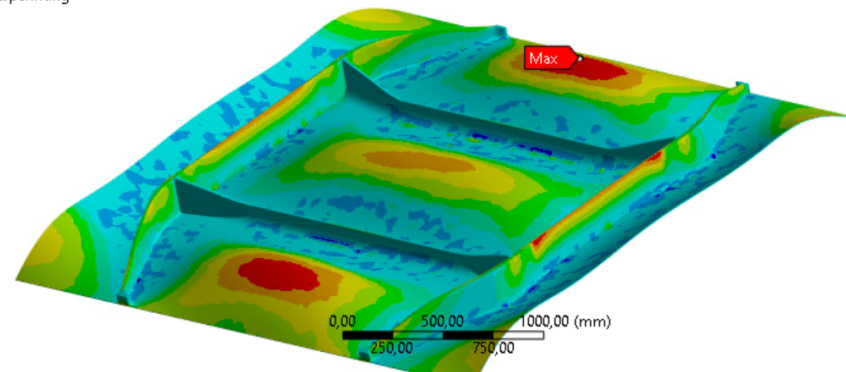
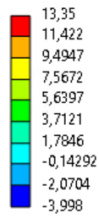


Figure A.14.: First principal stress of geometry 1e under pressure load [7].

A: Statisch-mechanische Analyse

Normalspannung

Typ: Normalspannung(Z-Achse)

Einheit: MPa

Globales Koordinatensystem

Zeit: 1 s

Max: 8,1152

Min: -10,818

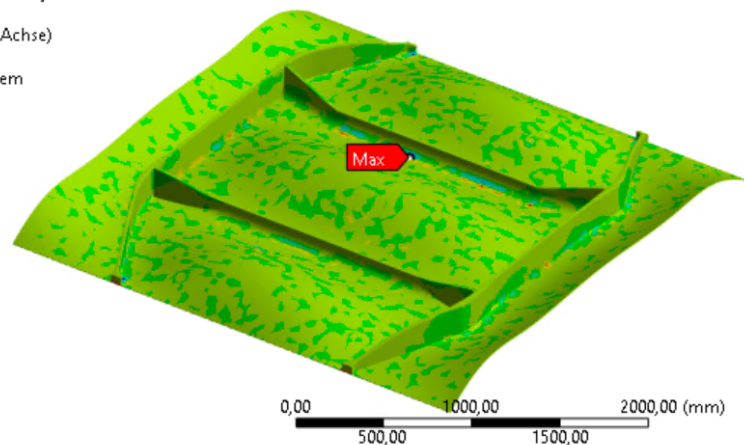
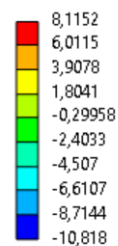


Figure A.15.: Normal stress in z-direction of geometry 1e under pressure load [7].

A: Statisch-mechanische Analyse
Gesamtverformung
Typ: Gesamtverformung
Einheit: mm
Zeit: 1 s
Max: 2,0548
Min: 0

2,0548
1,8265
1,5982
1,3699
1,1416
0,91325
0,69493
0,45662
0,22831
0

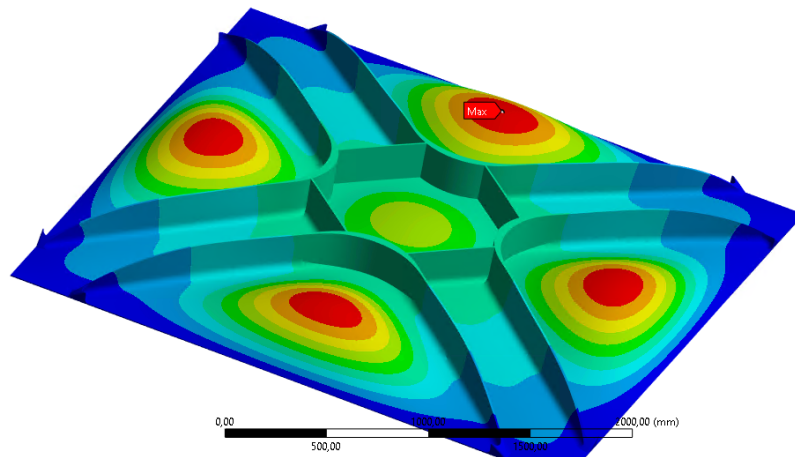


Figure A.16.: Deformation of geometry 2a under pressure load [7].

A: Statisch-mechanische Analyse
Maximale Hauptspannung
Typ: Maximale Hauptspannung
Einheit: MPa
Zeit: 1 s
Max: 13,758
Min: -1,1192

13,758
12,105
10,452
8,7987
7,1457
5,4927
3,8397
2,1867
0,53375
-1,1192

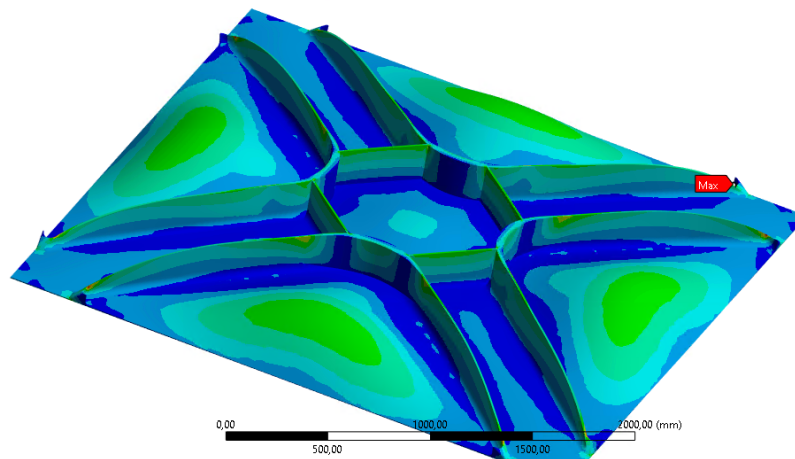


Figure A.17.: First principal stress of geometry 2a under pressure load [7].

