SECTION ACTIVE EXTRUDED GLASS STRUCTURAL ELEMENTS

AN EXPLORATIVE STUDY ON THEIR POTENTIAL FOR ARCHITECTURE

P5 Presentation | 01-07-2020

Student:
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PLAN FOR TODAY

INTRODUCTION

TAKE YOU THROUGH MY GRADUATION PROJECT

ANSWER QUESTIONS

INTRODUCTION

OUTLINE OF GRADUATION PROJECT

ANSWER QUESTIONS

INTRODUCTION

TOPIC

RELEVANCE

GOAL

TOPIC

RELEVANCE

GOAL

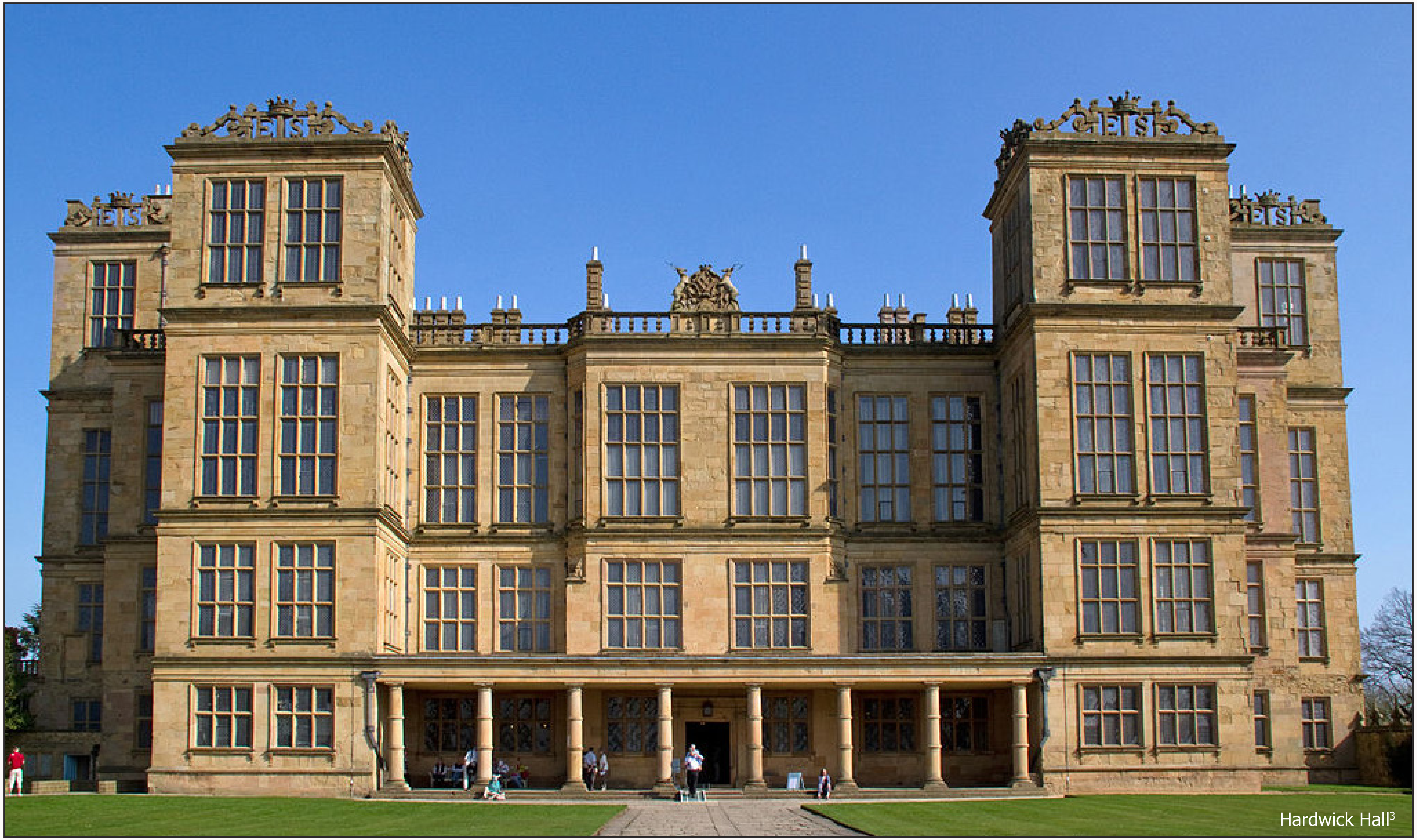
Apple Store 5th Ave[1]

METHODOLOGY

PART	*PROVIDES*
PERCEPTION OF GLASS	PROBLEM STATEMENT
COMPILING TOOLKIT	RESEARCH QUESTION
RESEARCHING MATERIAL PROPERTIES	INPUT PARAMETERS
ANALYTICAL DESIGN PROCESS	DRAFT DESIGN BY QUALIFYING FORCES
NUMERICAL DESIGN PROCESS	DIMENSIONED DESIGN BY QUANTIFYING FORCES
PHYSICAL TESTING DIMENSIONED DESIGN	VALIDATION NUMERICAL MODELS, PROOF
BUILDING SEQUENCE DESIGN	MANUFACTURING, INSTALLATION AND INSPECTION
VISUALISATIONS	SCENARIOS FOR IMPLEMENTATION
COMPARISON WITH EXISTING SYSTEMS	ANSWER TO RESEARCH QUESTION

METHODOLOGY / PERCEPTION OF GLASS / COMPILING CURRENT TOOLKIT / RESEARCHING MATERIAL PROPERTIES / ANALYTICAL DESIGN PROCESS / NUMERICAL DESIGN PROCESS / PHYSICAL TESTING OF THE DIMENSIONED DESIGN / BUILDING SEQUENCE DESIGN / VISUALISATIONS OF DESIGNED SYSTEM / COMPARISON WITH EXISTING SYSTEMS

Roman glass jewellery[2]

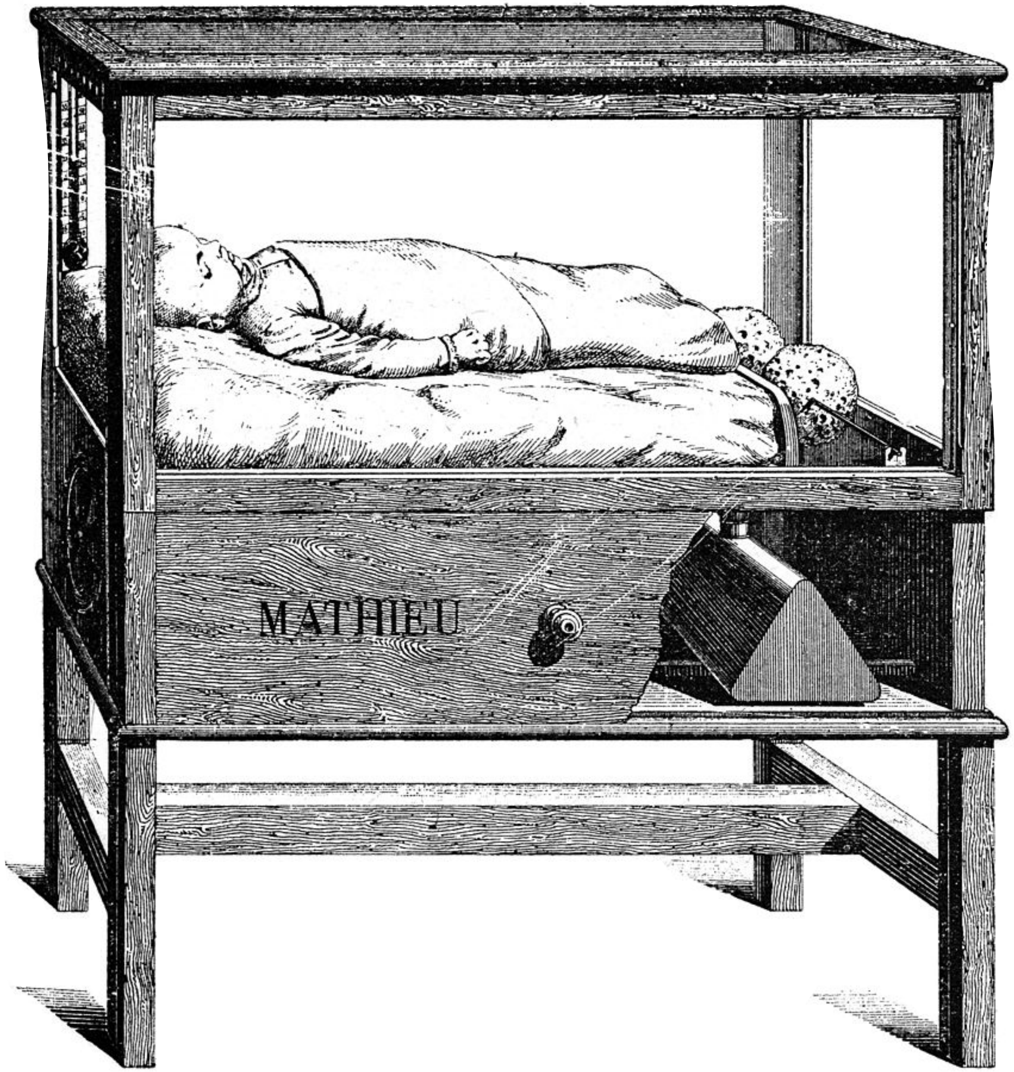


Hardwick Hall[3]


Horniman Museum and Gardens[4]

The Great Exhibition 1851[5]

56 Artillery Lane, London[6]



Glass incubator[7]


Reliance Building[8]

Battery Park[9]

SUMMARY OF PAST DEVELOPMENTS

JEWELS

SYMBOL OF PERSONAL WEALTH

WEALTH AND CULTIVATED LEARNING

SIGNIFIER OF PUBLIC NATIONAL IDENTITY

CLASS-BASED STRATIFICATION OF SHOPPING, SIGNALING AFFLUENCE

LOOKED HIGH-TECH

LOOKED CLEAN

GLASS FOR DAYLIGHT

LOOKED MODERN

Crystal Houses[10]

Van Gogh Museum[11]

Apple Store 5th Ave[1]

METHODOLOGY / **PERCEPTION OF GLASS** / COMPILING CURRENT TOOLKIT / RESEARCHING MATERIAL PROPERTIES / ANALYTICAL DESIGN PROCESS / NUMERICAL DESIGN PROCESS / PHYSICAL TESTING OF THE DIMENSIONED DESIGN / BUILDING SEQUENCE DESIGN / VISUALISATIONS OF DESIGNED SYSTEM / COMPARISON WITH EXISTING SYSTEMS

ESTIMATION OF FUTURE DEVELOPMENTS

KEEP STUNNING PEOPLE

KEEP UP WITH BUILDING REQUIREMENTS

PROBLEM STATEMENT:

THE TOOLKIT FOR ARCHITECTURAL GLASS NEEDS TO BE EXPANDED UPON

TO BE ABLE TO KEEP UP WITH FUTURE BUILDING REQUIREMENTS AND EXPECTATIONS.

Name Process	Description	Common uses
Soda-lime glass (or commercial glass)	- Least expensive and most common glass. Applications range from blown glass packaging to windowpanes. - Made up of silica sand (up to 75%), soda ash, lime (calcium oxide) and other additives. - It's a 'soft' glass that is relatively easy to mould and fabricate. It softens at around 400-500 C and so is economical for mass production. However, this also means that soda-lime glass is prone to shatter at high temperatures or in response to sudden changes in temperature. Costs: Low	Windowpanes (float glass), automotive windows, mirrors, packaging
Lead alkali glass: - lead glass - crystal glass	- Due to the lead content these glasses have a higher refractive index than other types. Increased refraction produces a clearer and more lustrous glass. - Lead alkali glass is silica based, but the lime is replaced by lead and the soda replaced with potash. If it has less than 25% lead it is known as crystal glass and when there is more than 25% lead it is known as lead glass. Over prolonged periods the lead content can leach, so this glass is not suitable for storing liquids and foods. - It is even 'softer' than soda-lime glass. - Cutting enhances the sparkle of the glass and as such is used in the production of decorative tableware, ornaments and jewellery. - Lead content makes it suitable for certain radiation shielding applications (more than 50% lead). Costs: Moderate to high	Vases, ornaments, jewellery, awards, prisms, lenses, radiation shielding
Borosilicate glass (or Duran, Simax, Pyrex)	- Primarily used for its resistance to high temperatures and thermal shock. - It contains up to 15% boric oxide and small amounts of other alkalis. - It is 'harder' and more durable than soda lime and lead alkali glass. - Borosilicate glass has a higher impact resistance. - It has low levels of thermal expansion and is resistant to thermal shock. - Its softening point is relatively high at 800-850 C. This makes it more difficult to mould and fabricate, but means that it can be used for high temperature applications. - It is more resistant to acids than soda lime glass and has moderate resistance to alkalis. Costs: Moderate to high	Ovenware, coffee pots, scientific glassware, sculpture, ornaments and complex profiles
High performance glasses: - glass ceramic - aluminosilicate glass - quartz glass	- These glasses have high working temperatures; they are relatively difficult to fabricate, but have superior resistance to heat and thermal shock. - High performance, high costs. - Glass ceramics are so called because they are shaped like glass in a molten state but heat-treated to give a high level of crystallinity, similar to ceramics. The resulting material is harder, more durable and resistant to rapid temperature change. - Aluminosilicate glass contains higher levels of aluminium oxide than other lower cost glasses. It is similar to borosilicate glass, but has improved resistance to chemicals, high temperatures and thermal shock. - Quart glass, also known as fused quartz and silica glass, is made up of almost pure silica (silicon dioxide). It has exceptional resistance to high temperatures, thermal shock and most chemicals. Costs: high to very high	Stove and fireplace doors, cooker tops, light covers for industrial applications.

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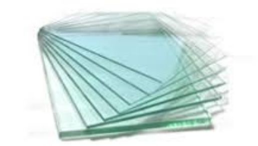
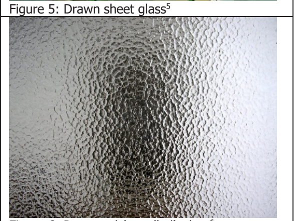
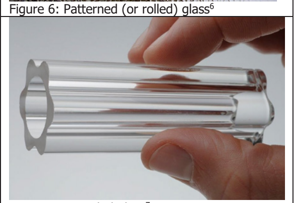
Name Process	Description	Common uses
Casting	Molten glass is poured into a mould.	Decorative items, solid items
Blowing (blow and blow)	Glass is injected into a mould and blown into a general shape. After transferring to a second mould, it is further blown into shape.	Narrow-neck containers
Blowing (press and blow)	Similar to blow and blow, but here in the first mould it's pressed into shape instead of blown.	Wide-mouth containers
Floating	Glass 'floats' from the melting tank through a separate float bath (liquid tin).	Panes
Drawing (by machine)	Glass rolls out of melting tank through rollers. Rollers give the glass its pattern.	Panes
Pressing	Pressed glass (or pattern glass) is glass made using a plunger to press molten glass into a mould.	Decorative items
Rolling	Similar to float glass, but rolled out of the melting tank by two rollers.	Glass panes
Extruding (direct)	The billet is compressed within the container and forced by the punch to flow through the die aperture. The cross section of the extruded product is determined by the shape of this aperture. During this process punch and extruded rod move in the same direction (Roeder, 1970)	Special chemical properties (unconventional): 1. Glasses with a steep viscosity-temperature curve (or short glasses). Their rather narrow temperature range for working is very inconvenient for shaping. 2. Glasses with a strong tendency to devitrify (become opaque amongst other things) 3. High melting glasses. Suitable for conventional glasses too if rods or tubes with other than circular cross sections are to be produced. Due to the comparatively low working temperature, surface tension does not have much effect; the products therefore have sharp edges and are very accurate in shape.
Extruding (inverted)	The hollow punch supporting the die in front is pressed against the billet, and the extruded rod inside the punch moves opposite to it.	

Name Process	Description	Common uses	Picture(s)
Cast glass	- Not very common in architecture, but can be used for making brick-like blocks. - Attention needs to be paid to the solidifying time and process of the element as this can have a large impact on planning and material properties.	Blocks, bricks	 Figure 3: Cast glass[3]
Float glass	- Most widely used type of glass. Thicknesses from 2 to 19 mm. - Maximum ribbon sizes of 3.2x6.0m. Can be coloured during the manufacturing process. - When lower amounts of Fe_2O_3, it is possible to reduce or even virtually eliminate the natural green tint of float glass (low-iron or clear-white glass).	Standard windows, façade elements	 Figure 4: Float glass[4]
Drawn sheet glass	- Drawn sheet glass and float glass have the same chemical composition as well as the same general physical properties. However, drawn sheet glass exhibits slight waves and "batter" in the surface perpendicular to the direction of drawing. - Thicknesses from 2 to 12 mm.	Windows, windows from older styles	 Figure 5: Drawn sheet glass[5]
Patterned (or rolled) glass	- The liquid glass melt, like an overflowing bath, is fed between one or more pairs of rollers to give it a characteristic surface texture as required. Therefore, the glass can be given two smooth surfaces, one smooth and one textured surface or two textured sides depending on the design of the roller or table surfaces. - Rolled glasses are translucent, they can not reproduce the transparency of float or drawn sheet.	Windows with privacy	 Figure 6: Patterned (or rolled) glass[6]
Extruded glass	- Extruded glass profiles are typically borosilicate glass, because soda lime is 'softer' and prone to breaking during processing. - Determined by the equipment, the extruded profiles could be of complex geometry and in large dimensions. Currently existing equipment can not produce these large elements as it has no applications that demand such dimensions yet.	[experimental] Hardly used in architecture yet	 Figure 7: Extruded glass[7]

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Name Process	Desc	
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Floating	Glass separ	
Drawing (by machine)	Glass Roller	
Pressing	Press using mould	
Rolling	Simila meltir	
Extruding (direct)	The b and fe die aperture. The cross section of the extruded product is determined by the shape of this aperture. During this process punch and extruded rod move in the same direction (Roeder, 1970)	1. Glasses with a steep viscosity-temperature curve (or short glasses). Their rather narrow temperature range for working is very inconvenient for shaping. 2. Glasses with a strong tendency to devitrify (become opaque amongst other things) 3. High melting glasses. Suitable for conventional glasses too if rods or tubes with other than circular cross sections are to be produced. Due to the comparatively low working temperature, surface tension does not have much effect; the products therefore have sharp edges and are very accurate in shape.
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Glass products[12-21]

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Drawn sheet glass	- Drawn she same chen same gene drawn shee "batter" in direction of - Thicknesse		
Patterned (or rolled) glass	- The liquid bath, is fe rollers to texture as r be given tv and one t sides deper table surfac - Rolled glas reproduce t sheet.		
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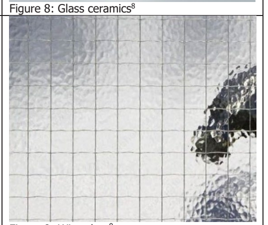
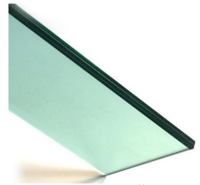
Glass ceramics	- Glass ceramics are produced just like float, drawn sheet or rolled glass. They can be coloured by adding further substances. The fracture pattern of glass ceramics is basically the same as that of float glass.	Not really used in architecture	 Figure 8: Glass ceramics[8]
Polished wire glass	- Clear soda-lime-silica glass whose surfaces have been polished and made parallel. Glass is produced by casting and then polished. A spot-welded wire mesh is inserted during the manufacture. It's not a safety glass and possesses no safety properties. It is mainly used for aesthetic reasons, as a fragment-bonding glass for roof glazing or sometimes as fire-resistant glass.	Workshop windows, privacy windows	 Figure 9: Wire glass[9]
Channel shaped glass	- Profiled glass element with textured surfaces which are produced by casting. Used for single skin or double skin (inner) walls. - The elements are produced U-shaped and then fitted together to form a wall.	Inner walls, facades	 Figure 10: channel shaped glass[10]
Laminated glass	- Element consisting of panes and intermediate layers. The laminating can make the glass stronger or stiffer or it can be used to make the element better insulating.	Windows, facades	 Figure 11: Laminated glass[11]
Laminated safety glass	- At least two panes and one intermediate layer. It's a safety glass because fragments are held together upon fracture.	Structural fins, balustrades	 Figure 12: Laminated safety glass[12]

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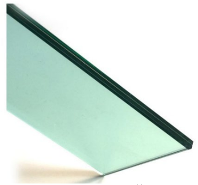
Laminated glass	- Element consisting of panes and intermediate layers. The laminating can make the glass stronger or stiffer or it can be used to make the element better insulating.	Windows, facades	 Figure 11: Laminated glass[11]
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Name Coating	Description	Common uses
Online coating	Spread over the upper surface while it is still hot during the production of float glass. Metal oxide.	Solar control
Offline coating: Magnetron sputtering	Method of coating. Acceleration of free electrons in an electric field which then collide with gas molecules. Finished product can usually only be left outside for a limited period.	Low-emissivity coatings
Offline coating: Evaporation	Not really used anymore	-
Offline coating: Sol-gel process	Glass is dipped in a liquid.	Solar control
Enamelling	Applying a coloured ceramic layer to the glass surface and then baking it into the glass.	Adding colours it's mostly for decorative purposes, not really used in architecture.
Acid etching	Patterns and pictures can be etched into the surface by masking certain areas.	Matt finish
Sand blasting	The element gets blasted by tiny sand particles at high speeds.	Matt finish
Edge works	Normal cut edge; simplest and used wherever the edge of the glass is placed in a frame and there is no danger of being injured by the sharp edge. Other types can be achieved by grinding and polishing.	-
Name treatment		
Bending	Flat panes reheated and bent. Watch for tolerances.	Facades, art
Thermally toughened safety glass (or toughened/tempered safety glass)	Reheated and cooled quickly. It creates additional compressive stresses in the surfaces which makes the glass stronger. Bending strength increases, likewise the thermal fatigue resistance. Can accommodate higher tensile forces due to the pre-stress. When breaks than into numerous small pieces whose edges are generally blunt. Can not be worked (drilled etc.) afterwards.	When failing of the element would likely cause injuries through large pieces of falling glass.
Heat strengthened glass	Higher bending strength and better thermal fatigue, but no a safety glass (toughened glass is). Different fracture pattern. Also can not be drilled etc. into afterwards.	Oftentimes used as structurally better inner layer(s) of laminated element with sacrificial layers on both sides.
Chemically strengthened glass	Chemical pre-stressing by ionic exchange. Glass is immersed in a hot molten salt. Can be cut afterwards, but loses its strengthening in the new edge.	Similar to heat strengthened glass, but structurally even better.

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Name Process	Description
Soda-lime glass (or commercial glass)	- Least expensive and most common glass. Applic from blown glass packaging to windowpanes. - Made up of silica sand (up to 75%), soda ash, li oxide) and other additives. - It's a 'soft' glass that is relatively easy to fabricate. It softens at around 400-500 C economical for mass production. However, this that soda-lime glass is prone to shatter at high te or in response to sudden changes in temperatu Costs: Low
Lead alkali glass: - lead glass - crystal glass	- Due to the lead content these glasses hav refractive index than other types. Increase produces a clearer and more lustrous glass. - Lead alkali glass is silica based, but the lime is lead and the soda replaced with potash. If it h 25% lead it is known as crystal glass and when t than 25% lead it is known as lead glass. Ove periods the lead content can leach, so this suitable for storing liquids and foods. - It is even 'softer' than soda-lime glass. - Cutting enhances the sparkle of the glass and as in the production of decorative tableware, orn jewellery. - Lead content makes it suitable for certain radiati applications (more than 50% lead). Costs: Moderate to high
Borosilicate glass (or Duran, Simax, Pyrex)	- Primarily used for its resistance to high tempe thermal shock. - It contains up to 15% boric oxide and small amou alkalis. - It is 'harder' and more durable than soda lime ar glass. - Borosilicate glass has a higher impact resistance - It has low ... thermal shc - Its softening it more diffi be used for - It is more r moderate re Costs: Moderate to hi
High performance glasses: - glass ceramic - aluminosilicate glass - quartz glass	- These glass relatively di to heat and - High perfor - Glass ceran glass in a n of crystallin harder, mo change. - Aluminosilic oxide than borosilicate high tempe - Quart glass made up c exceptional and most cl Costs: high to very hi

Name Process	Desc
Casting	Molte
Blowing (blow and blow)	Glass a ge secon
Blowing (press and blow)	Simila moulc blowr
Floating	Glass separ
Drawing (by machine)	Glass Roller
Pressing	Press using moulc
Rolling	Simila meltir
Extruding (direct)	The b and f die aperture. The cross section of the extruded product is determined by the shape of this aperture. During this process punch and extruded rod move in the same direction (Roeder, 1970)
Extruding (inverted)	The hollow punch supporting the die in front is pressed against the billet, and the extruded rod inside the punch moves opposite to it.

Name Process	Description	Common uses	Picture(s)
Cast glass	- Not very common in architecture, but can be used for making brick-like blocks. - Attention needs to be paid to the solidifying time and process of the element as this can have a large impact on planning and material properties.	Blocks, bricks	
Float glass	- Most widel from 2 to 1 - Maximum r coloured du - When lowe to reduce natural gre clear-white		
Drawn sheet glass	- Drawn she same chen same gene drawn shee "batter" in direction of - Thicknesse		
Patterned (or rolled) glass	- The liquid bath, is fe rollers to texture as r be given tv and one t sides deper table surfac - Rolled glas reproduce t sheet.		
Extruded glass	- Extruded borosilicate 'softer' ar processing. - Determinec profiles cou large dir equipment elements a demand su		

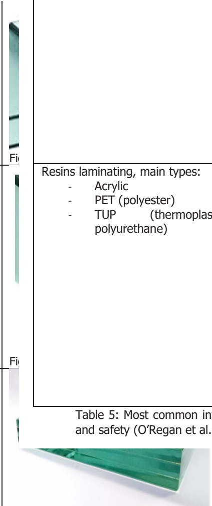
Glass ceramics	- Glass ceramics are produced just drawn sheet or rolled glass. The coloured by adding further substar fracture pattern of glass ceramics is the same as that of float glass.		
Polished wire glass	- Clear soda-lime-silica glass whose have been polished and made para is produced by casting and then pc spot-welded wire mesh is inserted c manufacture. It's not a safety g possesses no safety properties. It used for aesthetic reasons, as a f bonding glass for roof glazing or s as fire-resistant glass.		
Channel shaped glass	- Profiled glass element with texturec which are produced by casting. single skin or double skin (inner) wa - The elements are produced U-shaped and then fitted together to form a wall.		
Laminated glass	- Element consisting of panes and intermediate layers. The laminating can make the glass stronger or stiffer or it can be used to make the element better insulating.	Windows, facades	
Laminated safety glass	- At least two panes and one intermediate layer. It's a safety glass because fragments are held together upon fracture.	Structural fins, balustrades	

Figure 12: Laminated safety glass[12]

Name Coating	Description	Common uses
Online coating	Spread over the upper surface while it is still hot during the production of float glass. Metal oxide.	Solar control
Offline coating: Magnetron sputtering	Method of coating. Acceleration of free electrons in an electric field which then collide with gas molecules. Finished product can usually only be left outside for a limited period.	Low-emissivity coatings
Offline coating: Evaporation	Not really used anymore	-
Offline coating: Sol-gel process	Glass is dipped in a liquid.	Solar control
Enamelling	Applying a coloured ceramic layer to the glass surface and then baking it into the glass.	Adding colours it's mostly for decorative purposes, not really used in architecture.
Acid etching	Patterns and pictures can be etched into the surface by masking certain areas.	Matt finish
Sand blasting	The element gets blasted by tiny sand particles at high speeds.	Matt finish
Edge works	Normal cut edge; simplest and used wherever the edge of the glass is placed in a frame and there is no danger of being injured by the sharp edge. Other types can be achieved by grinding and polishing.	-
Name treatment		
Bending	Flat panes reheated and bent. Watch for tolerances.	Facades, art
Thermally toughened safety glass (or toughened/tempered safety glass)	Reheated and cooled quickly. It creates additional compressive stresses in the surfaces which makes the	When failing of the element would likely cause injuries through large
Heat strengthened glass		
Chemically strengthened		

Name Interlayer	Application process	Structural behaviour	Safety
Sheet laminating, main types: - PVB (poly vinyl butyral) - EVA (ethyl vinyl acetate) - ionoplast	PVB is the most common sheet interlayer material. The sheets of glass are assembled with an extruded sheet of interlayer between them. The 'sandwich' is then passed through an oven that heats it to approximately 70°C, from which it passes between rollers that squeeze out any excess air and form the initial bond. The laminate then moves to an autoclave where it is heated to approximately 140°C under a pressure of about 800kN/m² in a vacuum bag.	Generally, for the PVB and resin interlayer materials, short-term out of plane loads can be resisted by both laminates acting compositely. Due to creep in the interlayer elements with long-term out of plane loads are generally considered to act non-compositely, with the loads being shared by each laminate in proportion to their relative stiffness. Laminated glass panels with an ionoplast interlayer exhibit some composite action even during long-term loading conditions, although their strength is diminished somewhat. This is due to the stiffness of the ionoplast interlayer decreasing over time.	If one or both layers of glass in a laminated panel break, the broken pieces of glass will generally remain bonded to the interlayer.
Resins laminating, main types: - Acrylic - PET (polyester) - TUP (thermoplastic polyurethane)	The sheets of glass are brought together and held a certain distance apart by double-sided tape around their perimeter. Resin is then poured between the two sheets. When all the air has been displaced, the open edge is sealed and the resin cures and solidifies. Curing is via a chemical reaction or ultra violet light. Size is limited by the ability of the fabricator or by the size of the panes available.	Generally, for the PVB and resin interlayer materials, short-term out of plane loads can be resisted by both laminates acting compositely. Due to creep in the interlayer long-term out of place loads are generally considered to act non-compositely, with the loads being shared by each laminate in proportion to their relative stiffness.	If one or both layers of glass in a laminated panel break, the broken pieces of glass will generally remain bonded to the interlayer. Intumescent resin interlayers react to heat in such a way that during a fire they turn into foam. This change not only resists the passage of fire but also reduces the conduction and the radiation of heat through the glass. This protects people who may need to pass it on their way out of the building.

Table 5: Most common interlayers used in architecture with a brief description of the application process, structural behaviour and safety (O'Regan et al., 2015)

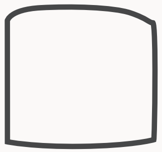
Glass products[12-21]

GLASS PANE

TERTIARY - FLOAT

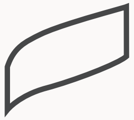
BENT GLASS PANE

TERTIARY - FLOAT



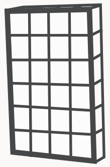
COLD BENT GLASS

TERTIARY - FLOAT



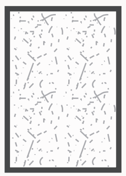
GLASS BLOCKS

TERTIARY - CAST



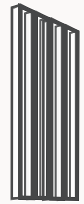
POLISHED WIRED GLASS

TERTIARY - GLOAT



CHANNEL SHAPED GLASS

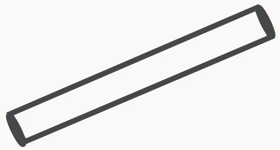
TERTIARY - CAST



POST-TENSIONED TRUSS

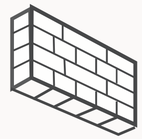
VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]



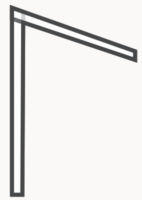
GLASS BLOCKS (STRUCTURAL)

SECTION ACTIVE - CAST



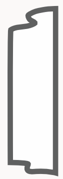
GLASS FIN

SECTION ACTIVE - FLOAT



BENT GLASS PANE (STRUCTURAL)

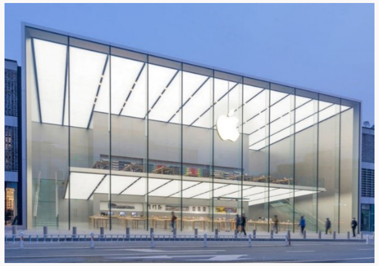
SURFACE ACTIVE - FLOAT



Current toolkit[22-31]

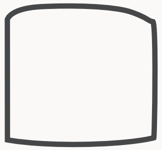
GLASS PANE

TERTIARY - FLOAT



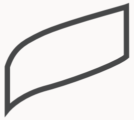
BENT GLASS PANE

TERTIARY - FLOAT



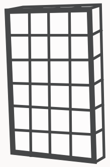
COLD BENT GLASS

TERTIARY - FLOAT



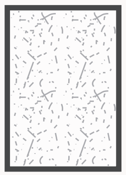
GLASS BLOCKS

TERTIARY - CAST



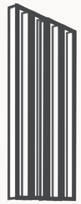
POLISHED WIRED GLASS

TERTIARY - GLOAT



CHANNEL SHAPED GLASS

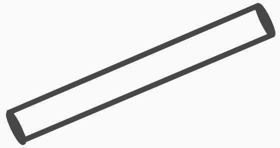
TERTIARY - CAST



POST-TENSIONED TRUSS

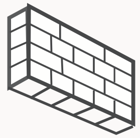
VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]



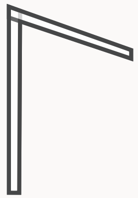
GLASS BLOCKS (STRUCTURAL)

SECTION ACTIVE - CAST



GLASS FIN

SECTION ACTIVE - FLOAT



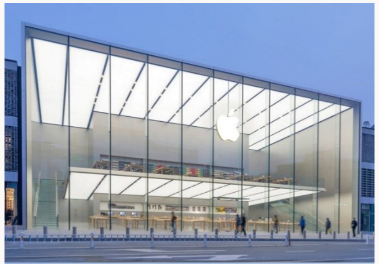
BENT GLASS PANE (STRUCTURAL)

SURFACE ACTIVE - FLOAT

Current toolkit[22-31]

GLASS PANE

TERTIARY - FLOAT

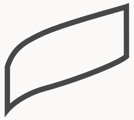


BENT GLASS PANE

TERTIARY - FLOAT

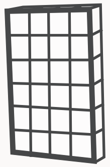
COLD BENT GLASS

TERTIARY - FLOAT



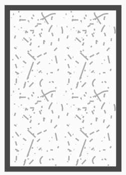
GLASS BLOCKS

TERTIARY - CAST



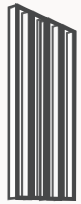
POLISHED WIRED GLASS

TERTIARY - GLOAT



CHANNEL SHAPED GLASS

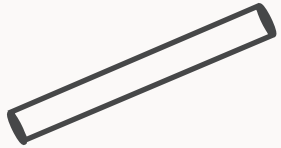
TERTIARY - CAST



POST-TENSIONED TRUSS

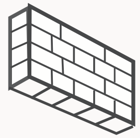
VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]



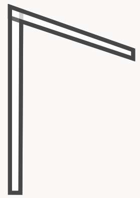
GLASS BLOCKS (STRUCTURAL)

SECTION ACTIVE - CAST



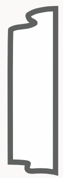
GLASS FIN

SECTION ACTIVE - FLOAT



BENT GLASS PANE (STRUCTURAL)

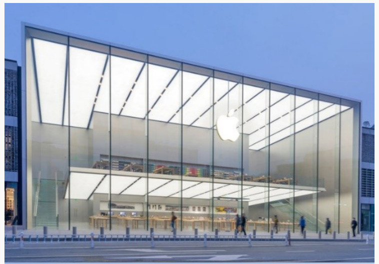
SURFACE ACTIVE - FLOAT



Current toolkit[22-31]

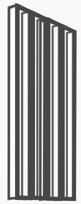
GLASS PANE

TERTIARY - FLOAT



CHANNEL SHAPED GLASS

TERTIARY - CAST



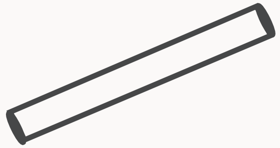
BENT GLASS PANE

TERTIARY - FLOAT

POST-TENSIONED TRUSS

VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]

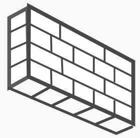


COLD BENT GLASS

TERTIARY - FLOAT

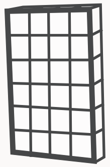
GLASS BLOCKS (STRUCTURAL)

SECTION ACTIVE - CAST



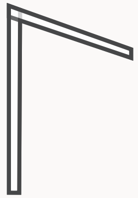
GLASS BLOCKS

TERTIARY - CAST



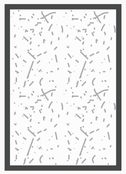
GLASS FIN

SECTION ACTIVE - FLOAT



POLISHED WIRED GLASS

TERTIARY - GLOAT



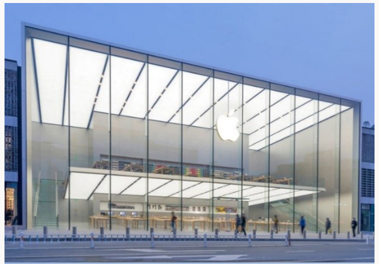
BENT GLASS PANE (STRUCTURAL)

SURFACE ACTIVE - FLOAT

Current toolkit[22-31]

GLASS PANE

TERTIARY - FLOAT



CHANNEL SHAPED GLASS

TERTIARY - CAST

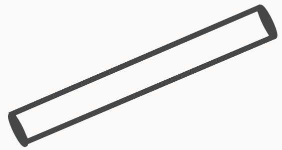
BENT GLASS PANE

TERTIARY - FLOAT

POST-TENSIONED TRUSS

VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]

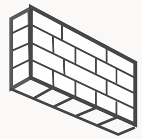


COLD BENT GLASS

TERTIARY - FLOAT

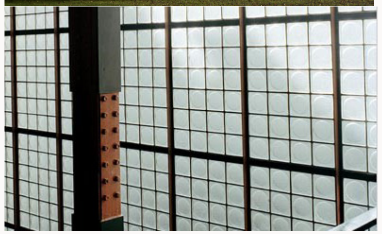
GLASS BLOCKS (STRUCTURAL)

SECTION ACTIVE - CAST



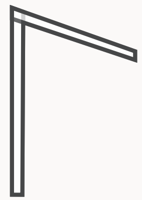
GLASS BLOCKS

TERTIARY - CAST



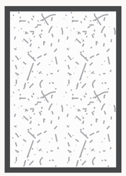
GLASS FIN

SECTION ACTIVE - FLOAT



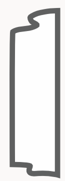
POLISHED WIRED GLASS

TERTIARY - GLOAT



BENT GLASS PANE (STRUCTURAL)

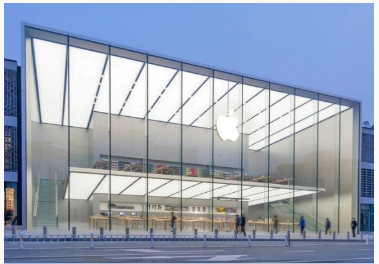
SURFACE ACTIVE - FLOAT



Current toolkit[22-31]

GLASS PANE

TERTIARY - FLOAT



CHANNEL SHAPED GLASS

TERTIARY - CAST

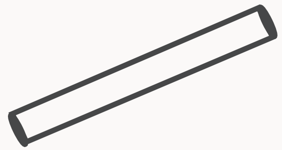
BENT GLASS PANE

TERTIARY - FLOAT

POST-TENSIONED TRUSS

VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]

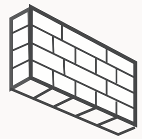


COLD BENT GLASS

TERTIARY - FLOAT

GLASS BLOCKS (STRUCTURAL)

SECTION ACTIVE - CAST

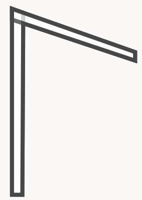


GLASS BLOCKS

TERTIARY - CAST

GLASS FIN

SECTION ACTIVE - FLOAT

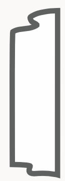


POLISHED WIRED GLASS

TERTIARY - GLOAT

BENT GLASS PANE (STRUCTURAL)

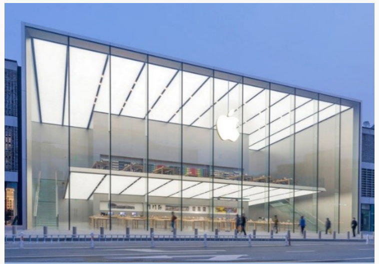
SURFACE ACTIVE - FLOAT



Current toolkit[22-31]

GLASS PANE

TERTIARY - FLOAT



BENT GLASS PANE

TERTIARY - FLOAT

COLD BENT GLASS

TERTIARY - FLOAT

GLASS BLOCKS

TERTIARY - CAST

POLISHED WIRED GLASS

TERTIARY - GLOAT

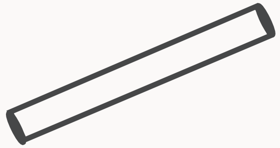
CHANNEL SHAPED GLASS

TERTIARY - CAST

POST-TENSIONED TRUSS

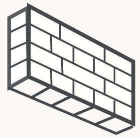
VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]



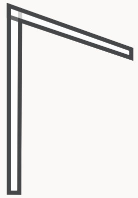
GLASS BLOCKS (STRUCTURAL)

SECTION ACTIVE - CAST



GLASS FIN

SECTION ACTIVE - FLOAT



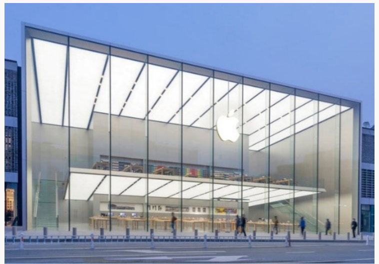
BENT GLASS PANE (STRUCTURAL)

SURFACE ACTIVE - FLOAT

Current toolkit[22-31]

GLASS PANE

TERTIARY - FLOAT



BENT GLASS PANE

TERTIARY - FLOAT

COLD BENT GLASS

TERTIARY - FLOAT

GLASS BLOCKS

TERTIARY - CAST

POLISHED WIRED GLASS

TERTIARY - GLOAT

CHANNEL SHAPED GLASS

TERTIARY - CAST

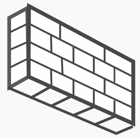
POST-TENSIONED TRUSS

VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]

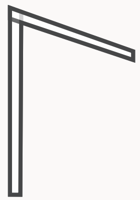
GLASS BLOCKS (STRUCTURAL)

SECTION ACTIVE - CAST



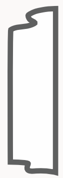
GLASS FIN

SECTION ACTIVE - FLOAT



BENT GLASS PANE (STRUCTURAL)

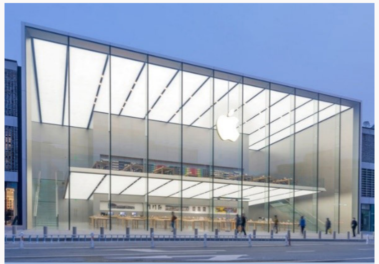
SURFACE ACTIVE - FLOAT



Current toolkit[22-31]

GLASS PANE

TERTIARY - FLOAT



CHANNEL SHAPED GLASS

TERTIARY - CAST

BENT GLASS PANE

TERTIARY - FLOAT

POST-TENSIONED TRUSS

VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]

COLD BENT GLASS

TERTIARY - FLOAT

GLASS BLOCKS (STRUCTURAL)

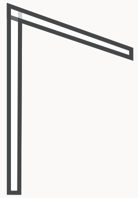
SECTION ACTIVE - CAST

GLASS BLOCKS

TERTIARY - CAST

GLASS FIN

SECTION ACTIVE - FLOAT



POLISHED WIRED GLASS

TERTIARY - GLOAT

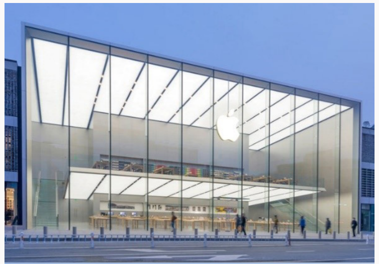
BENT GLASS PANE (STRUCTURAL)

SURFACE ACTIVE - FLOAT

Current toolkit[22-31]

GLASS PANE

TERTIARY - FLOAT



BENT GLASS PANE

TERTIARY - FLOAT

COLD BENT GLASS

TERTIARY - FLOAT

GLASS BLOCKS

TERTIARY - CAST

POLISHED WIRED GLASS

TERTIARY - GLOAT

CHANNEL SHAPED GLASS

TERTIARY - CAST

POST-TENSIONED TRUSS

VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]

GLASS BLOCKS (STRUCTURAL)

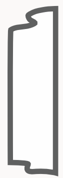
SECTION ACTIVE - CAST

GLASS FIN

SECTION ACTIVE - FLOAT

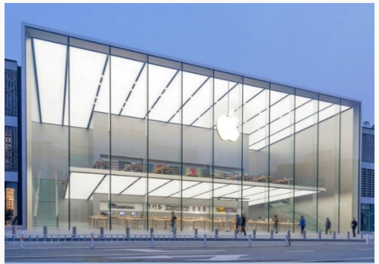
BENT GLASS PANE (STRUCTURAL)

SURFACE ACTIVE - FLOAT



Current toolkit[22-31]

GLASS PANE
TERTIARY - FLOAT



CHANNEL SHAPED GLASS
TERTIARY - CAST

BENT GLASS PANE
TERTIARY - FLOAT

POST-TENSIONED TRUSS
VECTOR ACTIVE - EXTRUDED
[EXPERIMENTAL]

COLD BENT GLASS
TERTIARY - FLOAT

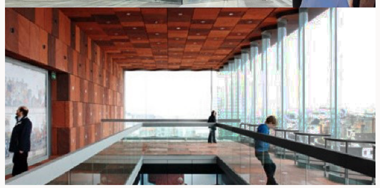
GLASS BLOCKS (STRUCTURAL)
SECTION ACTIVE - CAST

GLASS BLOCKS
TERTIARY - CAST

GLASS FIN
SECTION ACTIVE - FLOAT

POLISHED WIRED GLASS
TERTIARY - GLOAT

BENT GLASS PANE (STRUCTURAL)
SURFACE ACTIVE - FLOAT

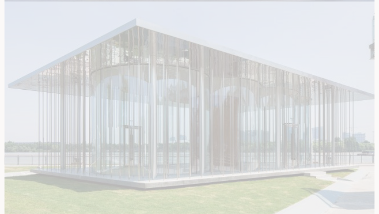


Current toolkit[22-31]

GLASS PANE
TERTIARY - FLOAT

CHANNEL SHAPED GLASS
TERTIARY - CAST

BENT GLASS PANE
TERTIARY - FLOAT



POST-TENSIONED TRUSS
VECTOR ACTIVE - EXTRUDED
[EXPERIMENTAL]

COLD BENT GLASS
TERTIARY - FLOAT

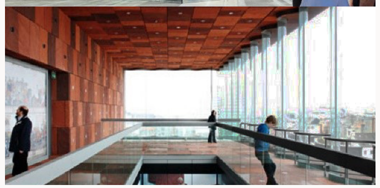
GLASS BLOCKS (STRUCTURAL)
SECTION ACTIVE - CAST

GLASS BLOCKS
TERTIARY - CAST

GLASS FIN
SECTION ACTIVE - FLOAT

POLISHED WIRED GLASS
TERTIARY - GLOAT

BENT GLASS PANE (STRUCTURAL)
SURFACE ACTIVE - FLOAT

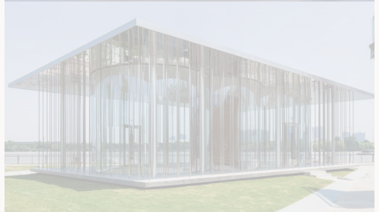


Current toolkit[22-31]

GLASS PANE
TERTIARY - FLOAT

CHANNEL SHAPED GLASS
TERTIARY - CAST

BENT GLASS PANE
TERTIARY - FLOAT



POST-TENSIONED TRUSS
VECTOR ACTIVE - EXTRUDED
[EXPERIMENTAL]

COLD BENT GLASS
TERTIARY - FLOAT

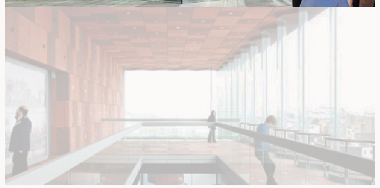
GLASS BLOCKS (STRUCTURAL)
SECTION ACTIVE - CAST

GLASS BLOCKS
TERTIARY - CAST

GLASS FIN
SECTION ACTIVE - FLOAT

POLISHED WIRED GLASS
TERTIARY - GLOAT

BENT GLASS PANE (STRUCTURAL)
SURFACE ACTIVE - FLOAT



Current toolkit[22-31]