A: Statisch-mechanische Analyse
Gesamtverformung
Typ: Gesamtverformung
Einheit: mm
Zeit: 1 s
Max: 6,1271
Min: 0

6,1271
5,4463
4,7655
4,0847
3,4039
2,7232
2,0424
1,3616
0,68079
0

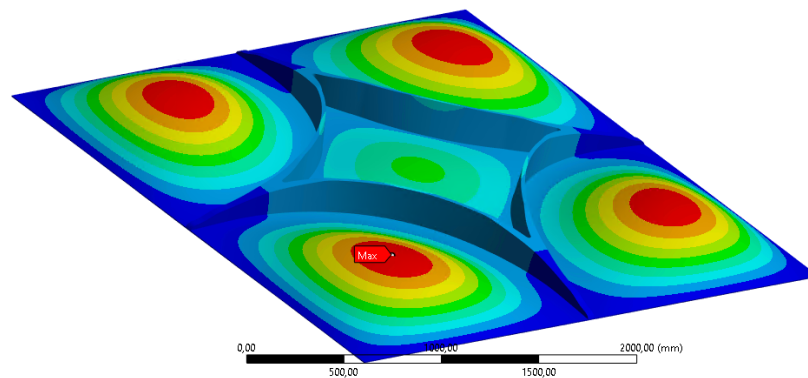


Figure A.18.: Deformation of geometry 2c under pressure load [7].

A: Statisch-mechanische Analyse
 Maximale Hauptspannung
 Typ: Maximale Hauptspannung
 Einheit: MPa
 Zeit: 1 s
 Max: 14,653
 Min: -2,6099

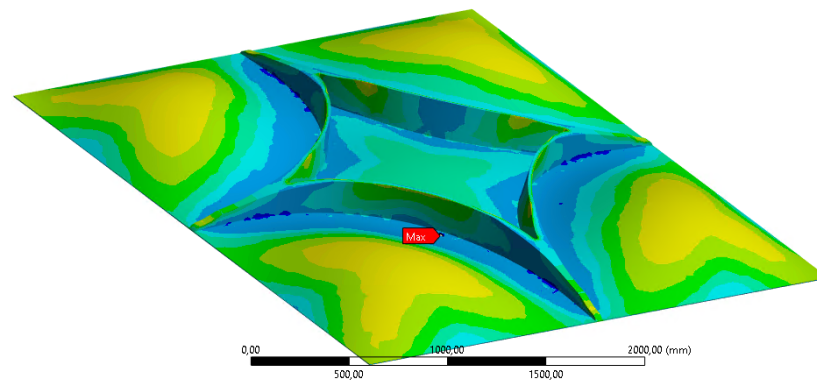
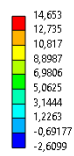


Figure A.19.: First principal stress of geometry 2c under pressure load [7].

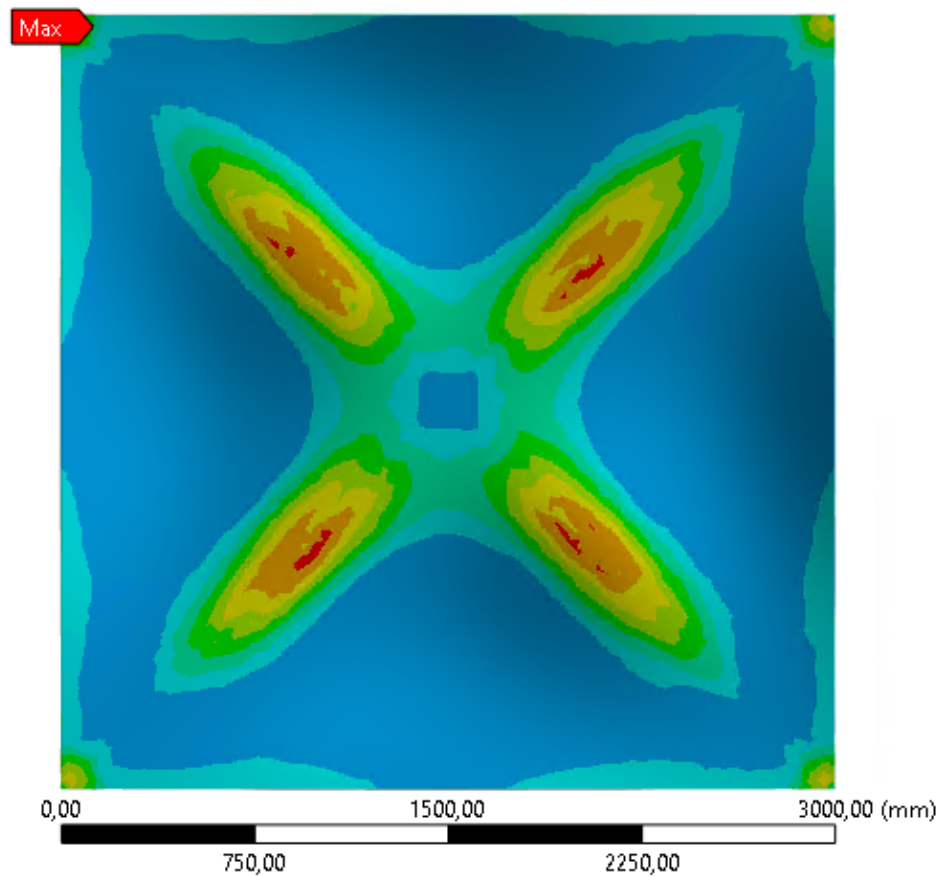


Figure A.20.: First principal stress of the back side of geometry 2c under pressure load [7].

A: Statisch-mechanische Analyse
 Normalspannung
 Typ: Normalspannung(Z-Achse)
 Einheit: MPa
 Globales Koordinatensystem
 Zeit: 1 s
 Max: 5,3877
 Min: -6,2028

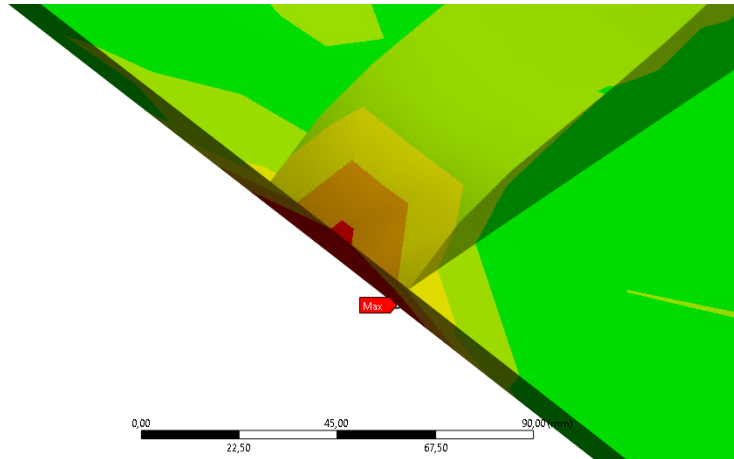
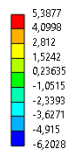


Figure A.21.: Normal stress in z-direction of geometry 2c under pressure load [7].

A: Statisch-mechanische Analyse
 Gesamtverformung
 Typ: Gesamtverformung
 Einheit: mm
 Zeit: 1 s
 Max: 5,4063
 Min: 0

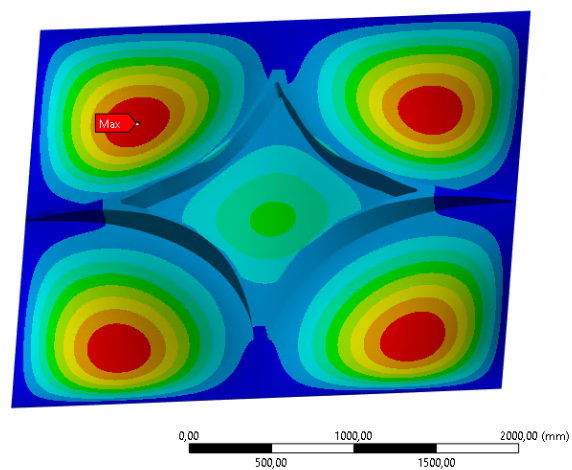
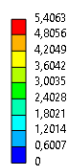


Figure A.22.: Deformation of geometry 2c under suction load [7].

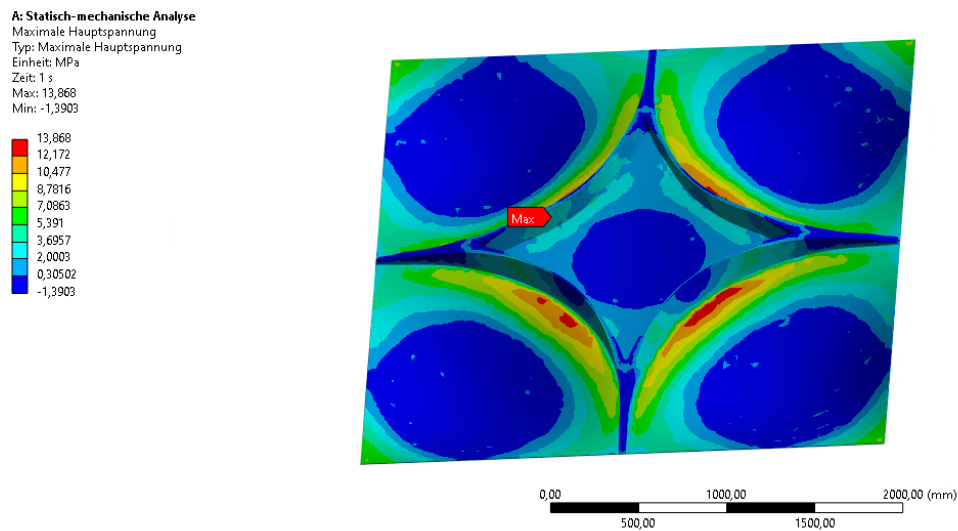


Figure A.23.: First principal stress of geometry 2c under suction load [7].

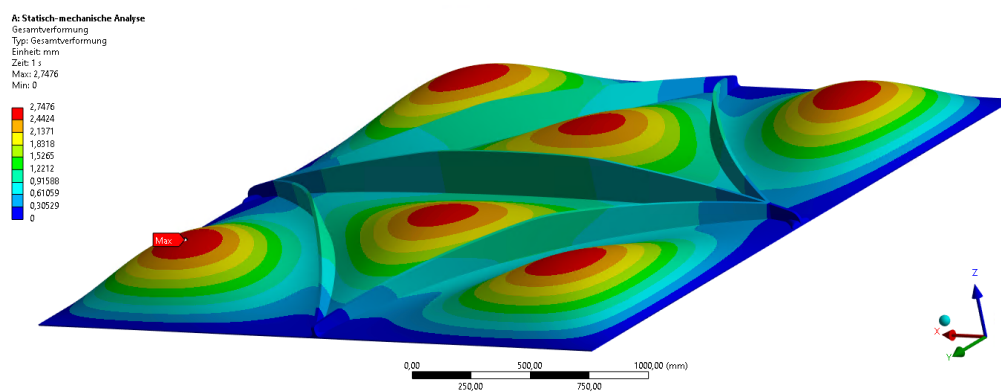


Figure A.24.: Deformation of geometry 2d under pressure load [7].

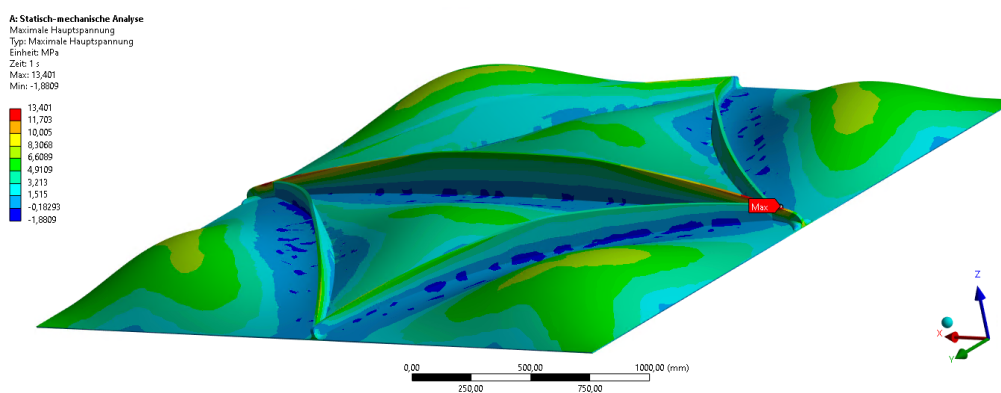


Figure A.25.: First principal stress of geometry 2d under pressure load [7].