GLASS PANE

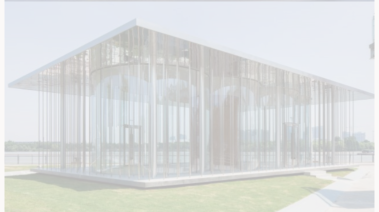
TERTIARY - FLOAT

CHANNEL SHAPED GLASS

TERTIARY - CAST

BENT GLASS PANE

TERTIARY - FLOAT



POST-TENSIONED TRUSS

VECTOR ACTIVE - EXTRUDED

[EXPERIMENTAL]

COLD BENT GLASS

TERTIARY - FLOAT

GLASS BLOCKS (STRUCTURAL)

SECTION ACTIVE - CAST

GLASS BLOCKS

TERTIARY - CAST

GLASS FIN

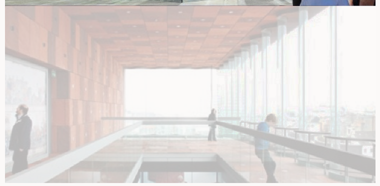
SECTION ACTIVE - FLOAT

POLISHED WIRED GLASS

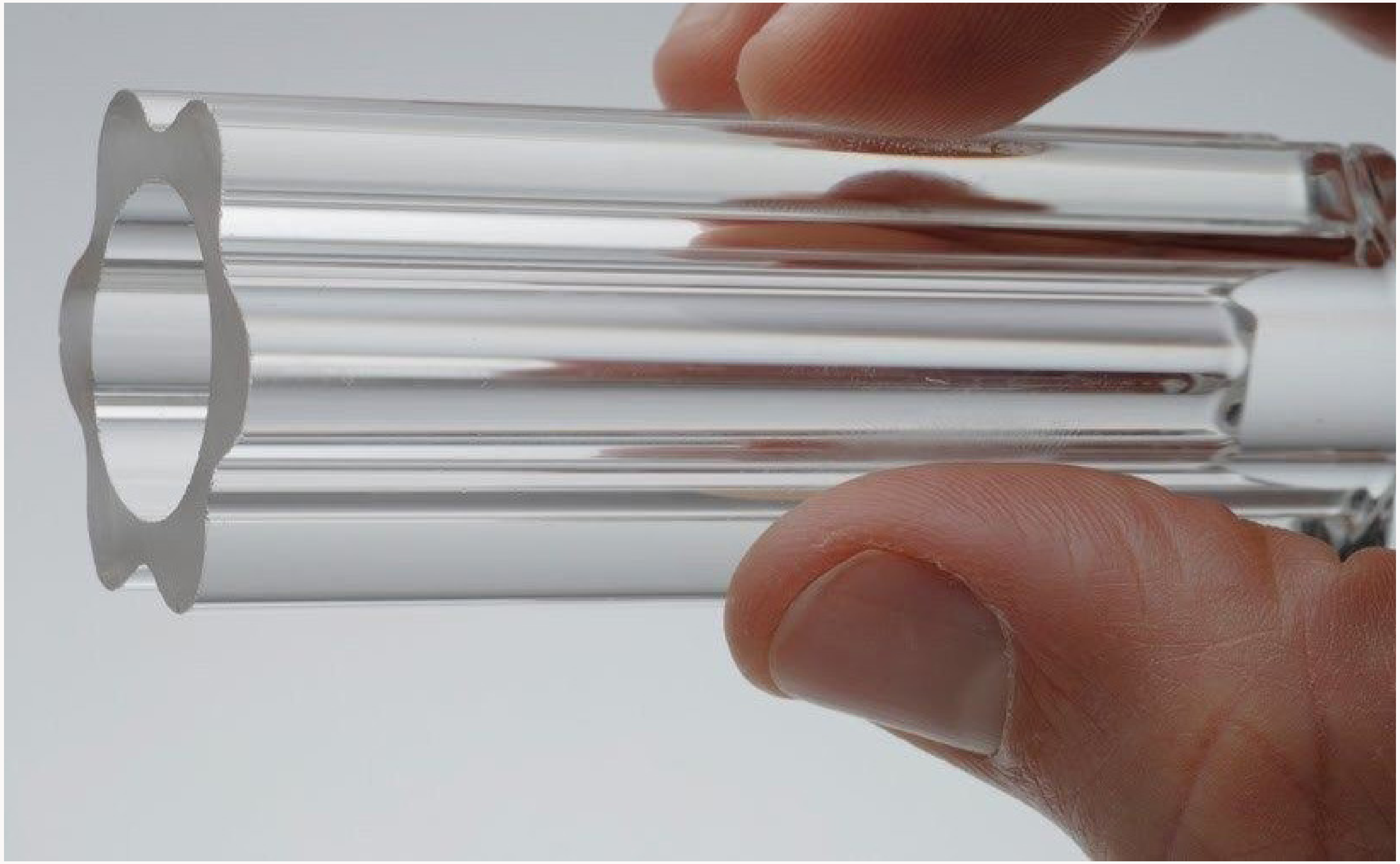
TERTIARY - GLOAT

BENT GLASS PANE (STRUCTURAL)

SURFACE ACTIVE - FLOAT



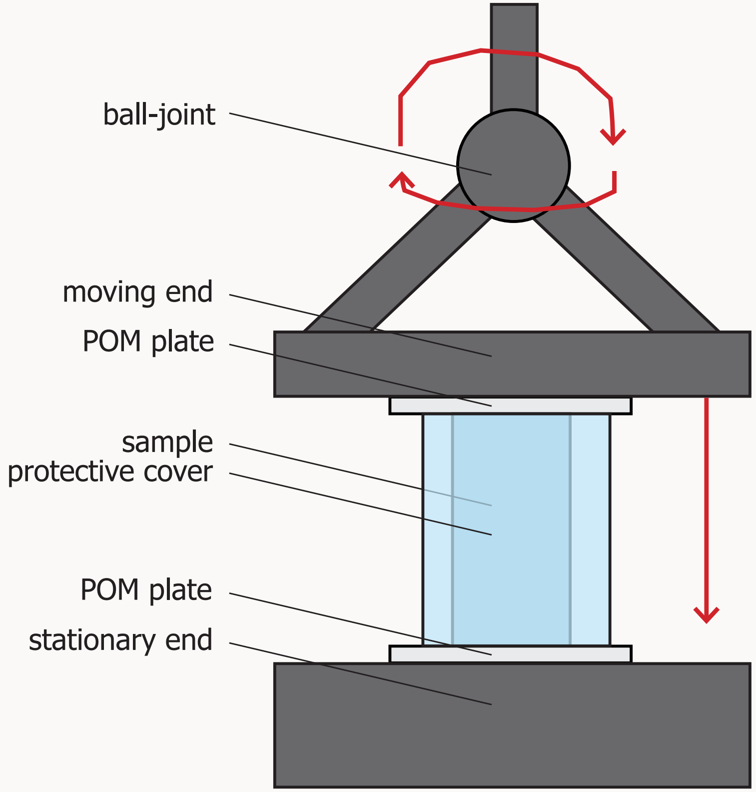
Current toolkit[22-31]

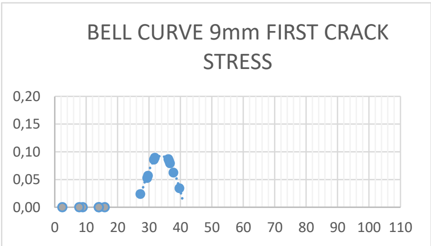


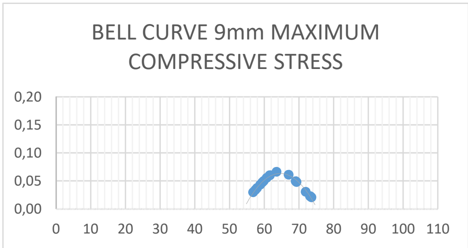
Extruded glass tube[16]

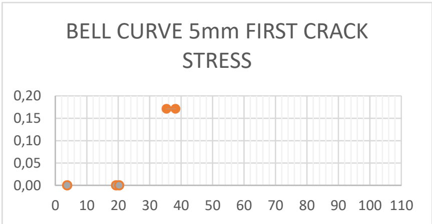
RESEARCH QUESTION:

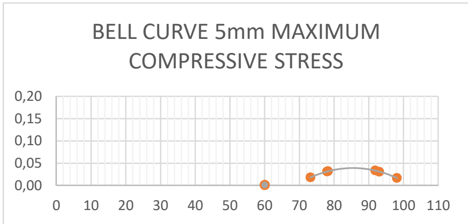
WHAT IS THE POTENTIAL OF SECTION-ACTIVE EXTRUDED GLASS STRUCTURAL ELEMENTS FOR ARCHITECTURAL DESIGN?

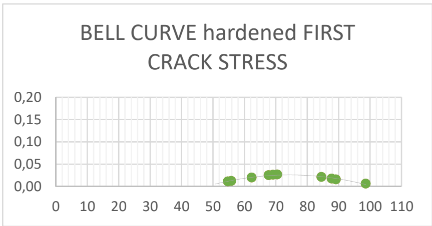

ball-joint
moving end
POM plate
sample
protective cover
POM plate
stationary end

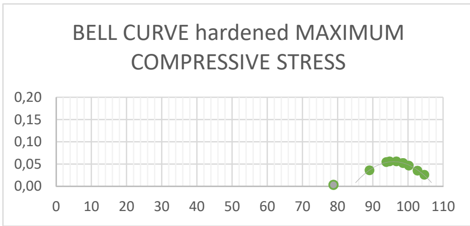

BELL CURVE 9mm FIRST CRACK STRESS

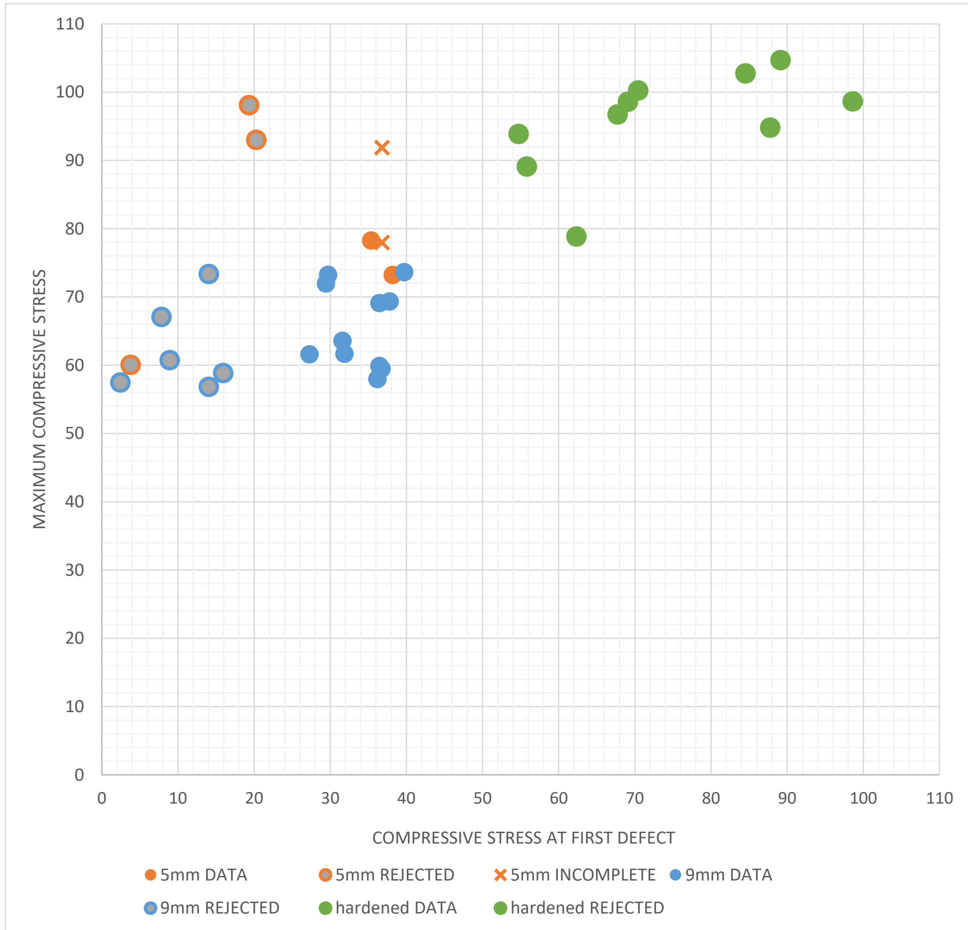

BELL CURVE 9mm MAXIMUM COMPRESSIVE STRESS


BELL CURVE 5mm FIRST CRACK STRESS


BELL CURVE 5mm MAXIMUM COMPRESSIVE STRESS


BELL CURVE hardened FIRST CRACK STRESS


BELL CURVE hardened MAXIMUM COMPRESSIVE STRESS


MAXIMUM COMPRESSIVE STRESS
COMPRESSIVE STRESS AT FIRST DEFECT
5mm DATA
5mm REJECTED
5mm INCOMPLETE
9mm DATA
9mm REJECTED
hardened DATA
hardened REJECTED

RESEARCH PROPOSAL

APPENDIX B: RESEARCH PROPOSAL
TENSILE STRENGTH EXTRUDED BOROSILICATE GLASS

This research proposal is part of a series of research proposals that collectively and with synergy contribute especially to evaluating the potential of section active extruded glass structural systems for architectural design.

Introduction

The architectural language of glass buildings is relatively new and especially the toolkit of structural glass elements has only begun to really develop lately. Glass buildings are mostly one of a kind public buildings and as glass has throughout its history always had an air of luxury and the smell of engineering miracles, nowadays they shine as the jewels of the built environment. They captivate people and offer a truly special experience.

Meanwhile firstly the demand for glass buildings is rising which means that the toolkit needs to be kept developing to avoid too much repetition and take away some of the wonder. Secondly the building requirements are getting stricter and we need to prevent being wasteful of material and energy which means that new additions to the toolkit should be safer and more sustainable.

A potential promising way of adding to the current toolkit is the extrusion of glass. This technique which is experimental for architecture could offer great visual variation to the toolkit while also benefitting of the properties of the borosilicate glass which is used in the production method.

Who has an interest in the topic?
Designers of the built environment and engineers working with glass structures in particular. Positive results of this experiment contribute to the architectural potential of an addition to their toolkit in shaping our world; specifically the toolkit of section active extruded glass structural elements.

How much is already known about the problem?
The structural performance of glass elements is determined not only by material properties but also by shape properties and surface quality. This is true because glass inherently has small cracks in its surface. The surface quality determines how big and frequent the cracks are. These cracks are especially important when the element is in tension because the cracks get pulled open. This is how large cracks come to be and they prelude the failing of the element. This means the amount of surface of the element is important too as it also determines the amount of small cracks.

What is missing from current knowledge?
Currently there is one building with extruded glass structural elements. These elements are vector active elements and are not used in tension. If you want to make section active system out of extruded glass element, the tensile strength needs to be known. Specifically tensile strength needs to be known for elements with the dimensions suitable for the built environment.

What new insights will your research contribute?
As the maximum tensile strength, characteristic strength, consistency and variation of it with the sample's dimensions become clear the material can be designed with structurally in tension. This is needed to evaluate the potential of the element for architectural implementation.

Why is this research worth doing?
To keep up with expectations and future building requirements, the toolkit of structural glass elements needs to be updated continuously. Positive results of this experiment contribute to the potential of adding a new production technique for making new elements for this toolkit. This new production technique would bring visual variety and also contribute to better performance properties like (fire) safety.

This research creates a basis for further research as the potential of extruded glass section active systems gets uncovered.

Problem statement
To be able to evaluate the architectural potential for section active extruded glass elements, the tensile strength needs to be known. As the tensile strength is not only influenced by material properties, but also by shape properties and surface quality, samples need to be tested with dimension that could potentially be useful for architectural systems.

Research questions
Main research question:
What is the maximum tensile stress to which the glass samples can be subjected to without a defect?

Sub research questions:
- What is the maximum tensile stress to which the glass samples can be subjected to without failing?
- How does observed sample quality relate to test performance?
- How does the sample's dimensions relate to test performance?
- How do the performances of the hardened samples relate to the non-hardened samples?
- How consistent are the test results?
- Are the forces induced equally?
- How does the glass fail and why?

Research design and methods

The type of this research is quantitative research through material testing. To [illegible] the research questions, the following methods are suitable. The best method [illegible] on availability of samples and test equipment. This is why advantages and disadvantages of all methods are discussed.

Split cylinder test
The split cylinder test is a test oftentimes used for concrete cylinders, but it works for tube-like profiles too. A profile lies on a side and gets squeezed by squashing it from the top in a standard testing machine like a Toni-bank. Tension gets induced by creating a moment. The moment and with it the stress is greatest where the arm for the moment is longest and this is likely where the glass will fail. The tension in the glass is calculated after reading strain gauges attached to the sample.

Advantages of this test method are:
- it's simple to prepare because no special test equipment needed
- the right kind of samples can be used without having to alter them

Disadvantages of this test method are:
- not only tension will be induced, there will also be some shear

Probably this is the preferred test method because of balance between accuracy and practicalities.

Four point bending test
A four point bending test is a standard test in the field of researching material properties. The profile is simply supported on two points and gets pressed down in-between by two point loads. The advantage of two points instead of one is that the moment is stable where the translation is the largest. This is where the glass is expected to fail. As the tensile strength is almost certainly much lower than the compressive strength, the stress calculated to be in the material upon failure is the max tensile strength.

Advantages of this test method are:
- it's simple to prepare because no special test equipment is needed

Disadvantages of this test method are:
- not only tension will be induced, there will also be some shear
- because the preferred sample is a tube it's [illegible] forces equally [illegible] needed because peak stresses need to be avoided, this method is best for testing rods

Probably this is not the best method because it's hard to load the tubular samples properly and as discussed earlier shape properties and dimensions are important for structural performances of glass which is why the tubular samples cannot be substituted by rods without losing significant accuracy in the results.

Rubber slice test
In this test a slice of rubber is placed inside a sample of small section height. The rubber is pressed down upon and due to its material properties, it translates this vertical load to horizontal expansion and it pushes against the glass with the aim to create omnidirectional pressure. Similar to the split cylinder test, the tension in the glass is calculated after reading strain gauges attached to the sample.

Advantages of this test method are:
- it's more accurate than the split cylinder test and the four point bending test. Because the stress is equal everywhere in the sample, the glass will fail at its weakest point. In the split cylinder test the stress could be highest where the glass is strongest (has least amount of imperfections) and the lowest stress the glass will fail at could possibly not be detected

Disadvantages of this test method are:

113

- the equipment needed for this test is not standard, if the equipment likely needs to be built from scratch which is more expensive and takes more time
- the samples can only be of little section height. This means that most likely the samples need to be altered before they are suitable. Additionally the samples are limited in wall thickness because otherwise the rubber will not generate enough pressure to make the glass fail
- the rubber slice does not really create omnidirectional pressure. It does not distribute equally over the height due to how it will expand

Probably this is not the best method because the equipment is non-standard and it might not be worth the effort of acquiring the equipment and right samples because of the still not entirely equally distributed stress in the material.

Hydraulic pressure test
This test method is similar to the rubber slice test. Except that in this test the pressure is created by a fluid which is being compressed by a hydraulic press.

Advantages of this test method are:
- it's more accurate than the rubber slice test, split cylinder test and the four point bending test because now the stress is really equal everywhere in the sample

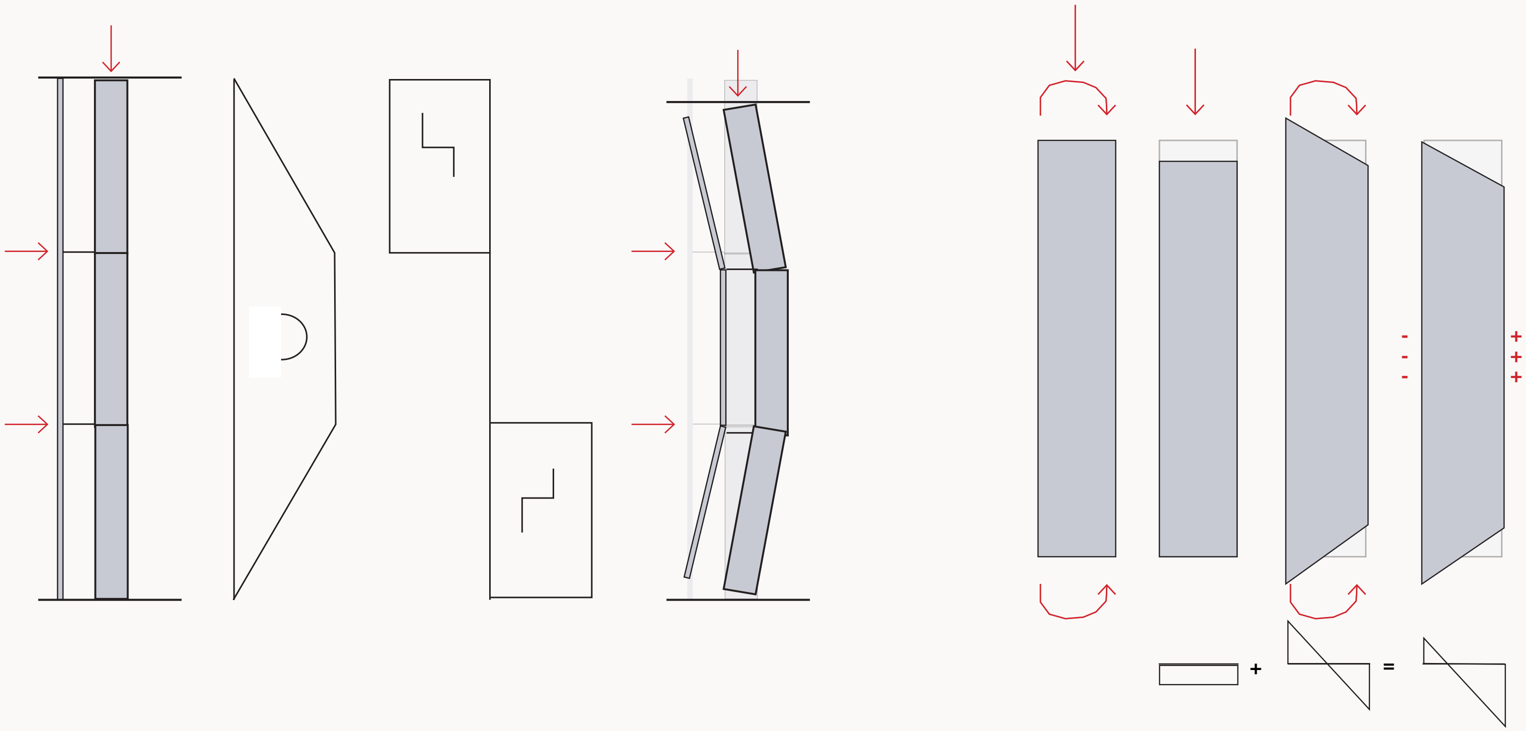
Disadvantages of this test method are:
- the equipment needed for this test is even more special and also harder to build from scratch than the equipment for the rubber slice test
- as is also the case for the rubber slice test the samples can only be of little section height and the samples are limited in the wall thicknesses they can have

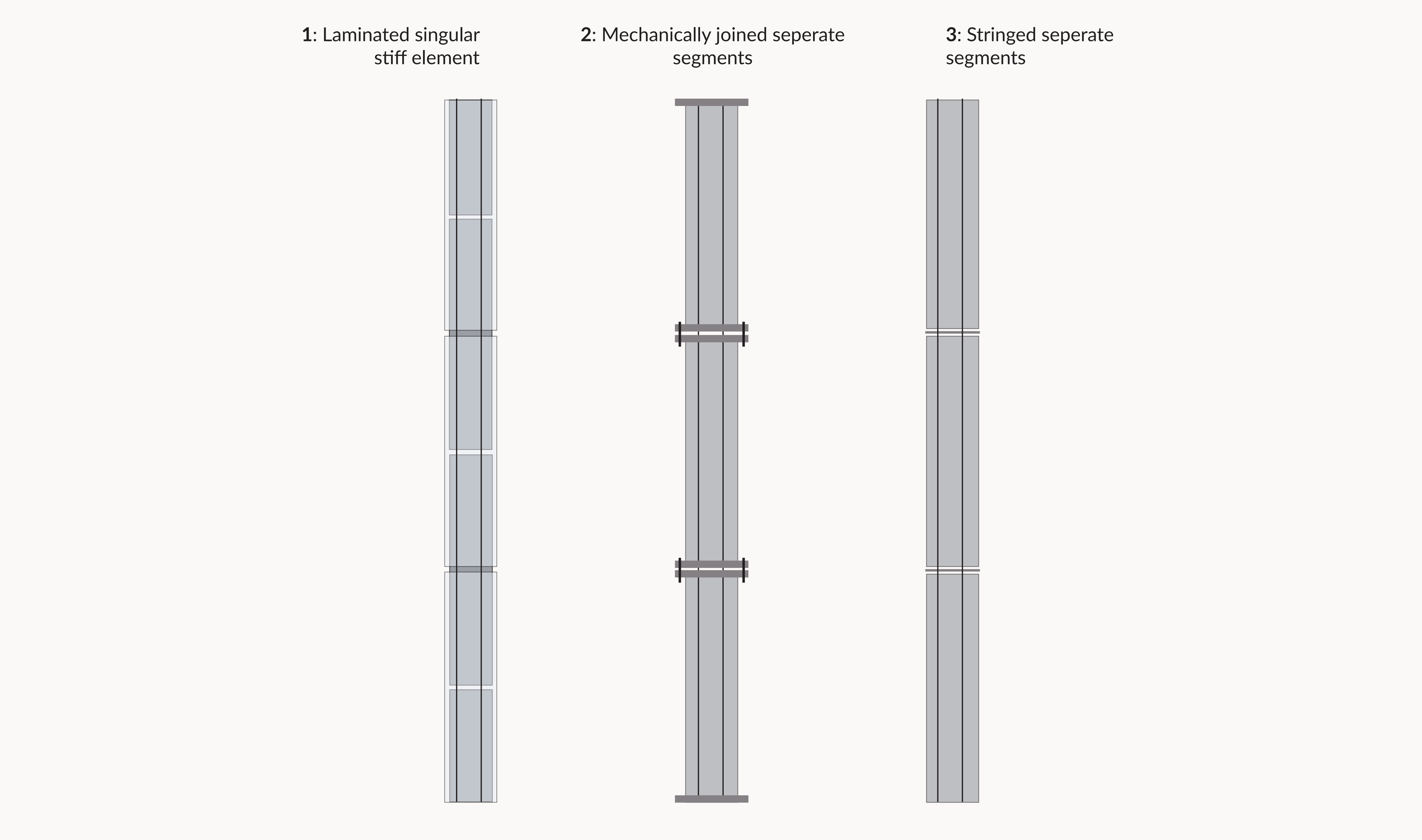
Probably this is not the best method because the equipment is even harder to come by than the equipment for the rubber slice test. If that is not a problem, this test is preferred over the rubber slice test (and the four point bending test) because of its accuracy. However, for this explorative research an answer with that accuracy is not needed. For now it's about feeling out the structural potential of this material. When designing a system, more tests need to be performed to evaluate the exact performances of the elements used.