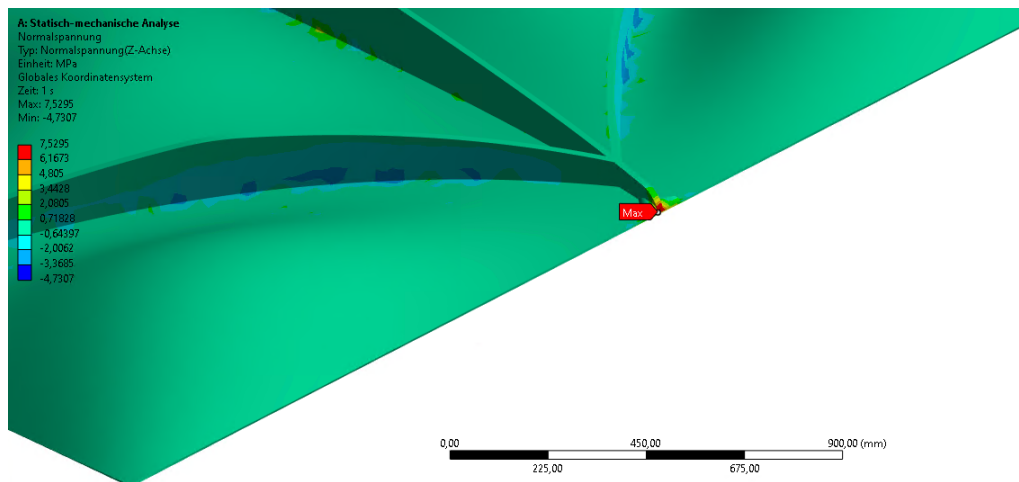


Figure A.26.: Normal stress in z-direction of geometry 2d under pressure load [7].

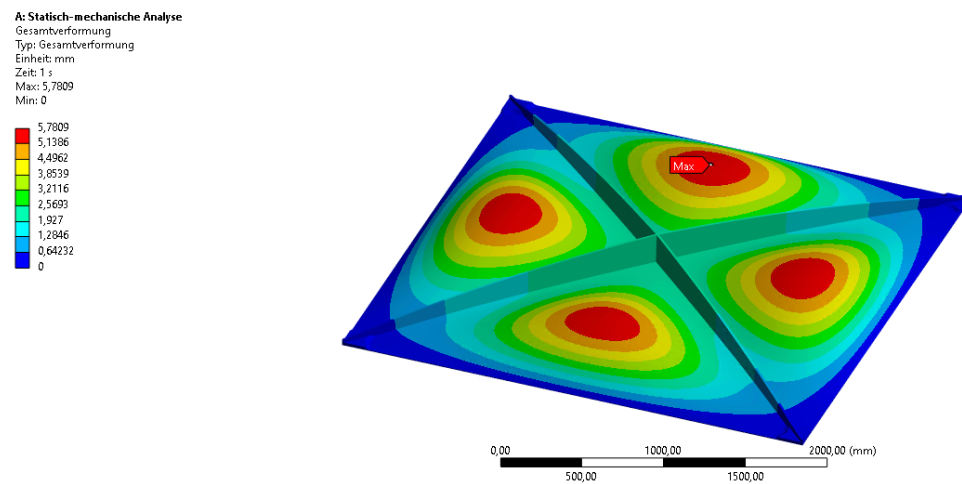


Figure A.27.: Deformation of geometry 2e under pressure load [7].

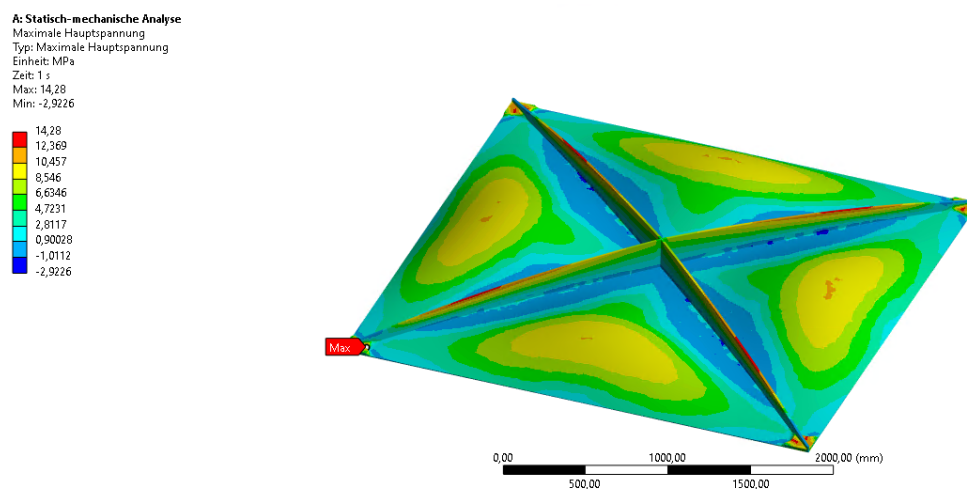


Figure A.28.: First principal stress of geometry 2e under pressure load [7].

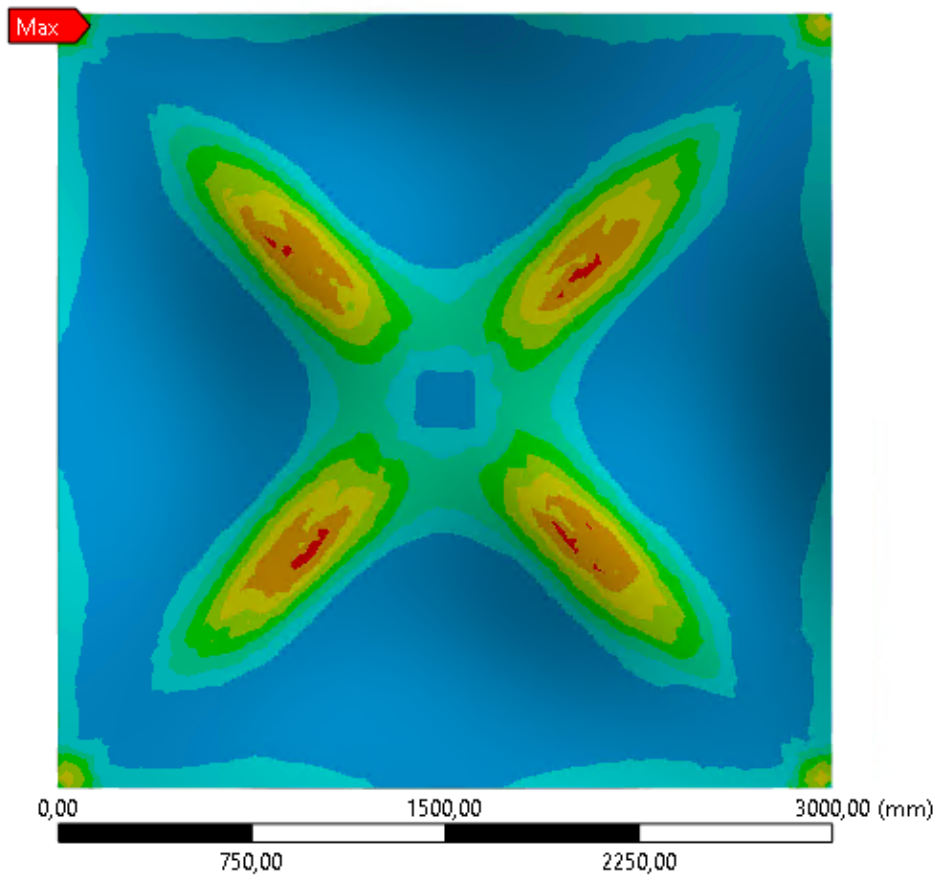


Figure A.29.: First principal stress of the back side of geometry 2e under pressure load [7].

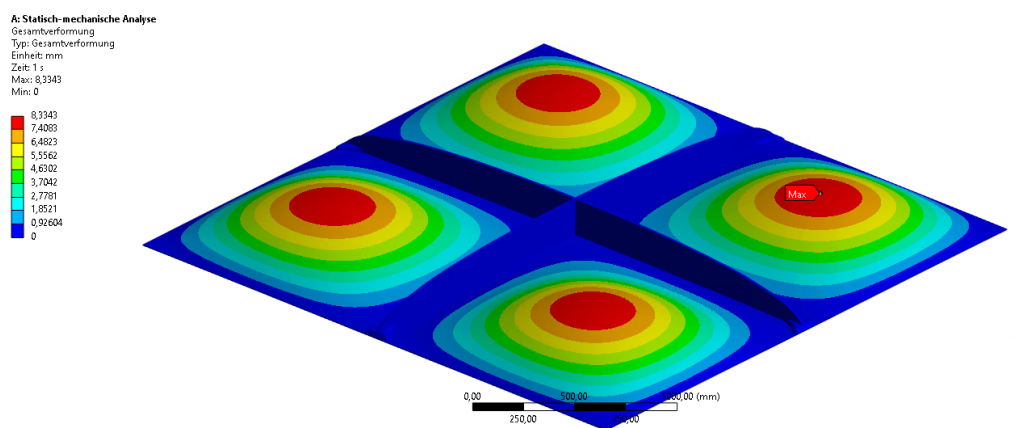


Figure A.30.: Deformation of geometry 2f under pressure load [7].

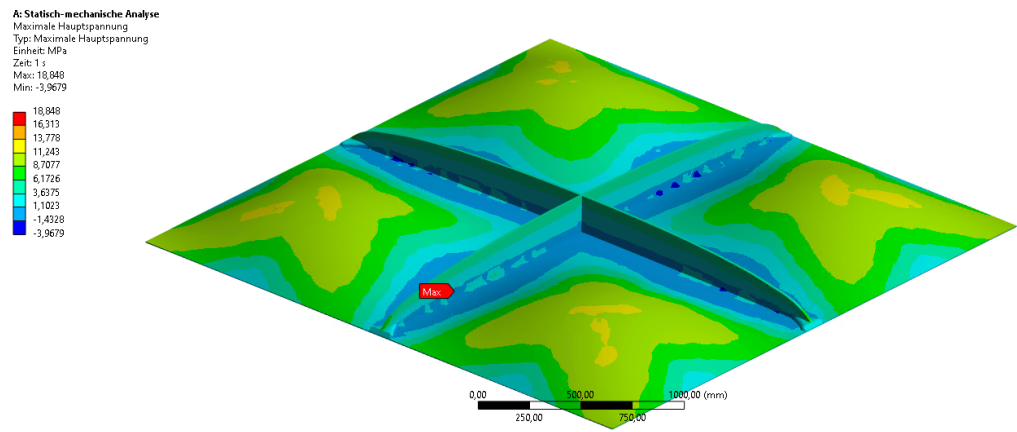


Figure A.31.: First principal stress of geometry 2f under pressure load [7].