Introducing of forces
To truly assess the tensile strength of the glass, peak stresses should be avoided. The most common way of doing this is by having a 'soft' material or intermediate layer between the glass and the load introducing surface. A material known to work well and easy to work with is POM, which is a high performance plastic. For the split cylinder test however, a simple MDF wooden plate would probably suffice.

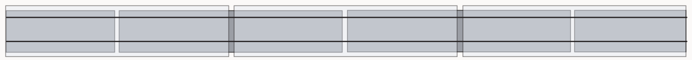
Practicalities
The experiment can be carried out in a manner of hours.
Before not being able anymore to conduct the experiment ourselves we already inspected, photographed, and documented most materials for one samples suitable for this test. With a proper collaboration these materials could possibly still be used.

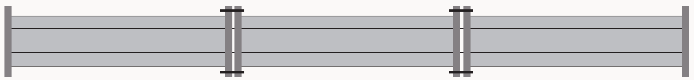
Suggested equipment
- Toni-bank connected to computer with controlling software
- Samples (already acquired and inspected): 17x 5mm WT 70mm OD glass tubes, 6x 9mm WT 70mm OD glass tubes, 10x 5mm WT 120mm OD glass tubes (hardened)
- Material for between machine and glass to induce forces equally: MDF plates
- Camera for pictures/videos
- Protection against glass shrapnel
- At least 2 strain gauges per sample





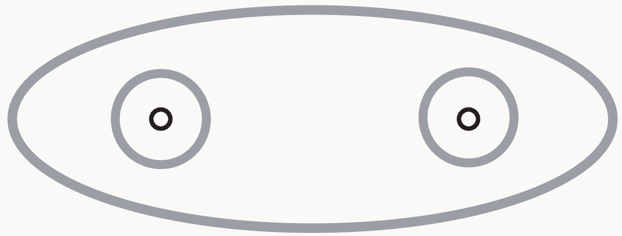
1: Laminated singular stiff element
2: Mechanically joined seperate segments
3: Stringed seperate segments



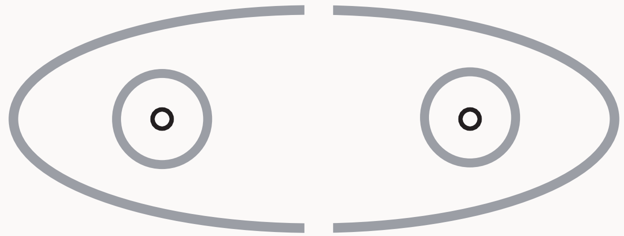


System	Description	Safety: Consequences of vandalism	Structural performance: Stiffness	Aesthetics: Transparency	Building sequence: Disassembly/ re-usability	Costs: Estimated costs	Remarks
Laminated	Has to be prefabricated and transported in one piece. Disassembly not possible because of the adhesive. Could be very transparent and achieved with very minimalistic detailing. Because of layering of the section, it could be well-resistant against vandalism but has to then be replaced as a whole.	++	+++	+++	0	+++	The in-ability to disassemble this system might be too big of a price to pay for maximum transparency. This maximum transparency could be compromised anyway because mountings for the facade panels need to be attached.
Joined	Fabricated in the factory in standard length units. These are tensioned apart from each other. Easy assembly on the site. Dry assembled. More detailing in sight. Individual segments not too resistant against vandalism but parts can be replaced individually and steel cables/rods can keep system in place.	++	++	+	+++	+	This is the system easiest to assemble, repair and recycle. The price to pay for this is less minimalistic detailing. This could be compensated by stating the facade should be attached to the system anyway and lengths of the elements can still differ.
Stringed	Delivered in standard lengths, the elements are tensioned on the site, which makes them a stiff whole. It's not as easy to install and repair as the bolted and not as minimalistic as the laminated, but has a bit of both qualities. Individual segments not too resistant against vandalism and system could be then very unstable, causing failure of other segments too. Cables/rods can keep system in place.	+	+	++	+	++	This system is the in-between. The main difference between this and the bolted system is that here the entire system is post-tensioned, while in the bolt system each element is post-tensioned separately.

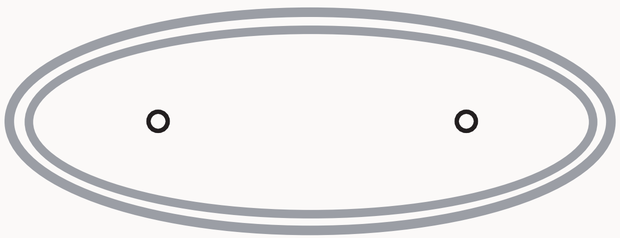
A: glass ellipse, glass tubes, steel rods



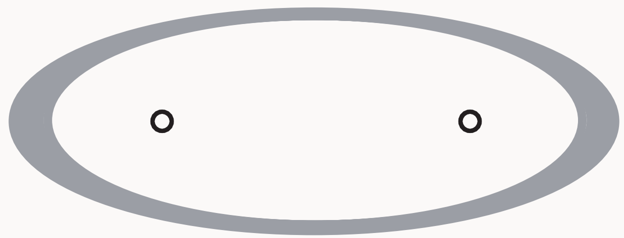
B: split glass ellipse, glass tubes, steel rods

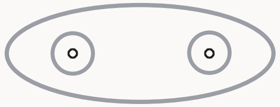


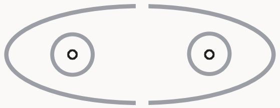
C: laminated glass ellipse, steel rods

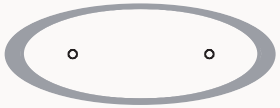


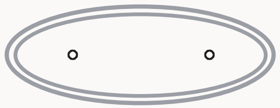
D: glass ellipse varying tickness, steel rods



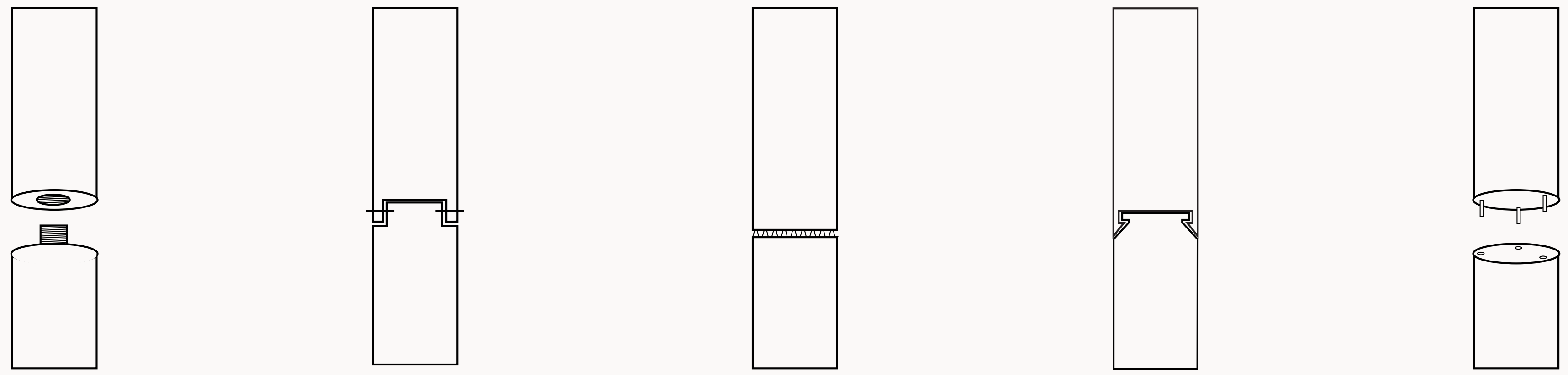




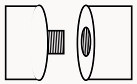
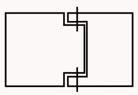
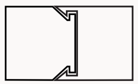
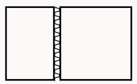
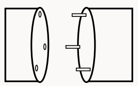


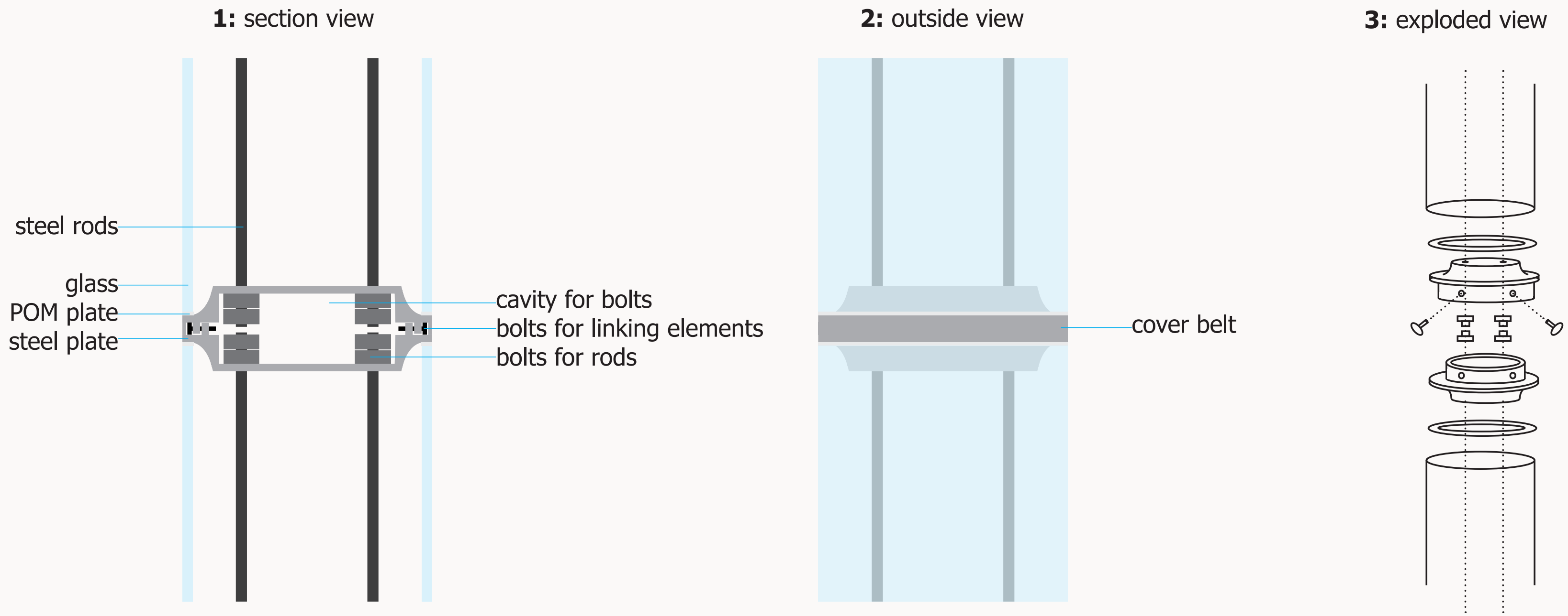


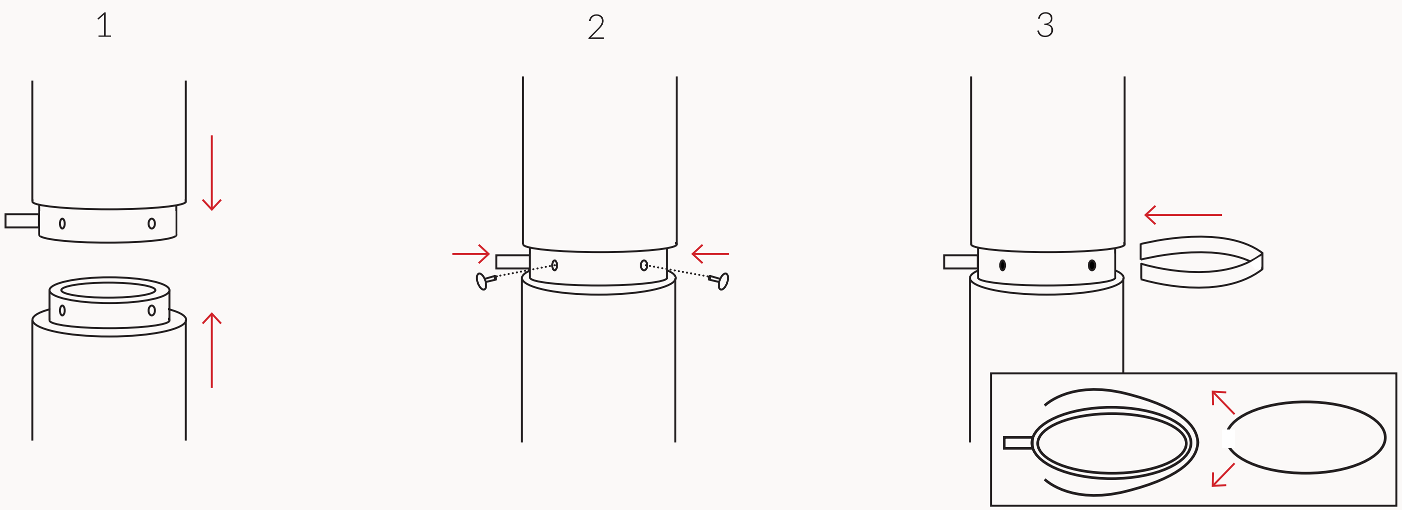
System	Description	Safety Capacity when broken	Structural performance Material efficiency	Aesthetics Transparency	Building sequence Easy to produce	Costs Estimated costs	Remarks
Ellipse + tubes	With the tubes placed all the way to the side, this section has most of the material at the right places for less of the cost than the varying thickness ellipse.	+	++	++	+++	+	This section could be the easiest to produce of all cross sections. It's an in between option with a balance of qualities.
Split section	This section is based upon a split ellipse that can convey shear despite the split but can be compressed separately. When dry assembled, no tension can occur in the glass, leaving the tension for the steel rod. Which would mean this section could have the greatest material efficiency.	++	+++	++	+	++	This section only works when detailed correctly and can be considered most experimental of all. When working, it could have the greatest material efficiency.
Varying thickness section	With a greater second moment than a regular ellipse, this section has a greater material efficiency. When just consisting out of one element, this option is very transparent, but preserves no structural integrity when attacked.	0	+++	+++	++	++	This section improves upon the laminated ellipse in regards of material efficiency and evens it in transparency. However, when consisting of just one element, this means that when vandalized, no structural integrity remains.
Laminated section	Ellipse conveys shear forces and is also coupling the moment. Multiple ellipses (probably two) laminated together for more stiffness and bigger surface area. When attacked, the inner ellipse could remain intact and so preserve some structural integrity.	++	++	+++	0	+	This section fits best with the laminated system and shares its benefits and problems. It's an all-in move. It likely requires special transport and careful installation. Making it is extraordinary difficult due to tolerances.

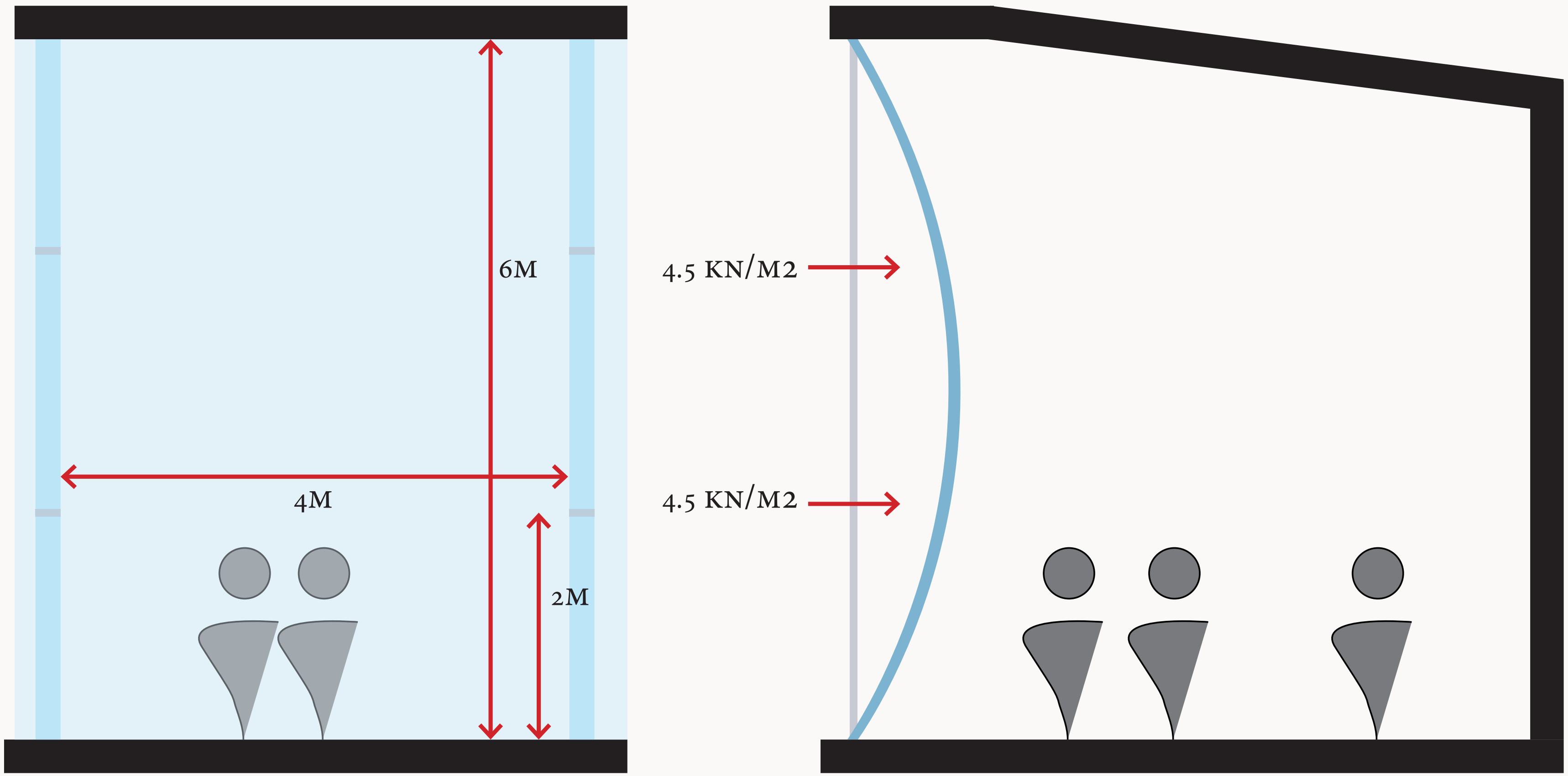


A: Screwed **B**: Bolted **C**: Glued/Welded **D**: Click-system **E**: Interlocking

	System	Description	Safety	Structural performance Stiffness	Aesthetics Minimalistic	Building sequence Quick/easy to assemble	Costs Estimated costs	Sustainability De-mountable	Remarks
	Screwed	Two elements screwed together.		+	++	+++	+	+++	This variant is strong regarding building sequence and aesthetics but not as stiff as some other variants.
	Bolted	Two elements bolted together.		++	++	++	++	+++	This variant scores good overall. It has no weak points if the connection can be hidden and it stands out on sustainability.
	Click-system	Two elements clicked together.		+	+++	+++	++	++	This variant installs very quickly but has to pay for it in structural performance.
	Welded/ glued	Two elements stuck to each other.		+++	+++	+	++	+	This variant is very strong structurally but lacks in building sequence and sustainability.
	Interlocking	Two elements geometrically interlocking.		+	+	+++	++	+++	This variant lacks structural performance and due to needed height is not as minimalistic.