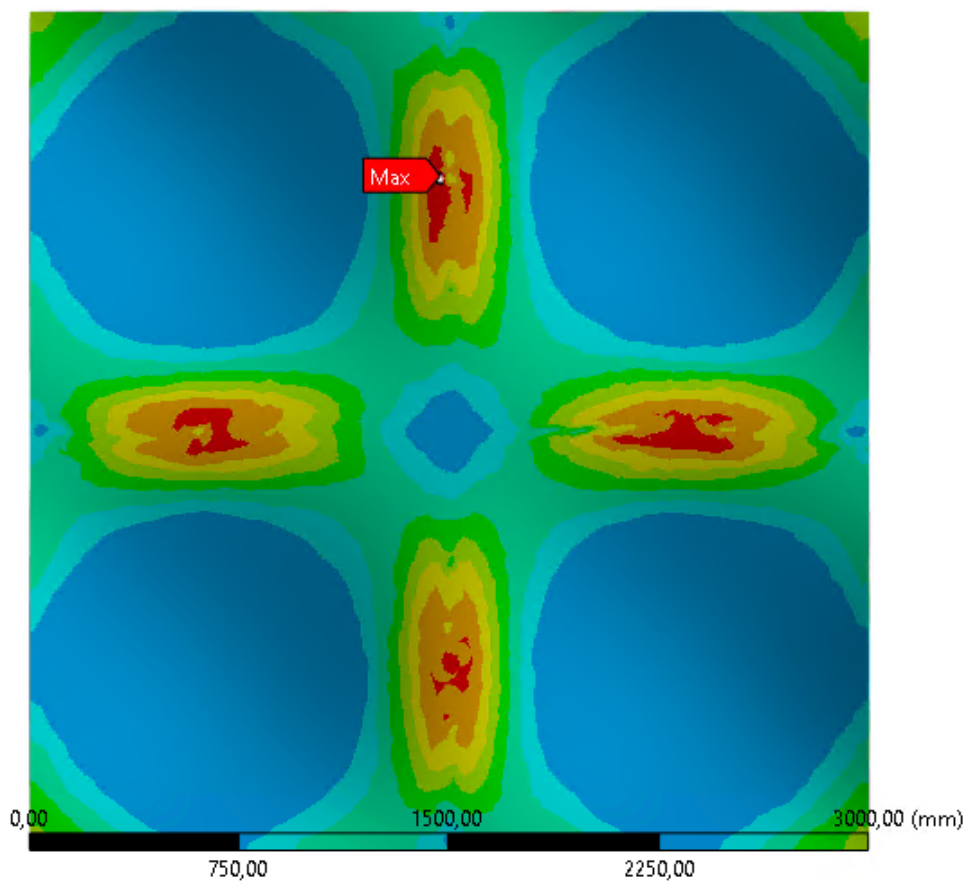


Figure A.32.: First principal stress of the back side of geometry 2f under pressure load [7].

A: Statisch-mechanische Analyse

Gesamtverformung

Typ: Gesamtverformung

Einheit: mm

Zeit: 1 s

Max: 7,2581

Min: 0

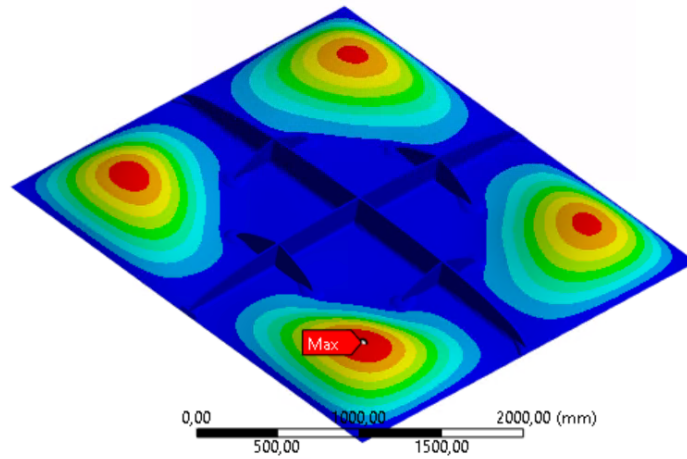
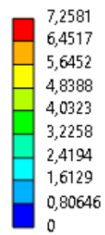


Figure A.33.: Deformation of geometry 2f.1 under pressure load [7].

A: Statisch-mechanische Analyse

Maximale Hauptspannung

Typ: Maximale Hauptspannung

Einheit: MPa

Zeit: 1 s

Max: 14,452

Min: -4,2785

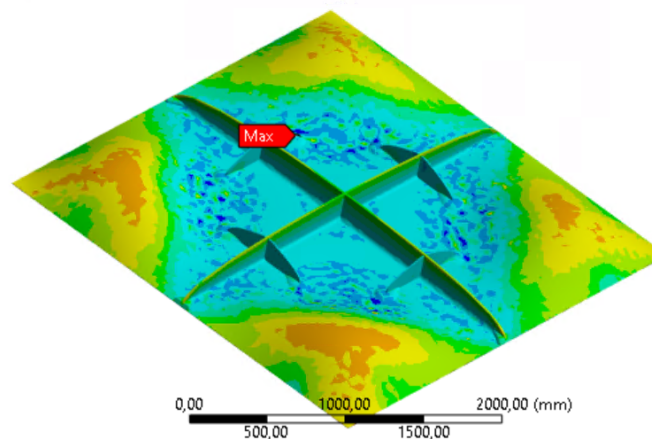
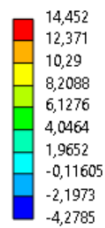


Figure A.34.: First principal stress of geometry 2f.1 under pressure load [7].

A: Statisch-mechanische Analyse
 Schubspannung
 Typ: Schubspannung(XY-Komponente)
 Einheit: MPa
 Globales Koordinatensystem
 Zeit: 1 s
 Max: 9,4815
 Min: -9,3328

9,4815
 7,391
 5,3005
 3,21
 1,1195
 -0,97093
 -3,0614
 -5,1519
 -7,2424
 -9,3328

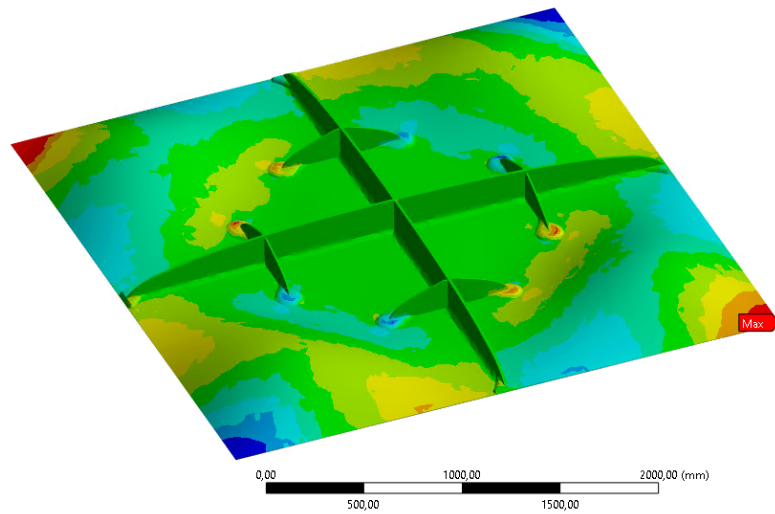


Figure A.35.: Maximum shear stress of geometry 2f.1 under pressure load [7].