1: section view
steel rods
glass
POM plate
steel plate
cavity for bolts
bolts for linking elements
bolts for rods
2: outside view
cover belt
3: exploded view


1
2
3
4



6M
4M
2M
4.5 KN/M2
4.5 KN/M2

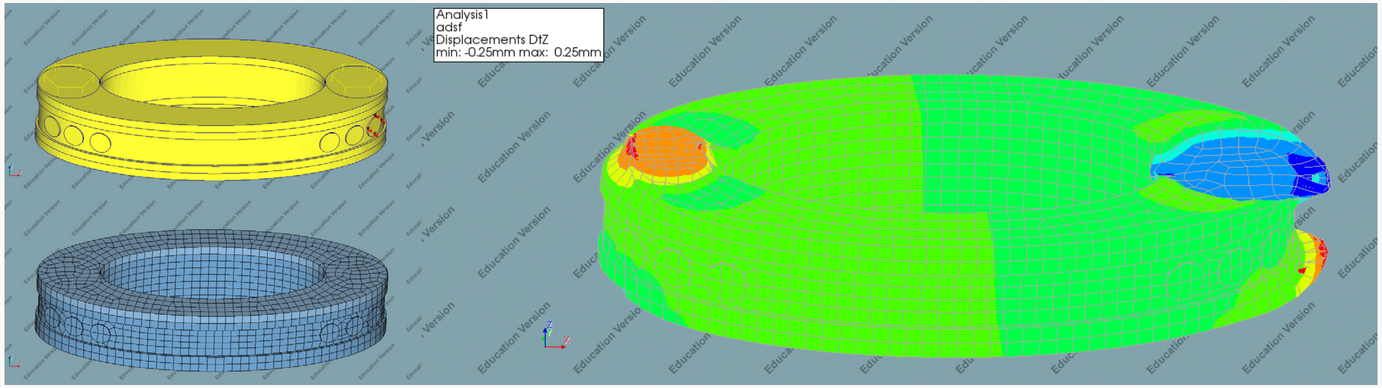
ULS

Part	Parameter	Calculated/ estimated dimension		Calculated stress [N/mm2]	Simulated dimension		Simulated (max) stress [N/mm2]		Allowable stress [N/mm2]	remarks
Glass										
	Isection		mm4			mm4		<	**33**	
Rods										
	Radius steel rods		mm					<	**550**	
Connection										
	Cap thickness		mm			mm	-----		-----	
	Side wall thickness	-----	mm	-----		mm	-----		-----	
	total				-----			<	**355**	

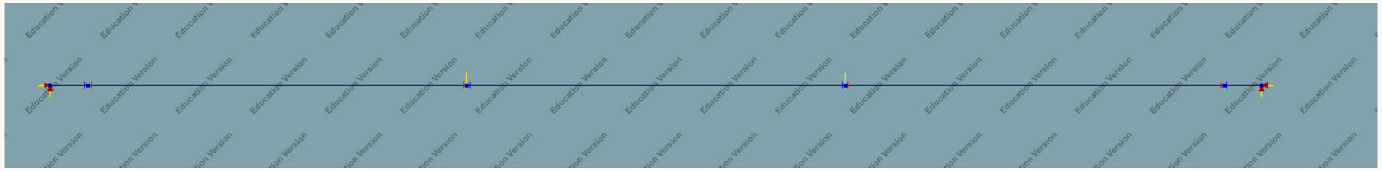
SLS

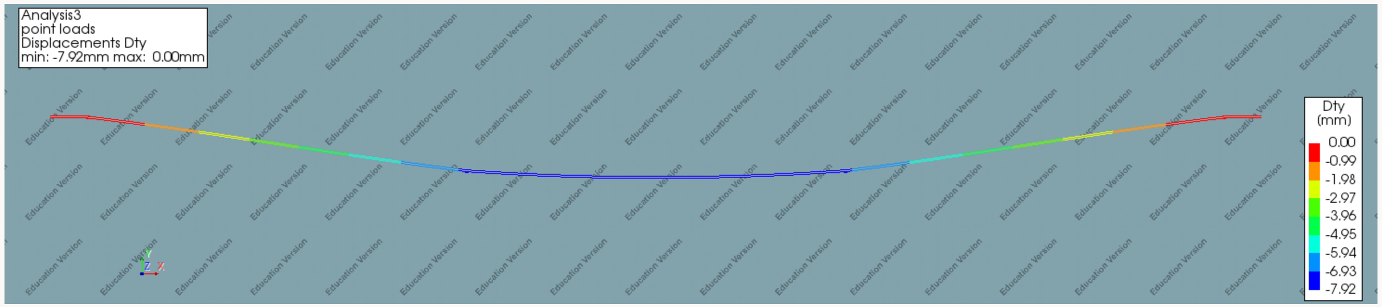
Part	Parameter	Calculated/ estimated dimension		Calculated deformation [mm]	Simulated dimension		Total deformation [mm]		Allowed deformation [mm]	remarks
Connection										
	Rotational stiffness connection	-----	Nm/radian	-----		Nm/radian	-----		-----	
Total system										
	Translation global model	-----			-----			<	**20**	
	Translation vandalized system	-----							-----	

Model name:	Connection for rotation
Default Mesher type:	Hexa/Quad
Default Mesher order:	Quadratic Linear Interpolation
Geometry:	Imported, structural solids
Material(s):	POM, Connection steel
Load(s):	Area loads
Supports:	T1 T2 T3

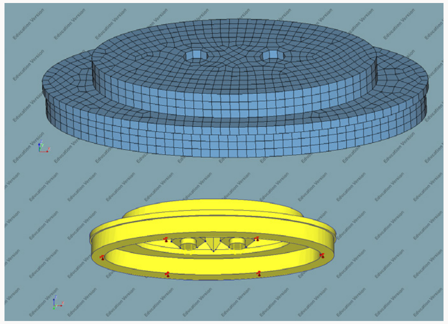


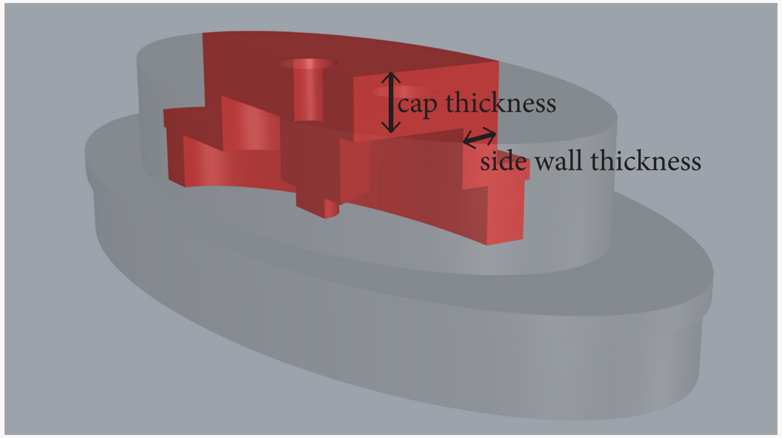
Model name:	Global model for displacement
Default Mesher type:	Hexa/Quad
Default Mesher order:	Quadratic Linear Interpolation
Geometry:	2D lines and vertexes
Material(s):	Glass, Rotational spring
Load(s):	Point loads
Supports:	T1 T2 T3 R1 R2 R3

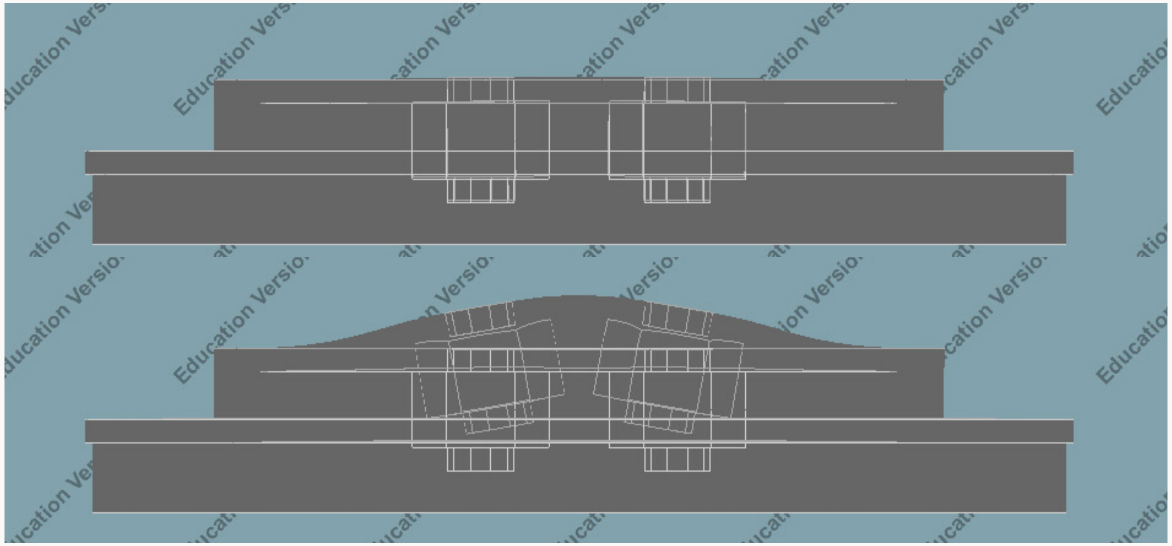


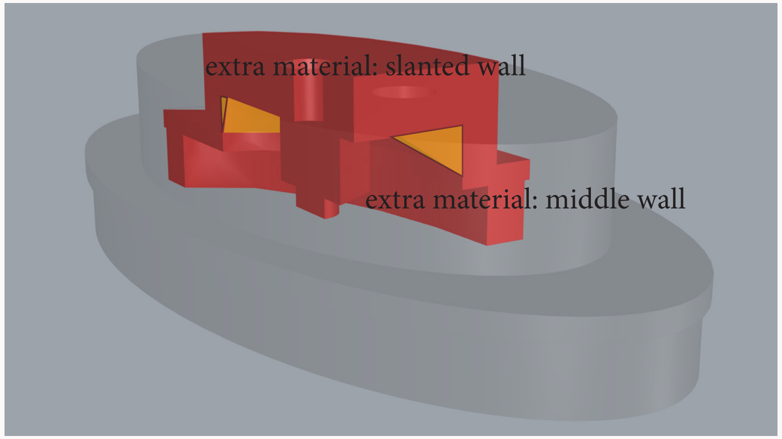


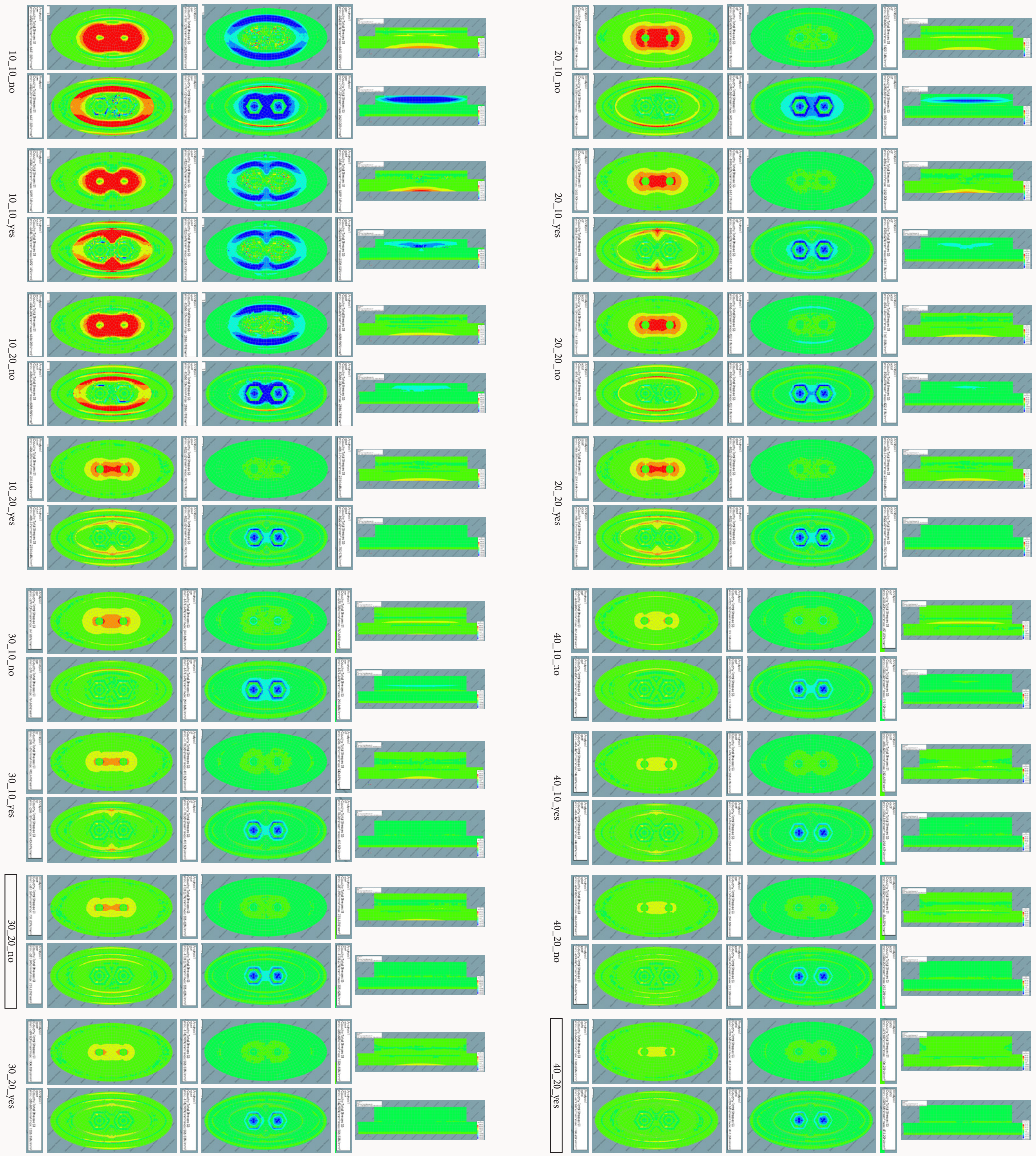
Model name: Cap with loads by rods
[cap thickness]_[side wall thickness_[extra material]
Default Mesher type: Hexa/Quad
Default Mesher order: Quadratic Linear Interpolation
Geometrystructural: Imported, structural solids
Material(s): Steel Connection
Load(s): Area loads
Supports: T1 T2 T3

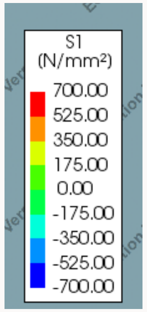


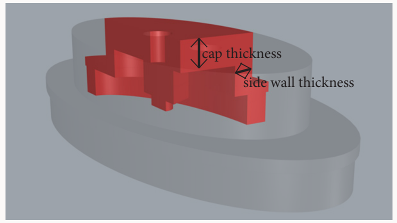


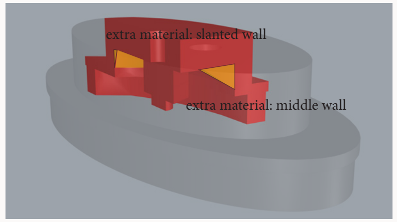




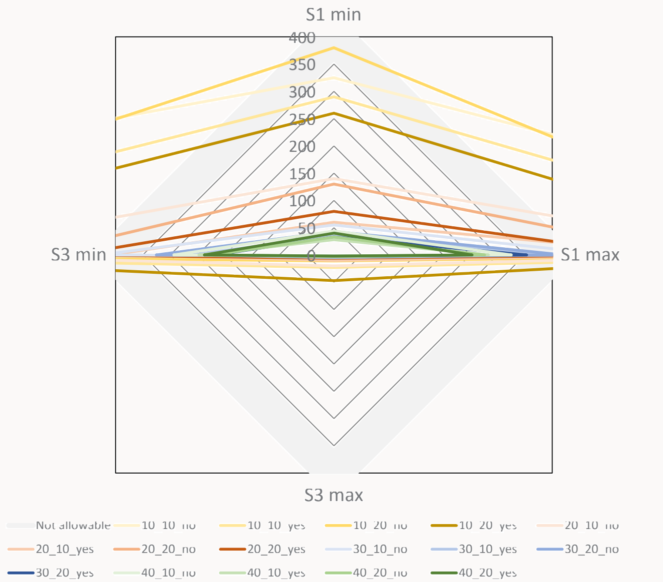








Maximum stress found in models for testing stress caused by rods on connection in N/mm2



Part	Parameter	Calculated/ estimated dimension		Calculated stress [N/mm2]	Simulated dimension		Simulated (max) stress [N/mm2]		Allowable stress [N/mm2]	remarks
ULS										
Glass										
	Isection	4,93E+08	mm4	31	3,16E+08	mm4	**31**	<	**33**	accurate calculations as expected
Rods										
	Radius steel rods	15	mm	**506**	-----		-----	<	**550**	may consider choosing steel with higher allowable stress
Connection										
	Cap thickness	7,45	mm	350	30	mm	-----		-----	with extra slanted walls + material in middle
	Side wall thickness	-----	mm	-----	20	mm	-----		-----	
	total				-		**353**	<	**355**	
SLS										
Part	**Parameter**	Calculated/ estimated dimension		Calculated deformation [mm]	Simulated dimension		Total deformation [mm]		Allowed deformation [mm]	remarks
Connection										
	Rotational stiffness connection	-----	Nm/radian	-----	3,01E+07	Nm/radian	-		-	
Total system										
	Translation global model	-----		2,09	-----		**7,9**	<	**20**	calculated is without connections - allowed is 1/300th of length
	Translation vandalized system	-----					308		-----	

RESEARCH PROPOSAL

APPENDIX C: RESEARCH PROPOSAL

STRUCTURAL PERFORMANCE PRELIMINARY DESIGN SECTION ACTIVE EXTRUDED GLASS SYSTEM

This research proposal is part of a series of research proposals that collectively and with synergy contribute especially to evaluating the potential of section active extruded glass structural systems for architectural design.

Introduction

The architectural language of glass buildings is relatively new and especially the toolkit of structural glass elements has only begun to really develop lately. Glass buildings are mostly one of a kind public buildings and as glass has throughout its history always had an air of luxury and the smell of engineering miracles, nowadays they shine as the jewels of the built environment. They captivate people and offer a truly special experience.

Meanwhile firstly the demand [illegible] is rising which means that the [illegible] needs to be kept developing to avoid too [illegible] repetition and take away some of the wo[illegible] the building requirements are getting stricter as we need to prevent being wasteful of material and energy which means that new additions to the toolkit should be safer and more sustainable.

A potential promising way of adding to the current toolkit is the extrusion of glass. This technique which is experimental for architecture could offer great visual variation to the toolkit while also benefitting of the properties of the borosilicate glass which is used in the production method.

Who has an interest in the topic?
Designers of the built environment and engineers working with glass structures in particular. Positive results of this experiment contribute to the architectural potential of an addition to their toolkit in shaping out world; specifically section active extruded glass structural elements.

How much is already known about the problem?
Section active structural glass systems are widely implemented in the architectural language of glass buildings. They are mostly structural glass fins. This well-known system has different accents structural challenges than a section active extruded glass system would have. Because of the ability of making tubular shapes it does not have to account for lateral buckling for example. Because of the freedom in designing the geometry of the glass sections it holds a lot of structural potential.

What is missing from current knowledge?
There currently are no section active extruded glass structurally elements implemented in architecture. The material properties have already been researched, but to get a proper understanding of the structural performance of such elements a designed system needs to be tested for the first time. It's important to also get an understanding of how the designed element fails. Does it fail in a safe way? Can it be foreseen? Can shrapnel hurt bystanders? And also, how can the designed system be altered to enhance its performance regarding structural performance and safety?

What new insights will your research contribute?
[illegible] research will offer [illegible] better [illegible] of [illegible] section active [illegible] systems in practice [illegible] it aims to push [illegible] to its structural limits and seeing what maximum load it can withstand. This could be one of the last steps in proving the potential of such systems for architectural implementation.

Why is this research worth doing?
To keep up with expectations and future building requirements, the toolkit of structural glass elements needs to be updated continuously. Positive results of this experiment contribute to the potential of adding a new production technique for making elements for this toolkit. This new production technique would bring visual variety and also contribute to better performance properties like (fire) safety.

This research creates a basis for further research as the potential of extruded glass section active systems gets uncovered.

Problem statement
To be able to evaluate the architectural potential for section active extruded glass elements, a draft designed system needs to be tested to get a better understanding of behaviour and structural capabilities. From the failing of the system, unexpected factors may be unveiled which can then be taken into account for further designs.

Research questions
Main research question:
- What is the maximum load the designed system can withstand without a defect?

Sub research questions:
- What is the maximum load the designed system can withstand?
- How does the designed system fail?
- Are there timely warning signs before failure?
- How consistent are the test results?
- Are the forces induced equally?

Research design and methods

The type of this research is quantitative research through material testing. To answer the research questions, one obvious method seems most suitable. This is why no other methods are discussed [illegible]

[illegible] point bending t[illegible]
[illegible] draft design would be to connect three segments of the designed system and perform a four point bending test on a universal test machine. The loads could then be conveyed on the connections at they would in reality.

Introducing of forces
To truly assess the structural performance of the designed element, peak stresses should be avoided. This is why the system should only be loaded on the connections only as the system is designed for.

Practicalities

The experiment can be carried out in a manner of days, production of the samples can take longer.

Suggested needed equipment
- Four point bending set-up
- Samples: If possible, two or even three copies of the designed system three segments each
- Camera for pictures/videos
- Protection against glass shrapnel