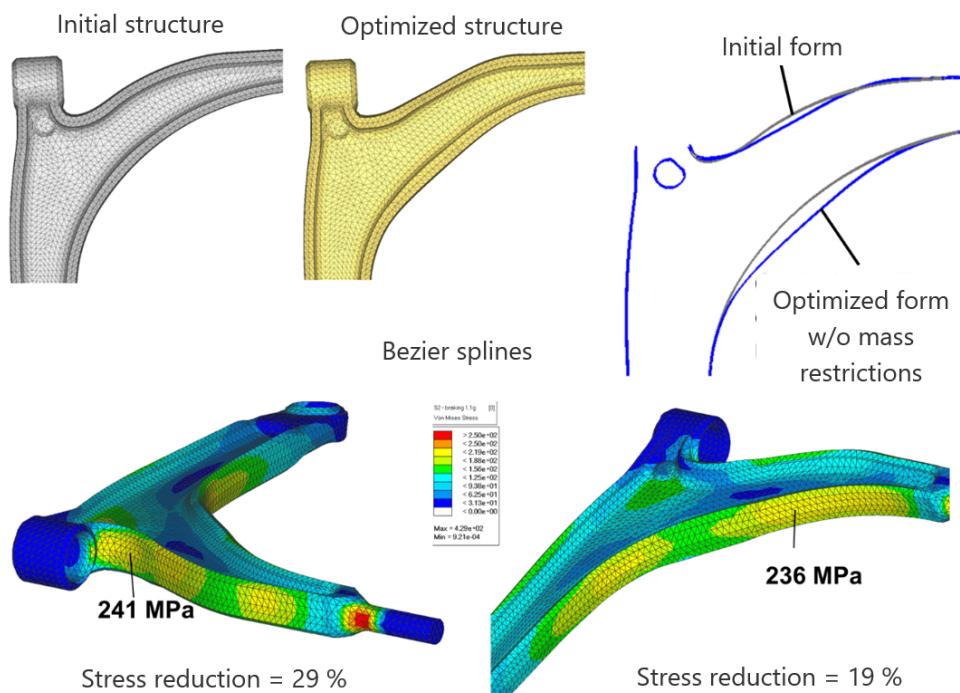


Figure A.36.: Example of shape optimization on a motor vehicle control arm [67].

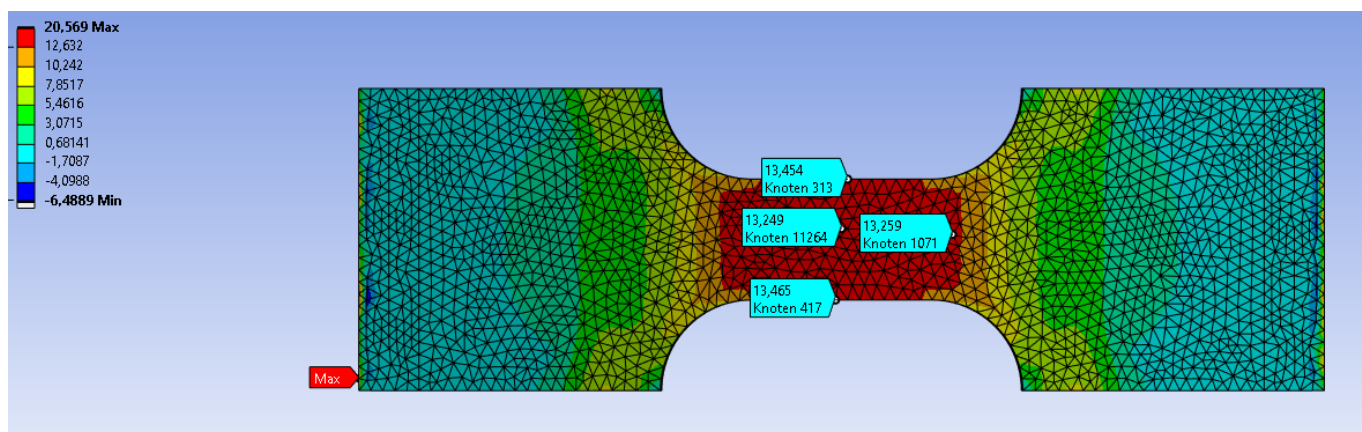


Figure A.37.: First principal stress of the test specimen under a load of $F=50\text{ N}$ [7].

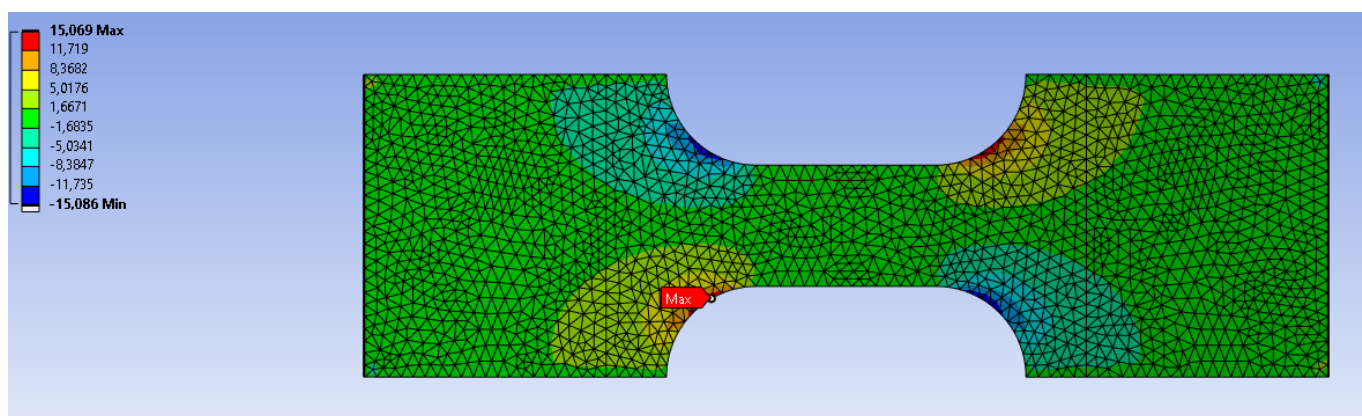


Figure A.38.: Maximum shear stress of the test specimen under a load of $F=50\text{ N}$ [7].