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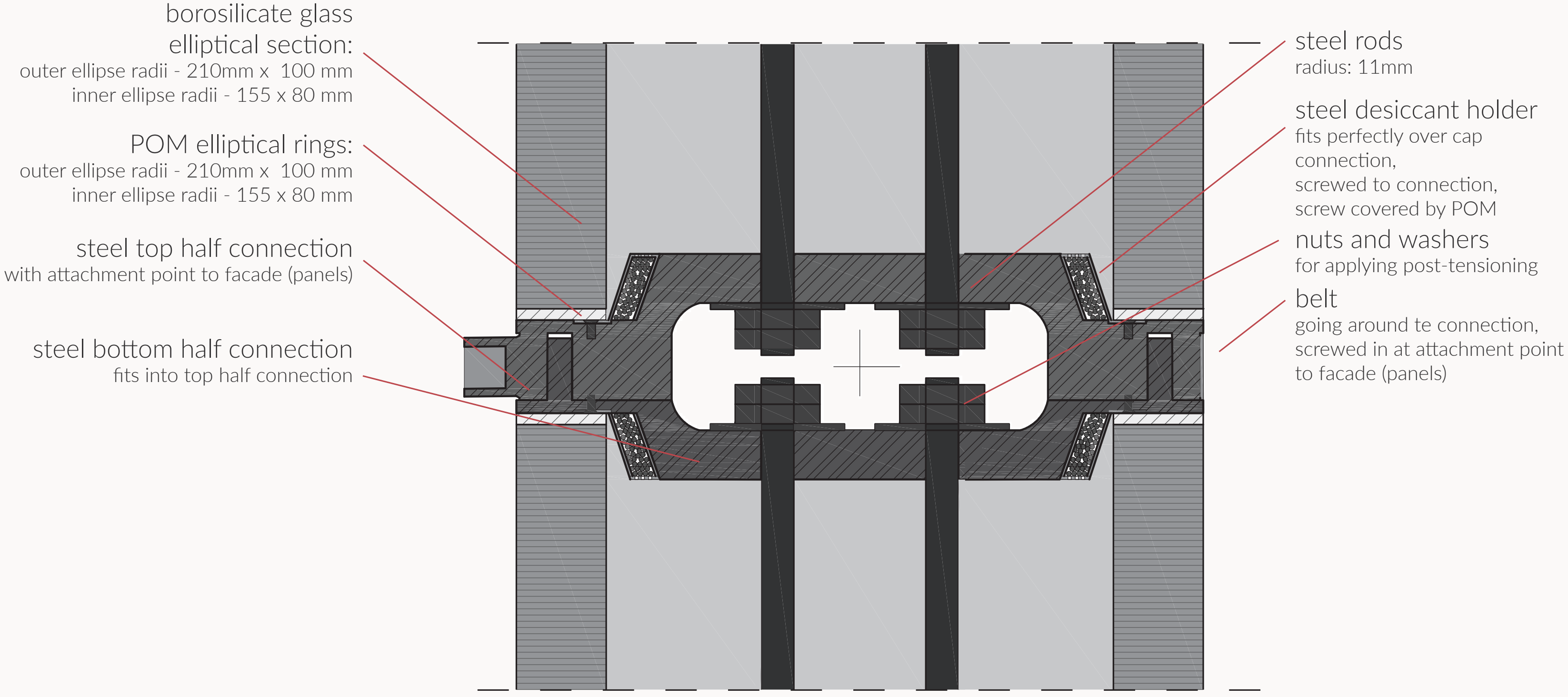
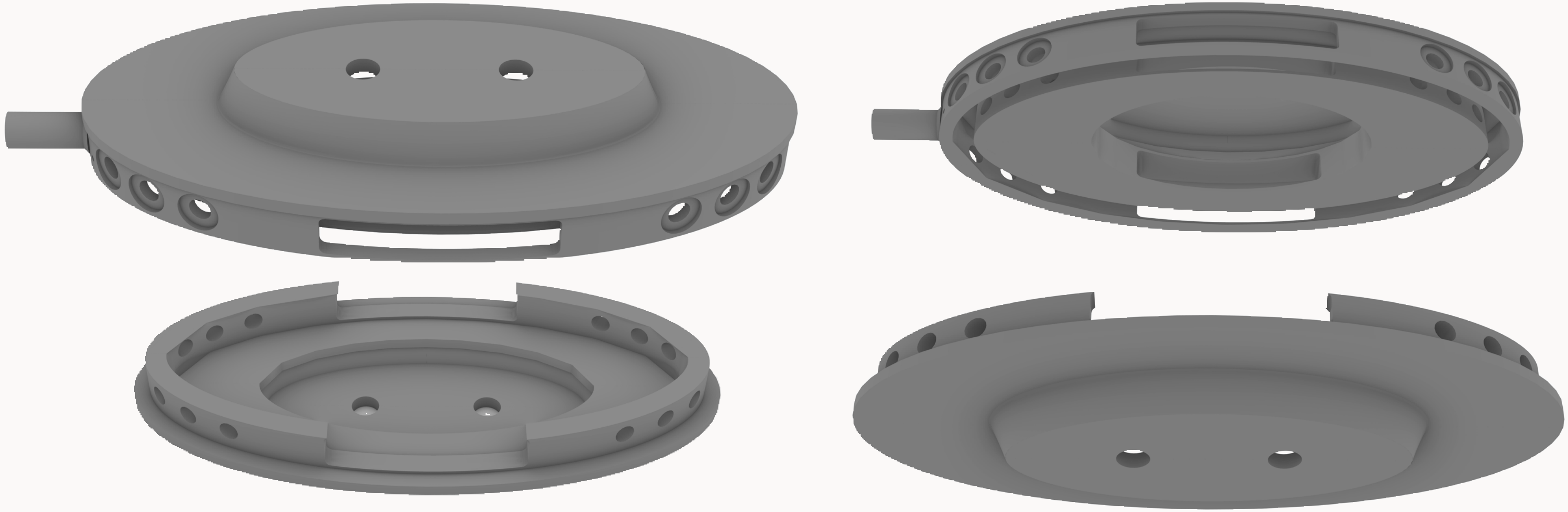
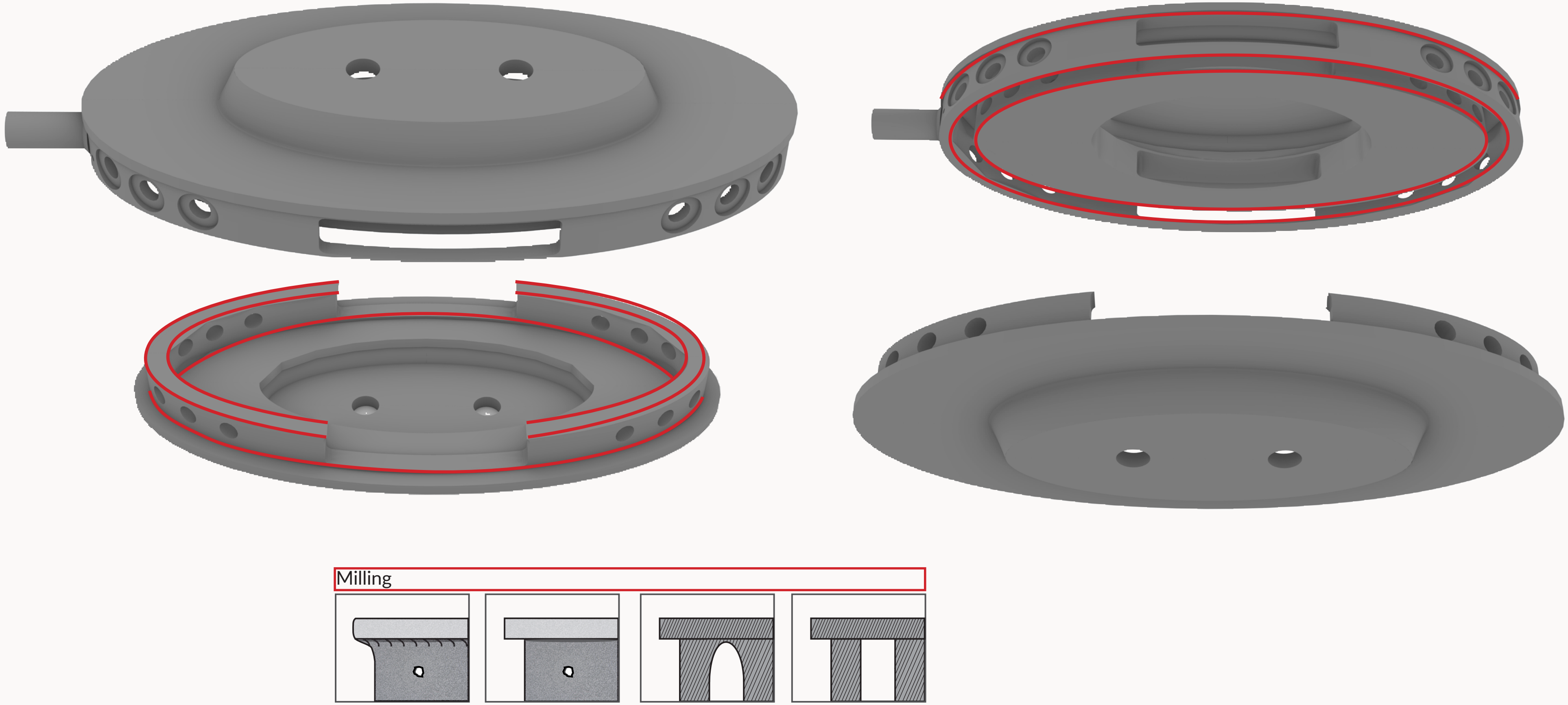
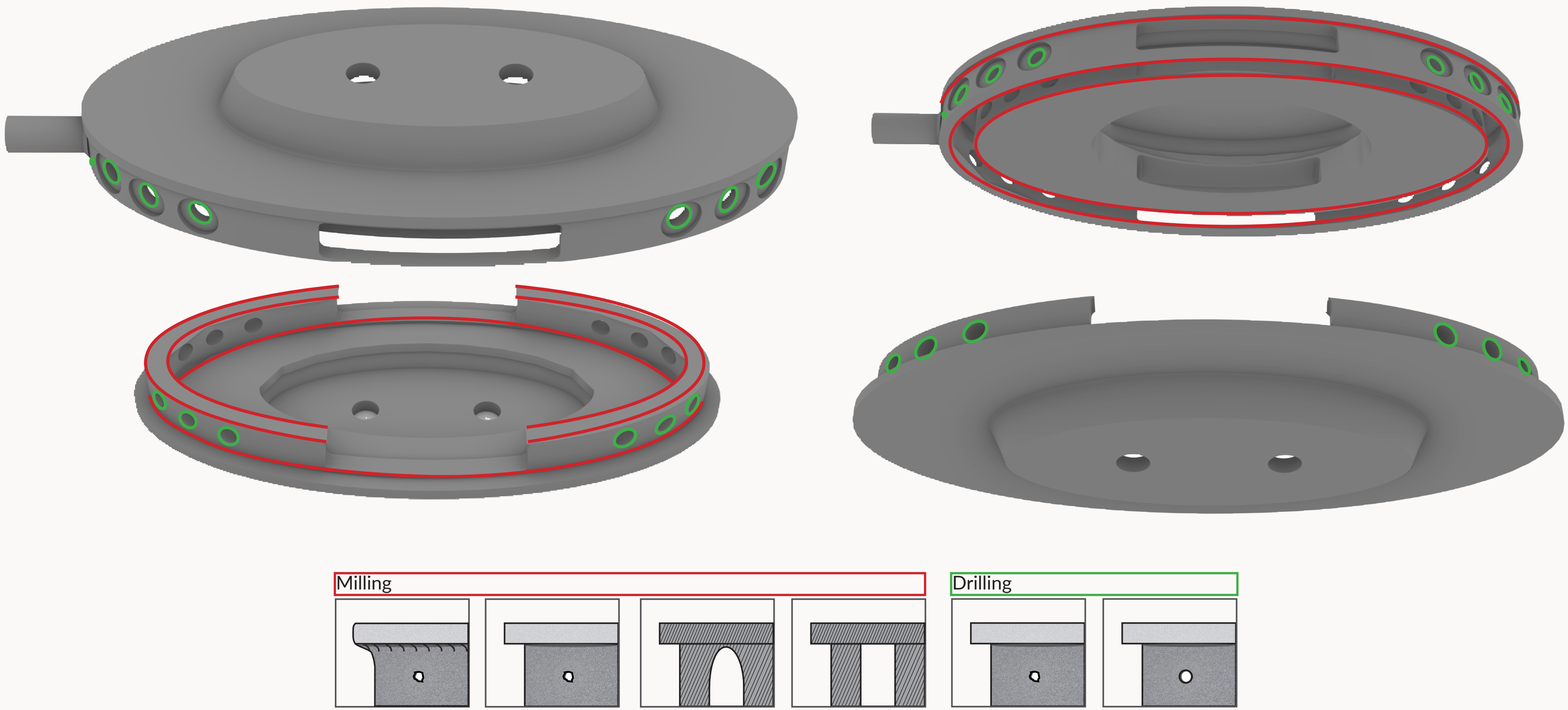


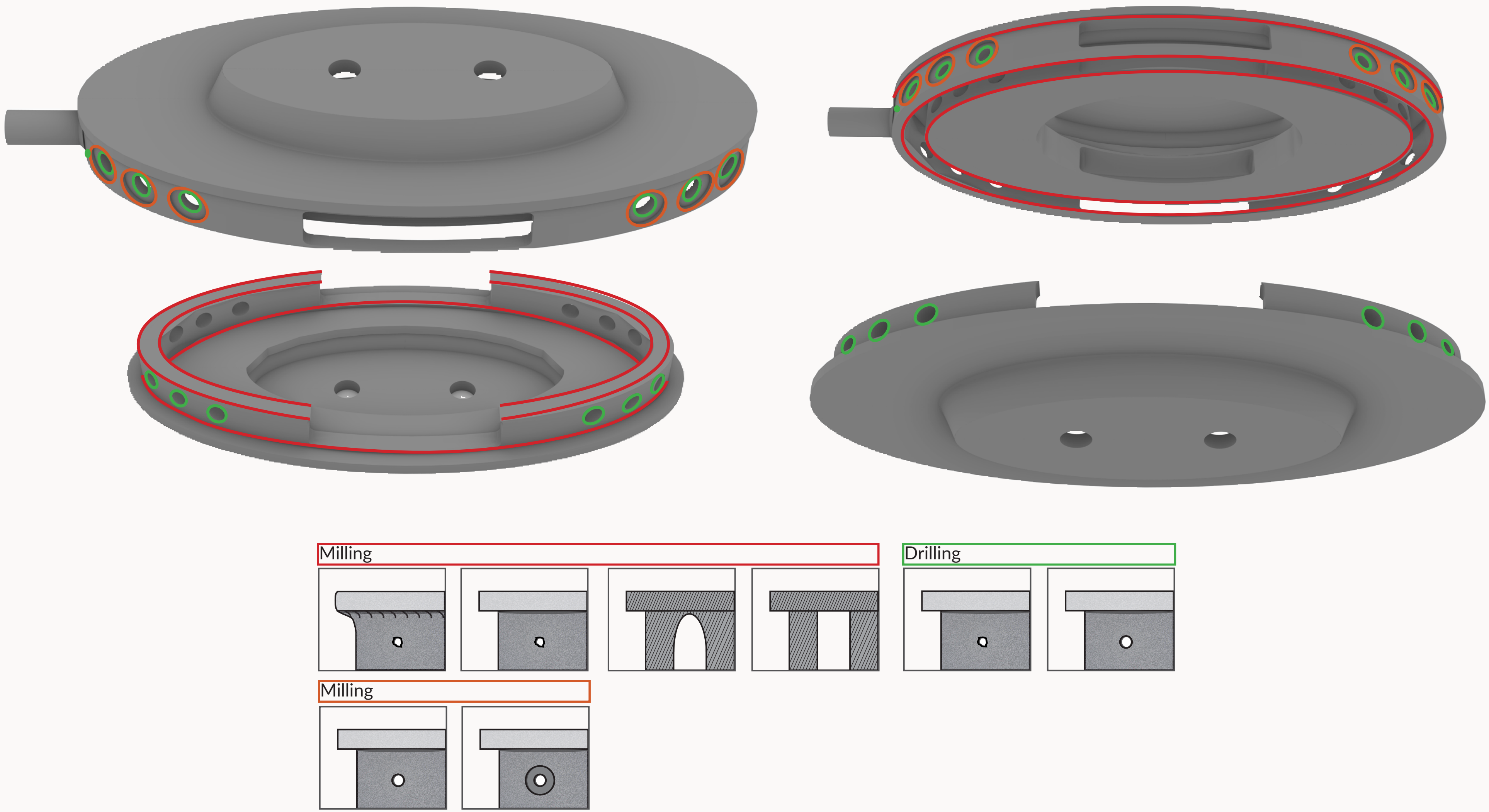
borosilicate glass
elliptical section:
outer ellipse radii - 210mm x 100 mm
inner ellipse radii - 155 x 80 mm
POM elliptical rings:
outer ellipse radii - 210mm x 100 mm
inner ellipse radii - 155 x 80 mm
steel top half connection
with attachment point to facade (panels)
steel bottom half connection
fits into top half connection
steel rods
radius: 11mm
steel desiccant holder
fits perfectly over cap connection,
screwed to connection,
screw covered by POM
nuts and washers
for applying post-tensioning
belt
going around te connection,
screwed in at attachment point
to facade (panels)

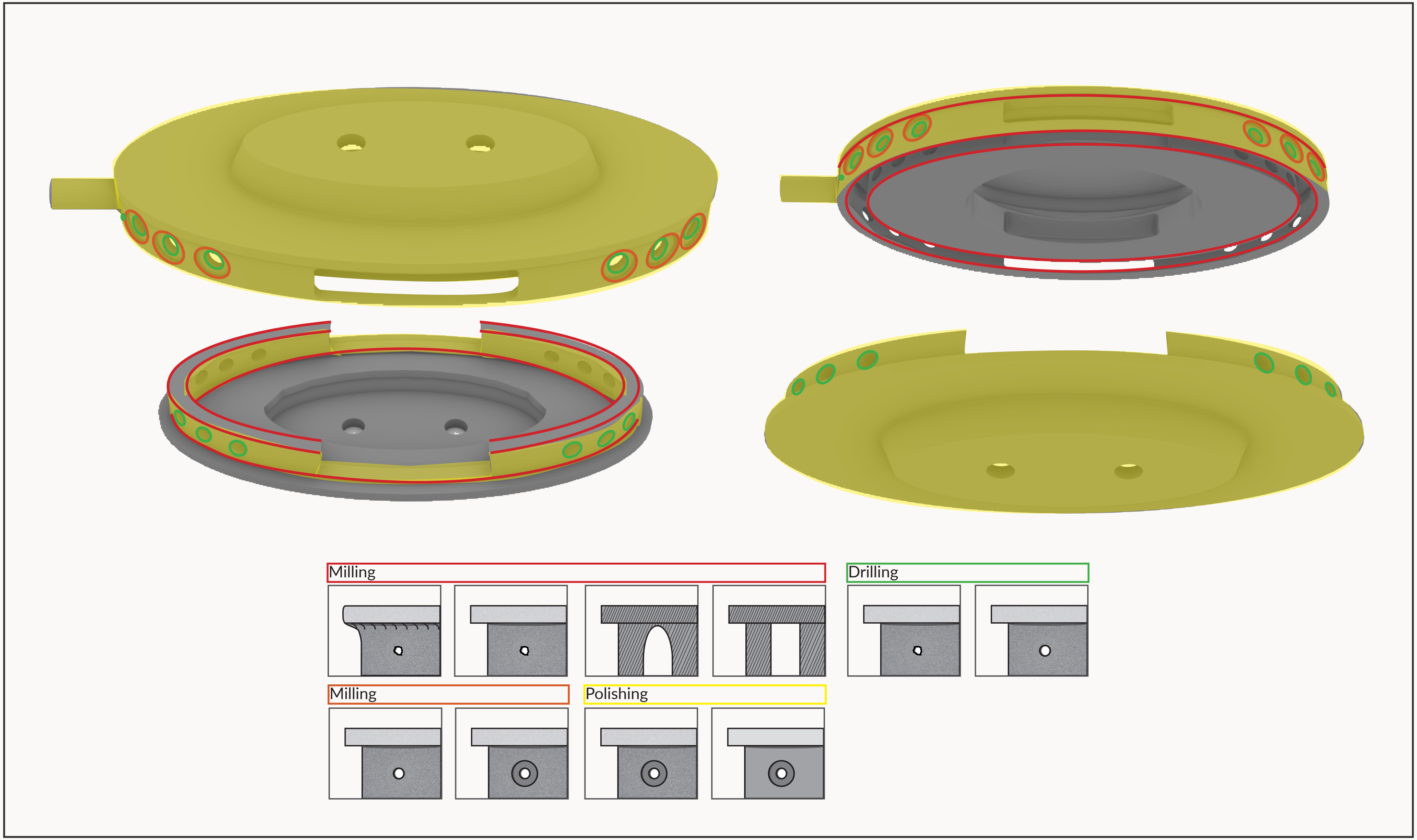
Borrosilicate glass Section
Steel rods
Steel connection (top half)
Steel connection (bottom half)
POM rings
Aluminum belt
Steel desiccant holder

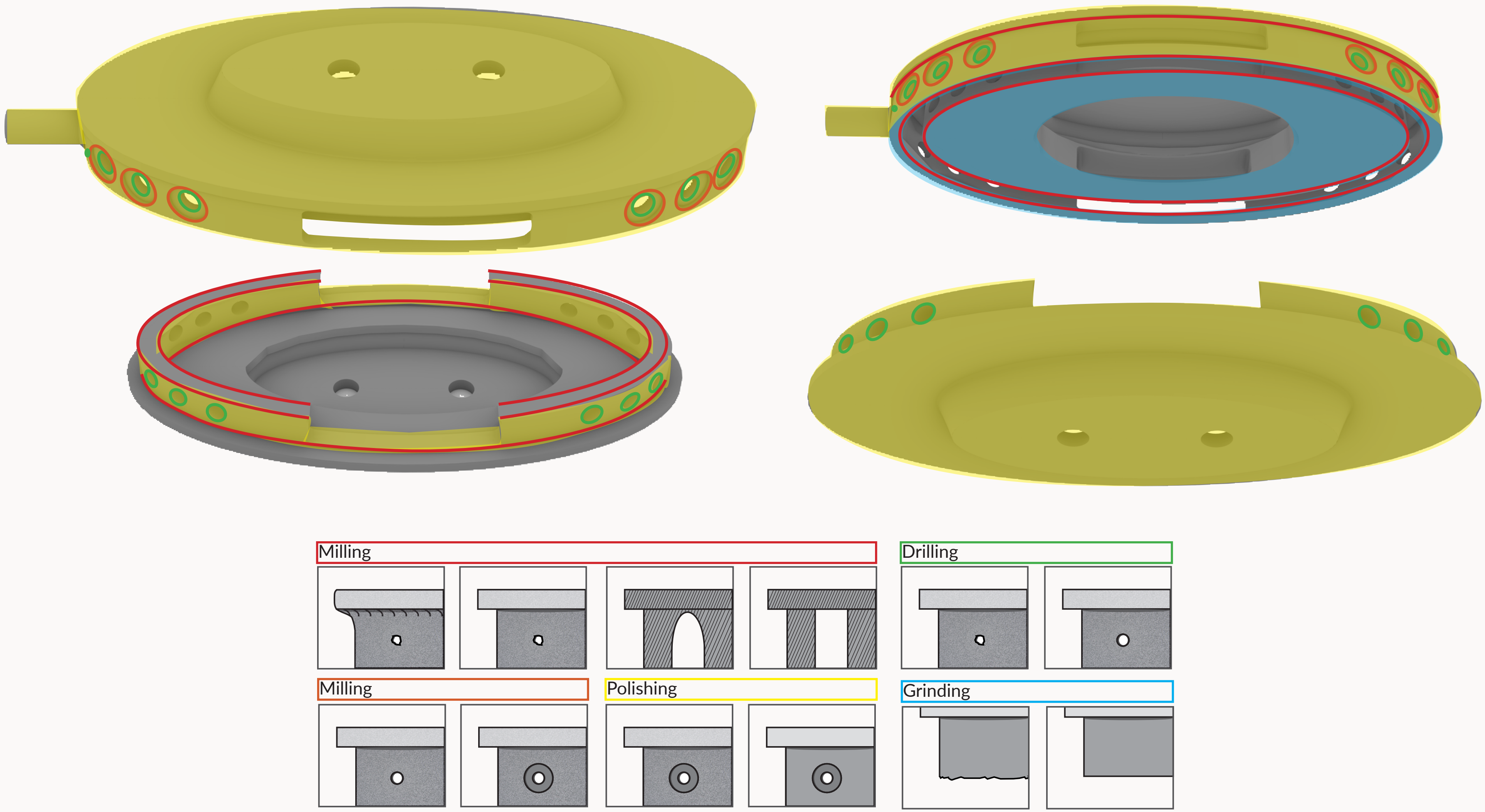


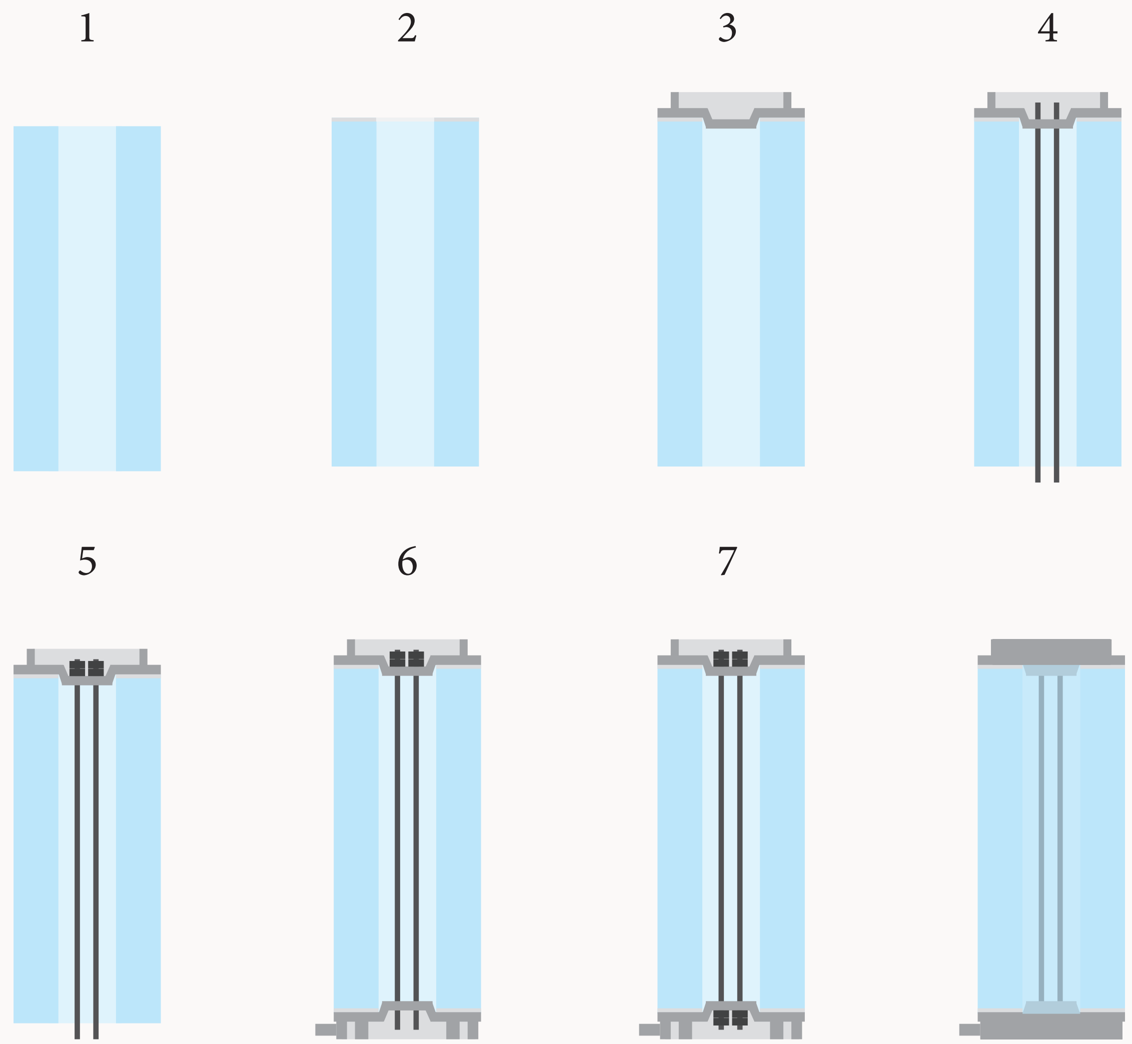

Milling


Milling
Drilling


Milling
Drilling
Milling


Milling
Drilling
Milling
Polishing


Milling
Drilling
Milling
Polishing
Grinding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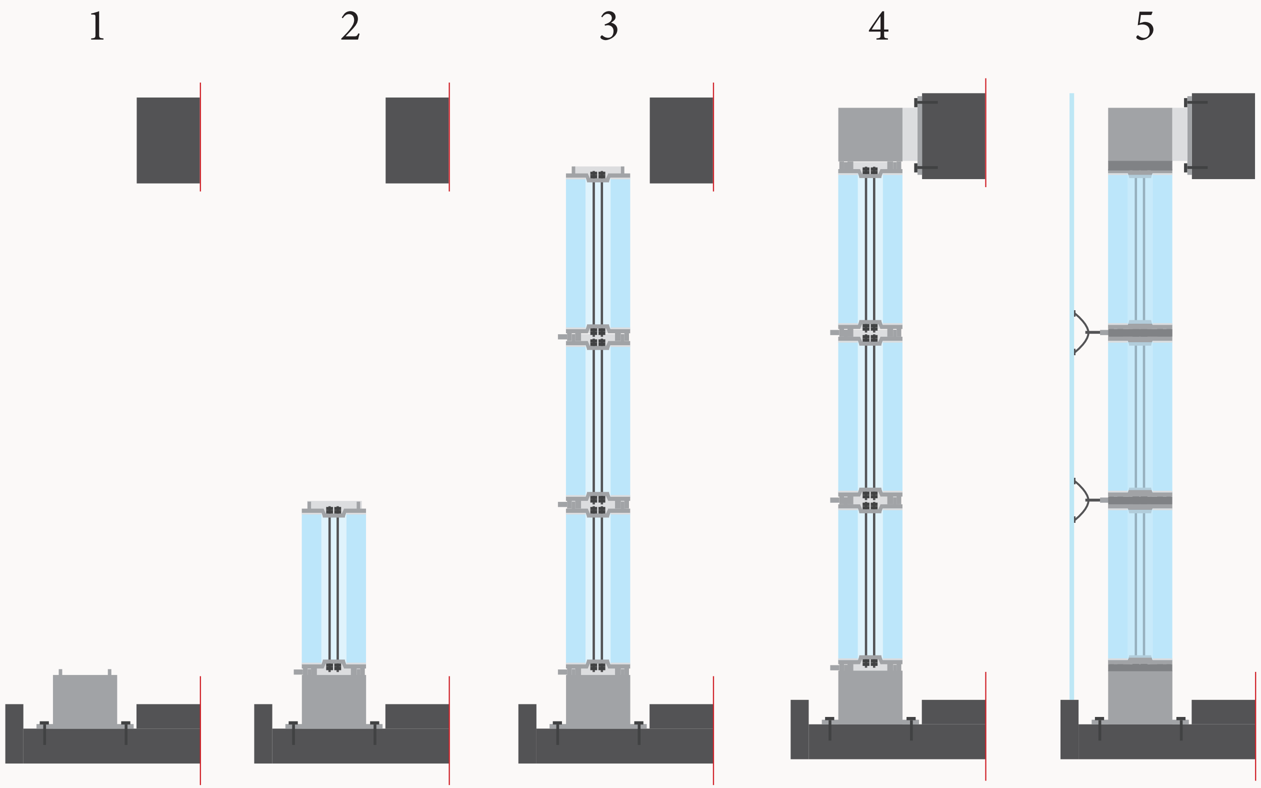
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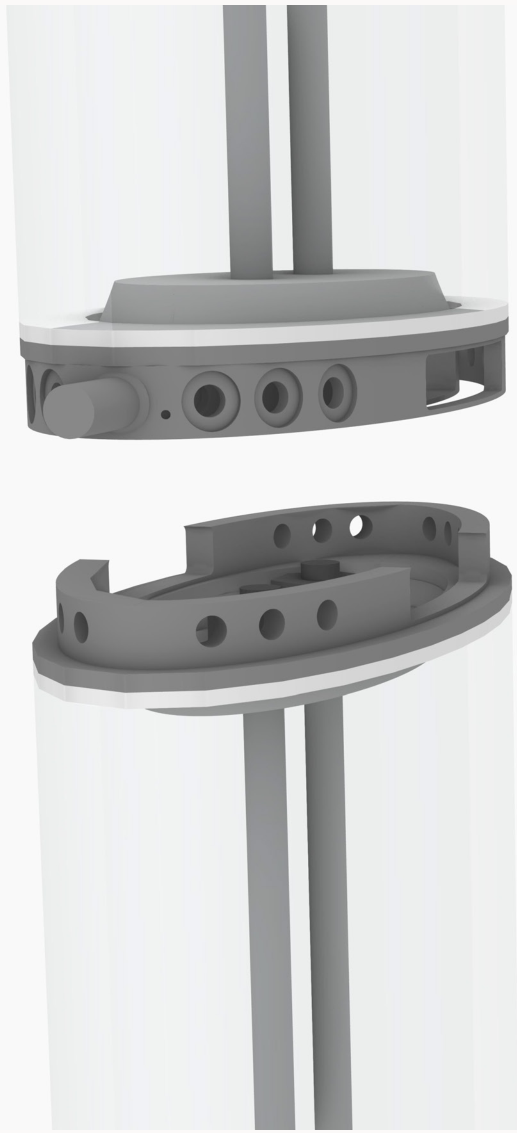