Table A.4.: Dimensions of the test specimens. t represents the thickness and min/max the deviations based on 5 measurements per entry.

#	t left side		t notches left side		t web		t notches web		t right side		t notches right side		length		width left side		width web		width right side		Residual stresses		Weight	Lifting
	mm	min/max	mm	min/max	mm	min/max	mm	min/max	mm	min/max	mm	min/max	mm	min/max	mm	min/max	mm	min/max	mm	min/max		g	mm	
N1-90	3.8	0.05	3	0.2 3.8	0.06	2.8	0.3	0.06	2.9	0.3	149.3	0.4	44.6	0.6	20.3	0.5	44	0.3	No			0		
N2-90	3.9	0.1	2.9	0.2 3.8	0.03	2.7	0.2	0.05	2.7	0.2	152.8	0.2	44.5	0.5	20.2	0.6	44.8	0.6	No			0		
N3-90	3.9	0.07	2.7	0.2 3.9	0.1	2.7	0.3	0.05	2.8	0.2	152	0.05	44.7	1	20.5	0.5	44.5	0.2	No			0		
N4-0	4	0.07	2.5	0.2 4.1	0.1	-	-	0.06	2.5	0.3	150	0.1	46.5	0.1	20.9	0.1	46.2	0.2	No			0		
N5-0	4.1	0.1	2.6	0.2 3.9	0.05	-	-	0.1	2.5	0.2	150	1	45.7	0.2	21.1	0.05	45.4	0.2	No			0		
N6-0	4.1	0.1	2.3	0.3 3.9	0.05	-	-	0.1	2.4	0.2	150.3	0.2	46	0.1	21.7	0.05	46.1	0.1	No			0		
90-1	3.3	0.1	3.2	0.1 3.4	0.1	3.3	0.05	3	2.9	0.1	143.5	0.3	33.2	0.4	13.4	0.3	33.3	0.3	No		31.4	0.9		
90-2	3.4	0.07	3.3	0.1 3.4	0.1	3.3	0.05	3.5	3.4	0.05	142.8	0.2	32.9	0.3	13.3	0.2	33.1	0.2	No		28.1	2		
90-3	3.8	0.15	3.5	0.1 3.5	0.1	3.3	0.06	3.8	3.6	0.1	142.8	0.3	32.7	0.2	13.4	0.2	32.7	0.2	No		26.7	1		
90-4	3.5	0.08	3.4	0.05 3.3	0.1	3.3	0.08	3.2	3.1	0.1	143.4	0.2	33.5	0.1	13.8	0.2	33.5	0.2	No		33.1	0.5		
90-5	3.2	0.1	3.1	0.1 3.2	0.07	3.1	0.05	3.6	3.5	0.2	143.6	0.2	33.5	0.1	13.7	0.2	33	0.2	No		30.3	1.2		
45-1	2.7	0.1	2.6	0.1 3	0.2	2.9	0.1	2.1	2	0.1	149.4	0.5	40.2	0.4	20.7	0.3	40.4	0.3	No		28.1	2.8		
45-2	2.3	0.1	2.2	0.05 2.4	0.1	2.3	0.1	2.5	2.4	0.1	147.8	0.4	40.3	0.3	20.7	0.2	41.2	0.2	No		25.5	0		
45-3	2.8	0.1	2.7	0.1 3.2	0.07	3.1	0.07	2.7	2.6	0.08	149.6	0.3	40.4	0.4	20.9	0.3	41.4	0.3	No		34.1	0.9		
45-4	2.8	0.2	2.7	0.08 2.5	0.1	2.4	0.1	2.5	2.4	0.09	149.7	0.4	41.2	0.3	21.2	0.2	41	0.2	No		31.4	0.1		
45-5	2.4	0.1	2.3	0.1 2.8	0.07	2.7	0.1	2.7	2.6	0.1	149.3	0.3	41.1	0.3	20.9	0.2	40.7	0.2	No		27.2	0.05		
0-1	2.7	0.1	2.6	0.08 2.8	0.06	-	-	3	2.9	0.1	151.8	0.4	43	0.05	21.7	0.05	43.1	0.07	No		34.5	0.9		
0-2	2.5	0.1	2.4	0.07 2.6	0.08	-	-	2.4	2.3	0.1	151.1	0.3	42.6	0.05	21.8	0.05	44.1	0.1	No		31.4	1		
0-3	1.9	0.1	1.8	0.06 2.4	0.07	-	-	2.3	2.2	0.08	151.3	0.3	43.1	0.07	22.4	0.05	45.2	0.07	No		28.3	0.8		
0-4	2	0.15	1.9	0.1 2.5	0.06	-	-	2.3	2.2	0.1	151.3	2.3	42	0.08	22.3	0.05	47.3	0.3	No		27.9	0.7		
0-5	2.3	0.1	2.2	0.07 2.4	0.08	-	-	2.1	2	0.1	150.1	1.2	43.6	0.2	22	0.1	43.2	0.2	No		22.4	0		
0-6	2.3	0.1	2.2	0.08 2.7	0.1	-	-	2.3	2.2	0.1	150.2	1.6	42.5	0.1	22.1	0.05	42.7	0.05	No		22.5			
0-7	2.7	0.1	2.6	0.06 2.8	0.07	-	-	2.5	2.4	0.08	149	0.5	41.4	0.06	19.5	0.07	41.1	0.05	No		28.3			