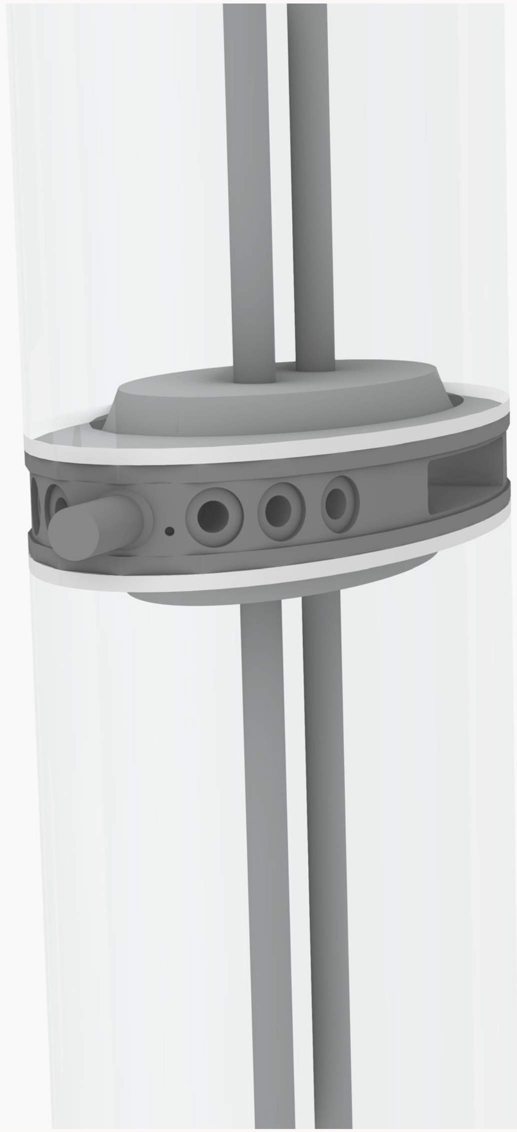

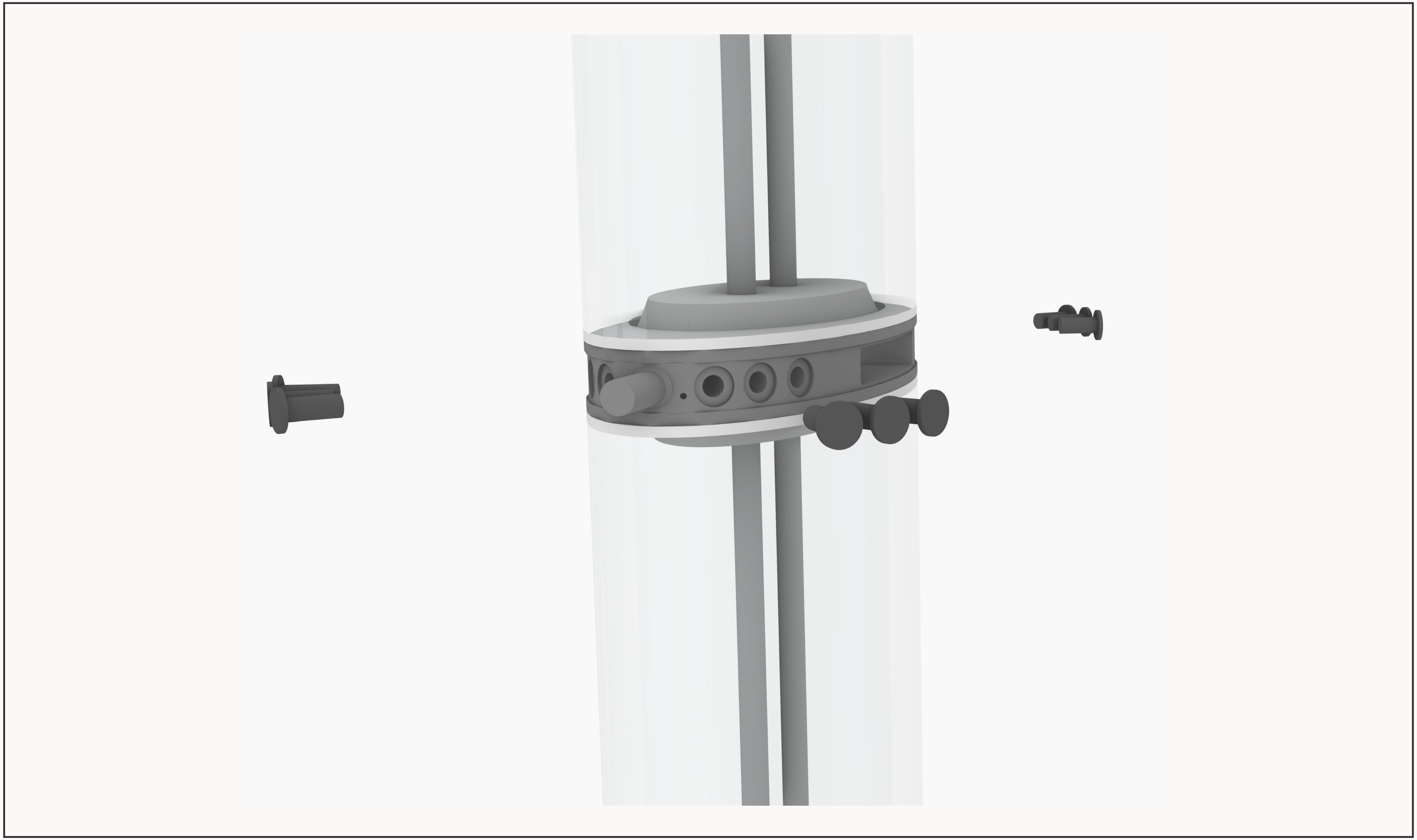

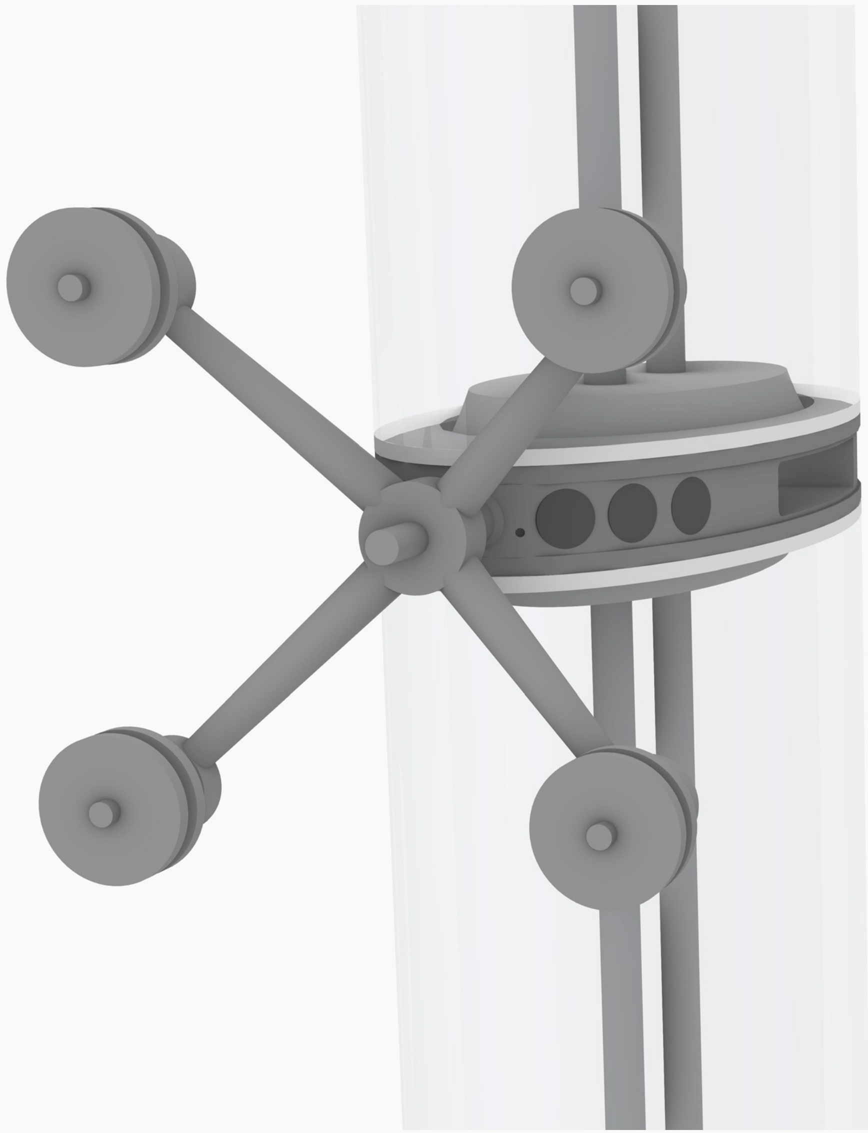

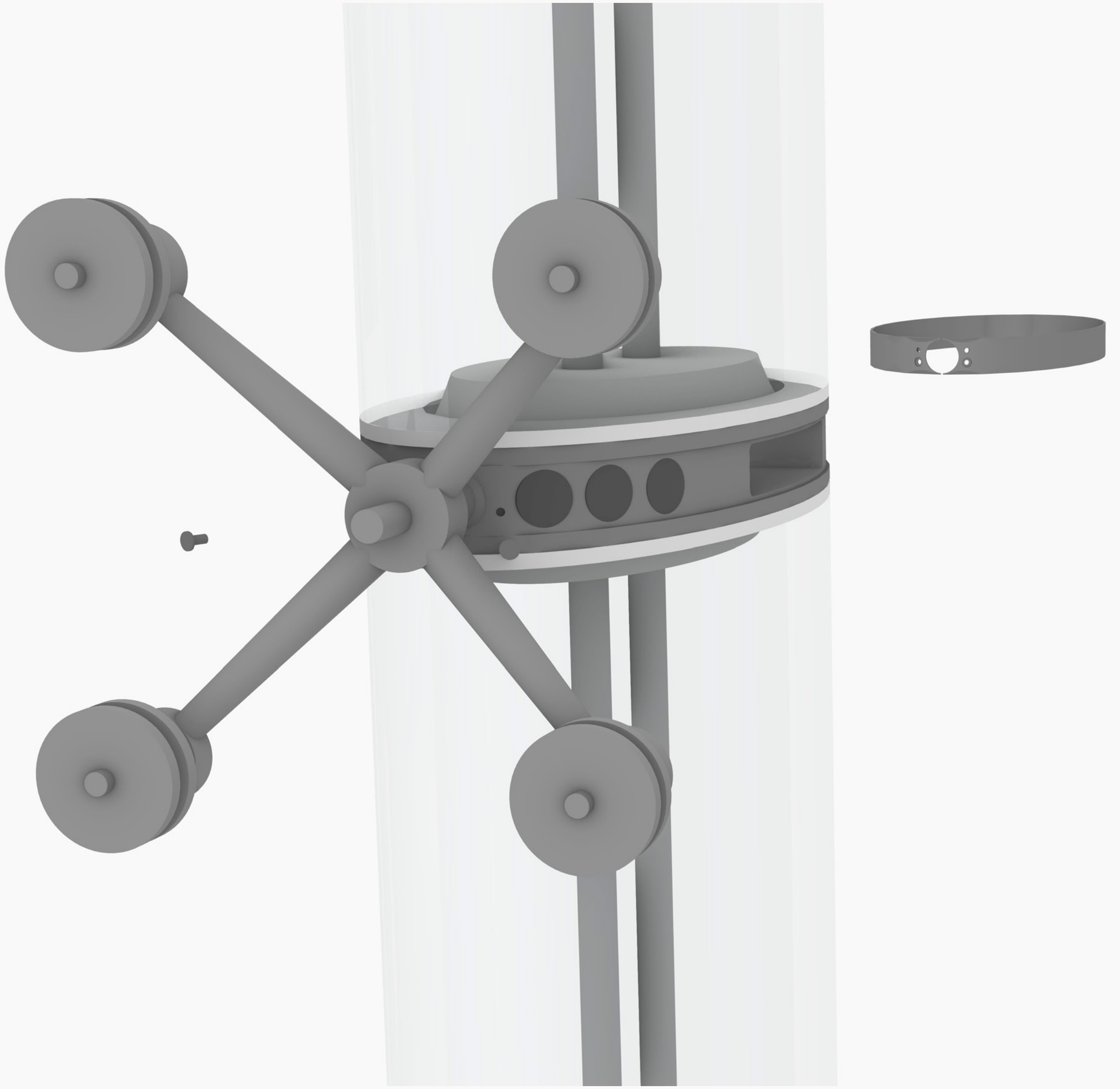

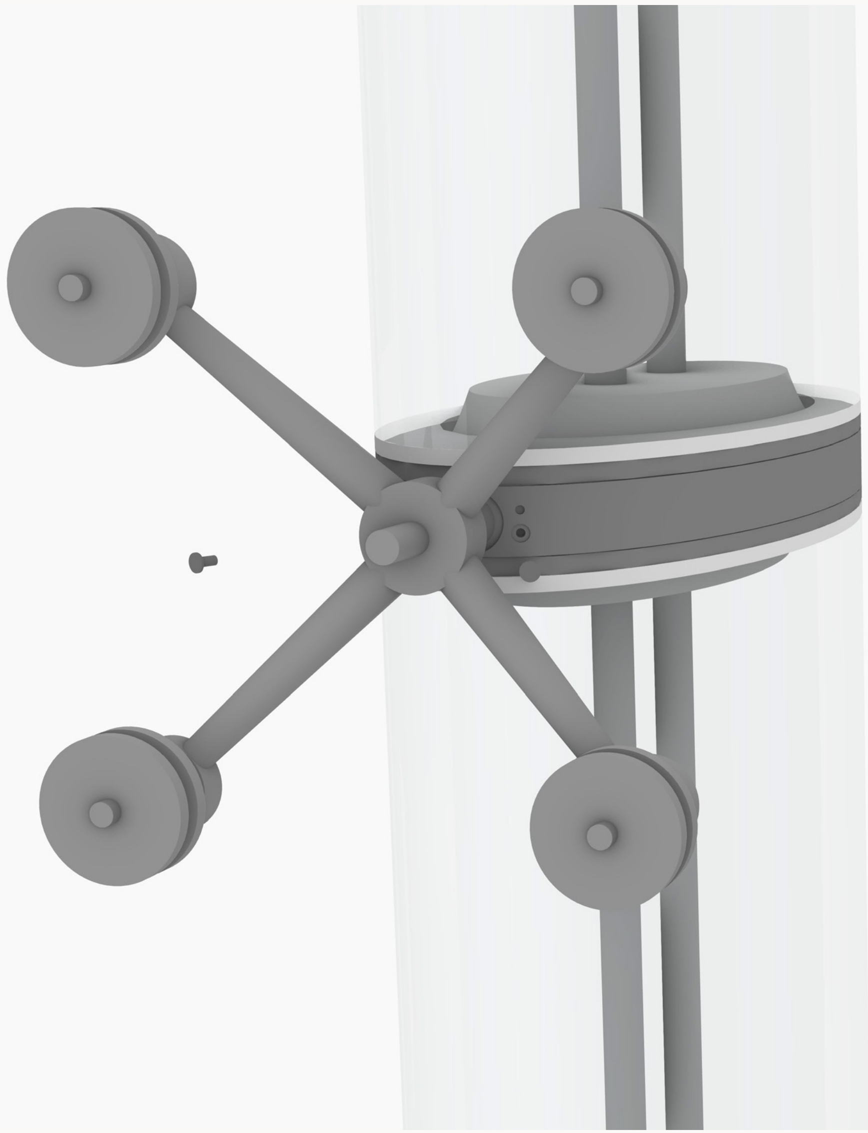

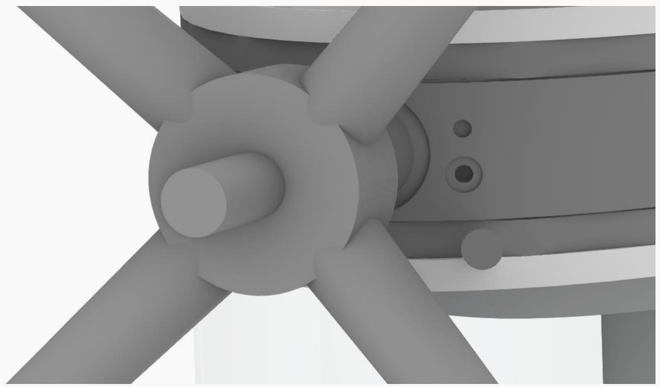

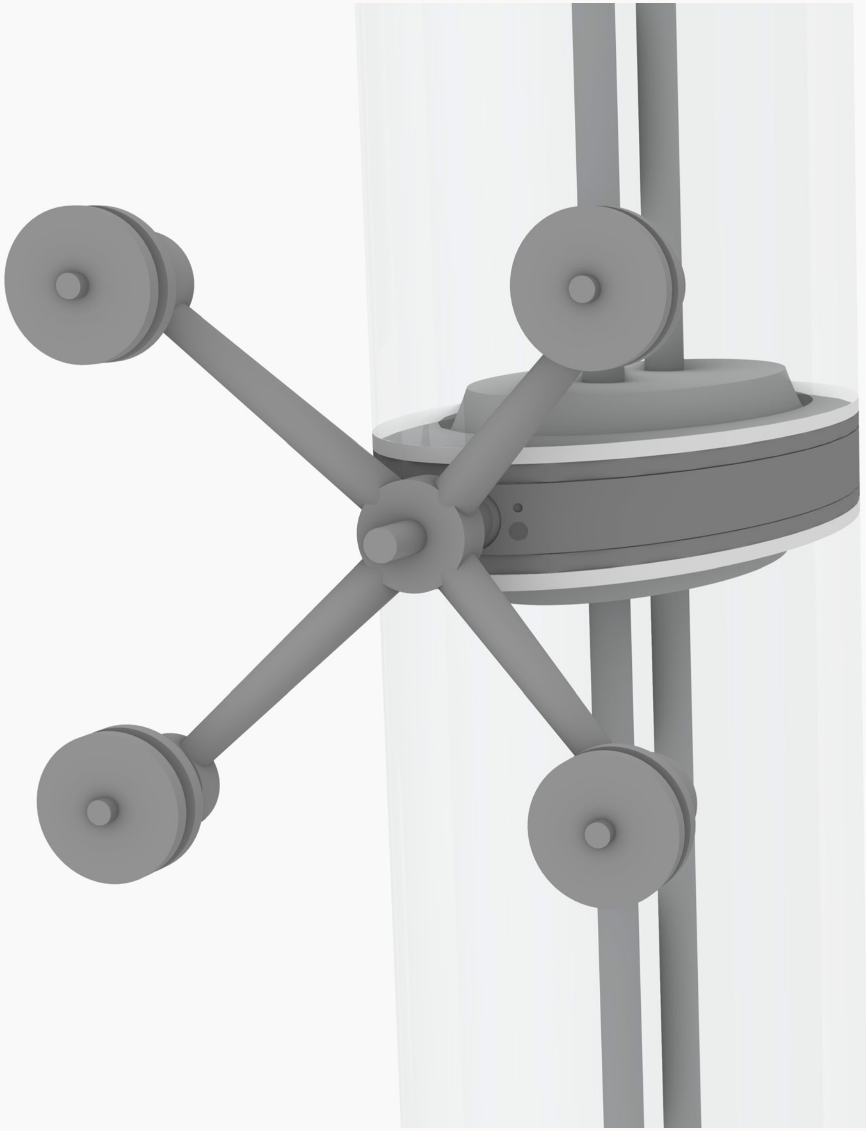

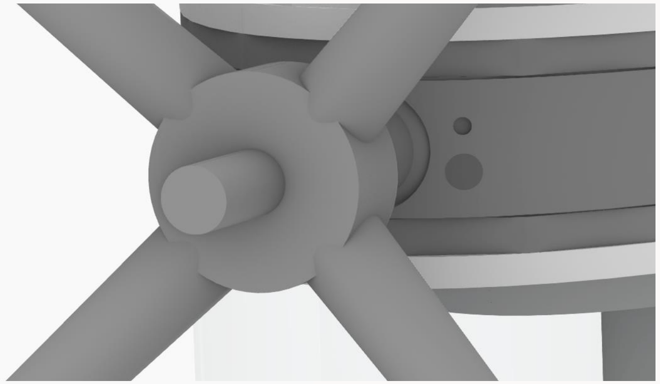

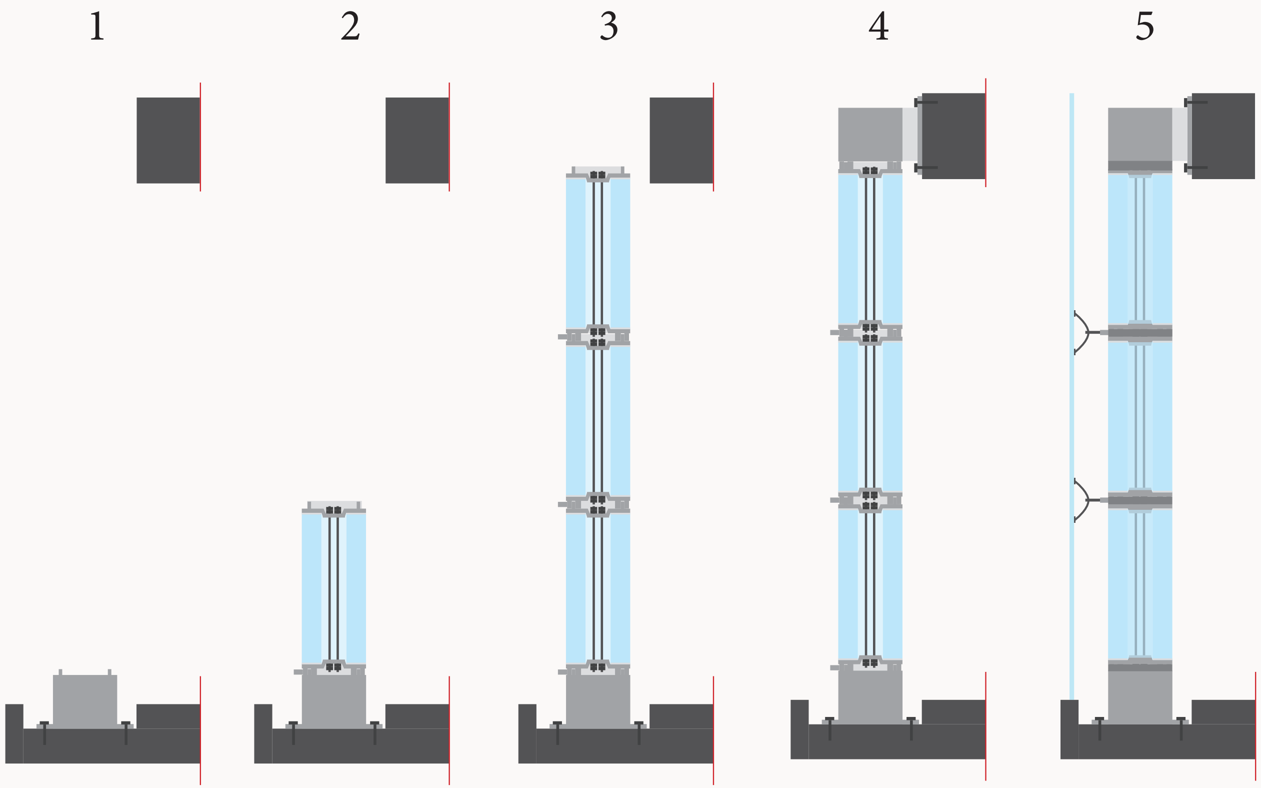
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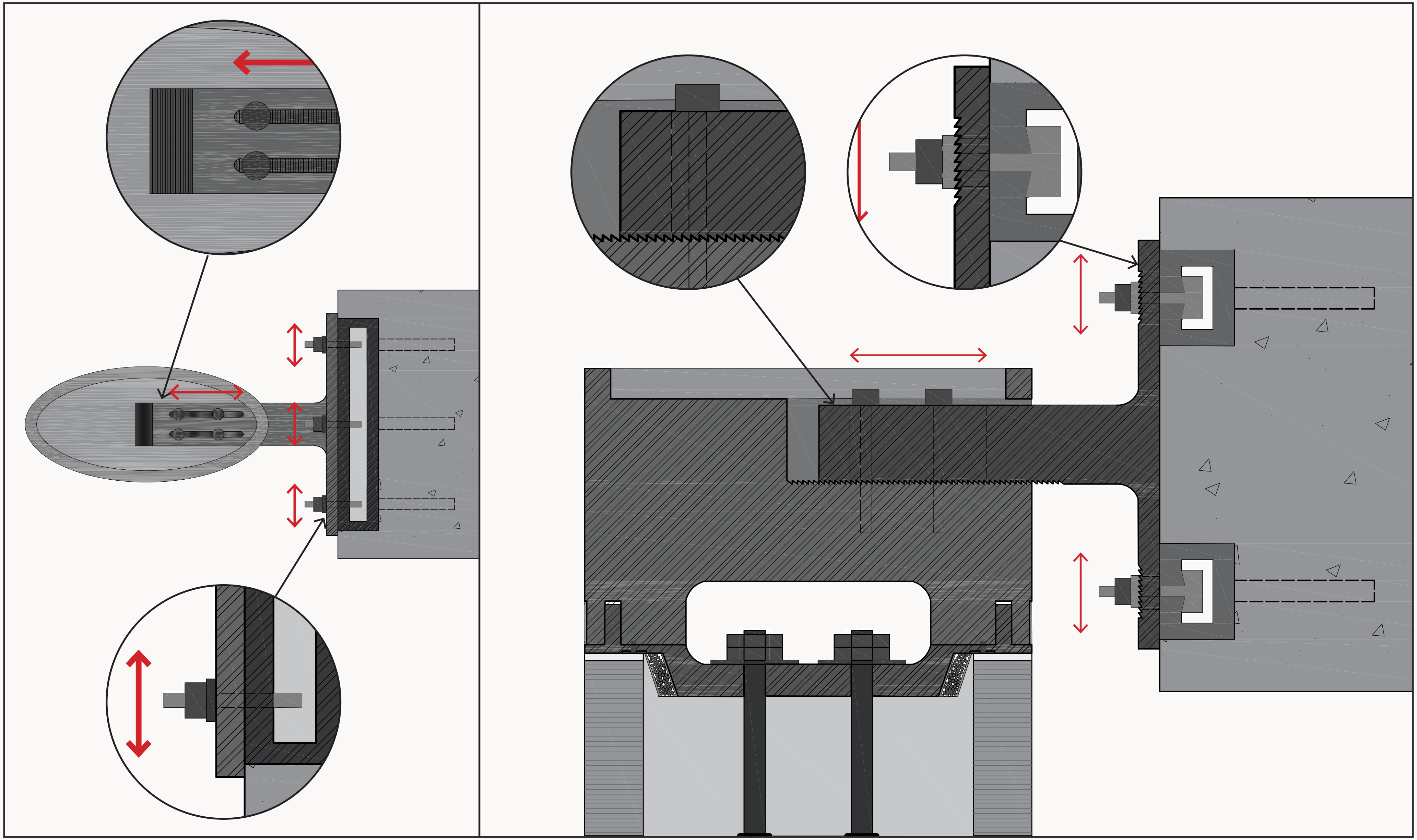

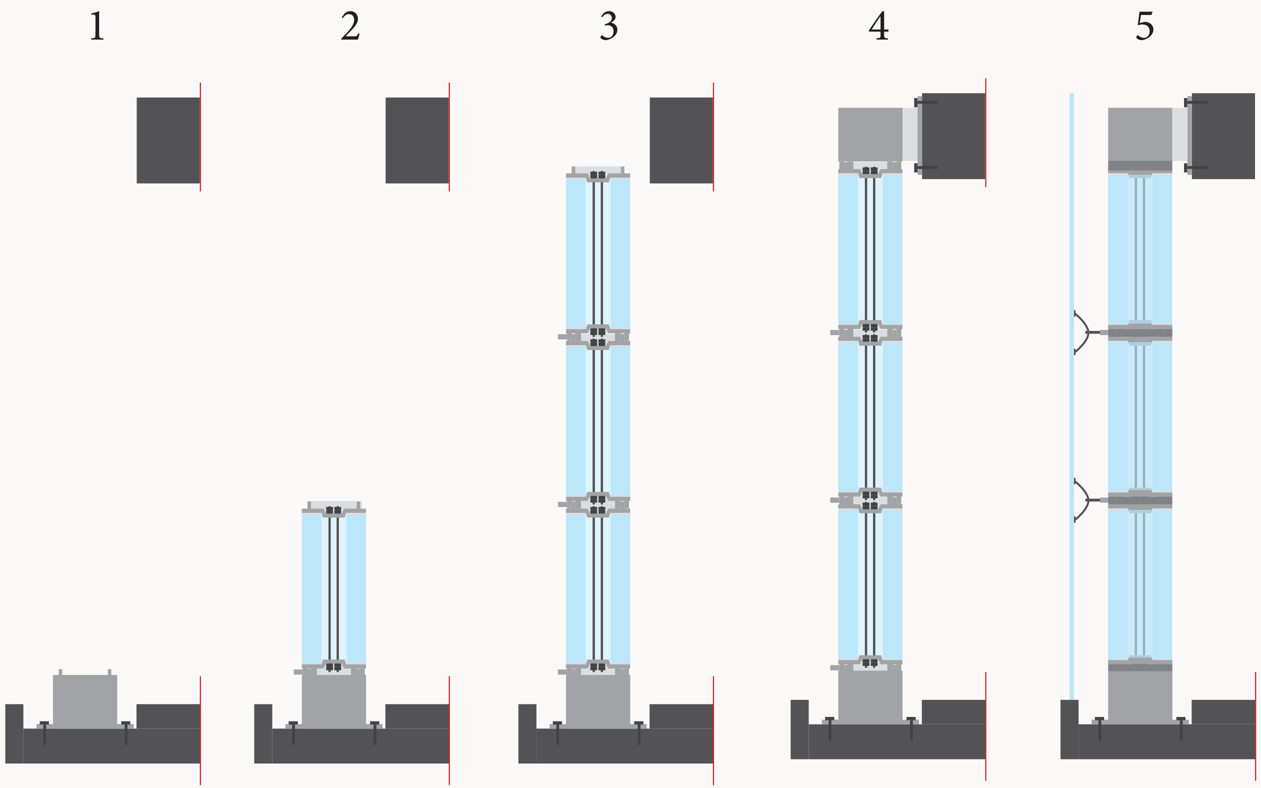
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LUMION
PRO STUDENT


LUMION
PRO STUDENT


LUMION
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LUMION
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	Exceeding optimal current glass designs	*Comparable with optimal current glass designs*	*Little below standards of current glass designs*	*Far below standards of current glass designs*
Criteria	**Very high potential**	**High potential**	**Medium potential**	**Low potential**
Structural performance	Structural performance of element better than structural fin of the same dimensions.	Structural performance of element comparable with structural fin of the same dimensions.	Structural performance of element worse than structural fin of the same dimensions, but still reasonably applicable.	Structural performance far worse than structural fin of the same dimensions. Silly dimensions needed to make it applicable.
Building sequence	Very fast installation, requires no man hours on site. Easy maintenance and replacement of parts. Better building sequence than structural fin façade.	Fast installation, requires little specialist man hours on site. Easy maintenance and replacement of individual parts possible. Comparable with installing structural fin façade.	Medium fast installation, requires some specialist man hours on site. Maintenance requires special equipment and/or people and replacement of individual parts is hard.	Slow installation, requires a lot of specialist man hours on site. Maintenance requires special equipment and people and replacement of individual parts is very hard or not possible.
Safety	Element gives timely warning before failure. Element well resistant to vandalism: no health danger for people upon failure and losing very little structural capacity.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is resistant to vandalism. Comparable to safety glass brick façade or glass structural fin.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is little resistant to vandalism.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is very little resistant to vandalism.
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Costs	Cheaper than glass structural fin	Comparable regarding costs with glass structural fin	Slightly more expensive than glass structural fin.	Much more expensive than comparable glass brick façade
Aesthetics	Offers a very different experience than existing products, adding great variety.	Offers a different experience than existing products, adding good variety.	Offers a slightly different experience than existing products, adding little variety.	Offers a very similar experience as existing products, adding very little variety.

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AN EXPLORATIVE STUDY ON THEIR POTENTIAL FOR ARCHITECTURE

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Main mentor:
Ir. A.H. Snijder
Structural Design & Mechanics

Second mentor:
Dr.ing. M. Bilow
Building Product Innovation

Consultant:
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Architectural Glass

Delegate examiner:
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P5 Presentation | 01-07-2020

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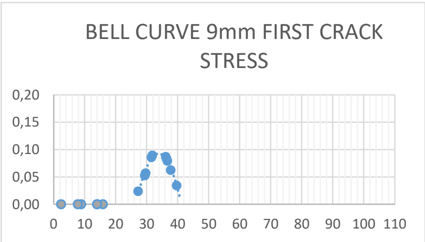
				compressive force at first crack [kN]	compressive stress at first crack [N/mm²]	z-distribution	maximum compressive force [kN]	maximum compressive stress [N/mm²]	z-distribution
group name	**9mm**		STRG	134	36,2	0,0867	214,8	58,0	0,0370
surface area	3704	mm^2	3.1	136	36,7	0,0792	220,4	59,5	0,0473
OD	70	mm	8.1	110	29,7	0,0569	271,3	73,2	0,0227
WT	9	mm	9.1	101	27,3	0,0237	228,2	61,6	0,0596
			11.1	147	39,7	0,0341	272,8	73,6	0,0205
samples	17	#	12.1	109	29,4	0,0526	266,6	72,0	0,0303
Avg first crack	33,9	N/mm^2	13.1	59	15,9	0,0000	218,0	58,9	0,0430
SD	3,9	N/mm^2	17.1	140	37,8	0,0624	256,9	69,3	0,0479
Avg max	64,5	N/mm^2	18.1	117	31,6	0,0858	235,5	63,6	0,0661
SD	6,0	N/mm^2	19.1	118	31,9	0,0892	228,5	61,7	0,0600
			20.1	135	36,4	0,0831	256,0	69,1	0,0494
			21.1	33	8,9	0,0000	225,1	60,8	0,0551
			34.2	135	36,4	0,0831	221,8	59,9	0,0498
			38.3	52	14,0	0,0000	271,7	73,4	0,0220
			40.3	9	2,4	0,0000	212,9	57,5	0,0337
			41.4	52	14,0	0,0000	210,6	56,8	0,0296
			42.4	29	7,8	0,0000	248,5	67,1	0,0607
group name	**5mm**		STRG	81	38,2	0,1710	166,0	78,3	0,0320
surface area	2121	mm^2	24.1				165,4	78,0	0,0312
OD	70	mm	26.2	75	35,4	0,1710	155,3	73,2	0,0181
WT	5	mm	27.2	41	19,3	0,0000	208,0	98,1	0,0169
			30.2	8	3,8	0,0000	127,4	60,1	0,0010
samples	6	#	31.3	43	20,3	0,0000	197,3	93,0	0,0307
Avg first crack	36,8	N/mm^2	33.3				194,9	91,9	0,0337
SD	1,4	N/mm^2							
Avg max	85,4	N/mm^2							
SD	9,3	N/mm^2							
group name	**hardened**		D03	324	87,8	0,0176	350,0	94,8	0,0558
surface area	3691	mm^2	D04	329	89,1	0,0160	386,5	104,7	0,0258
OD	120	mm	D08	364	98,6	0,0064	364,2	98,7	0,0521
WT	5	mm	D10	250	67,7	0,0253	357,1	96,8	0,0559
			D11	255	69,1	0,0263	364,0	98,6	0,0522
samples	10	#	D15	230	62,3	0,0199	291,1	78,9	0,0032
Avg first crack	74,0	N/mm^2	D16	202	54,7	0,0112	346,5	93,9	0,0543
SD	14,3	N/mm^2	D17	260	70,4	0,0270	370,1	100,3	0,0464
Avg max	95,8	N/mm^2	D19	312	84,5	0,0213	379,3	102,8	0,0349
SD	7,1	N/mm^2	D20	206	55,8	0,0124	329,0	89,1	0,0359


BELL CURVE 9mm FIRST CRACK STRESS
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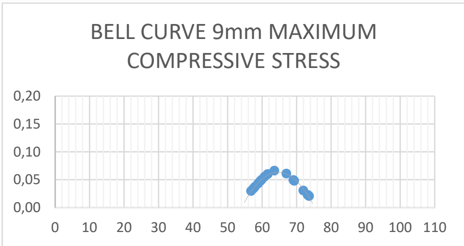
0 10 20 30 40 50 60 70 80 90 100 110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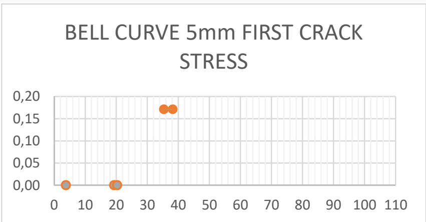
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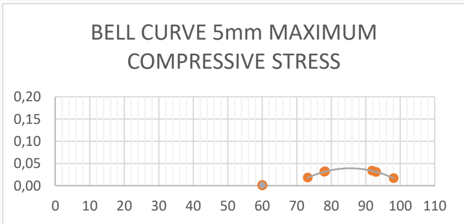
BELL CURVE 5mm MAXIMUM COMPRESSIVE STRESS
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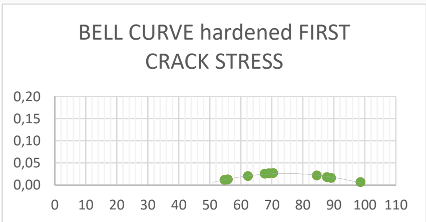
BELL CURVE hardened FIRST CRACK STRESS
0,20
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0,05
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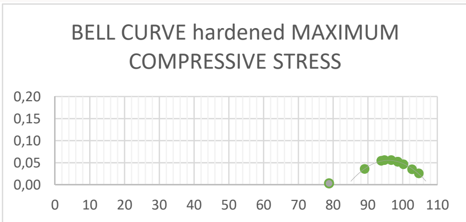
0 10 20 30 40 50 60 70 80 90 100 110


BELL CURVE hardened MAXIMUM COMPRESSIVE STRESS
0,20
0,15
0,10
0,05
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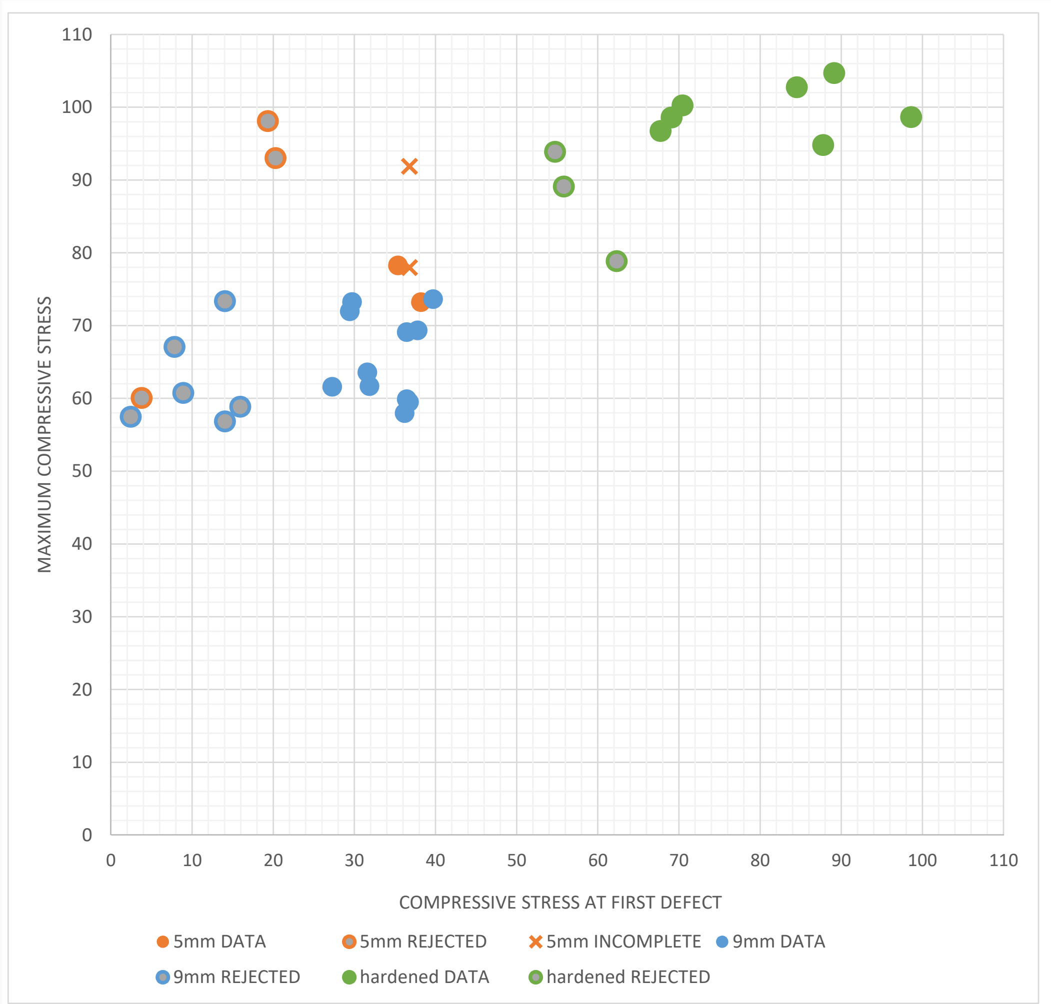
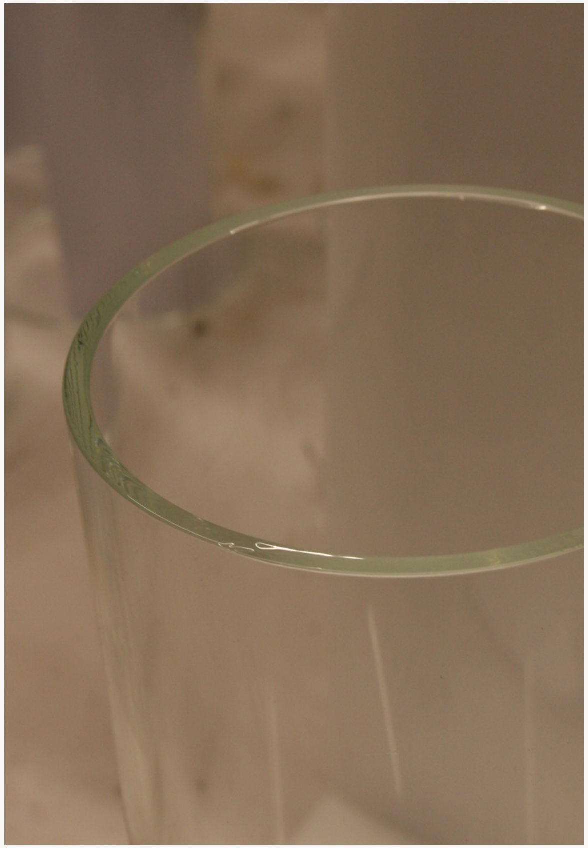
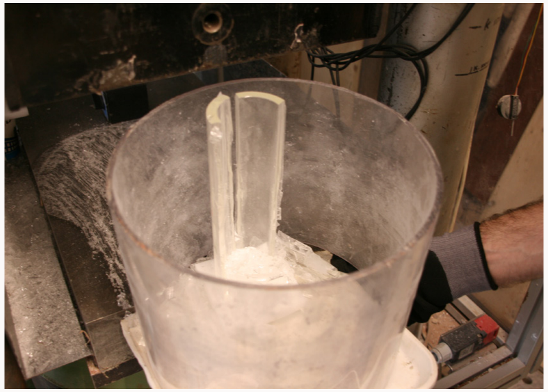
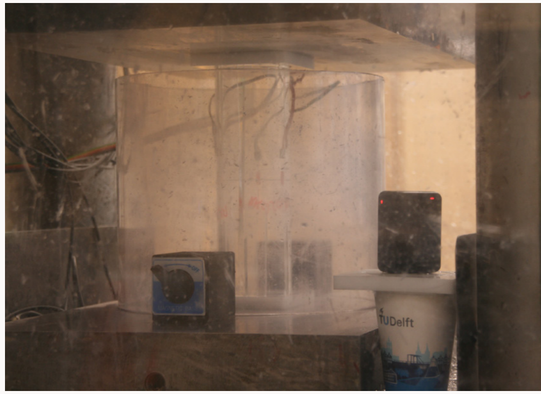
0 10 20 30 40 50 60 70 80 90 100 110


MAXIMUM COMPRESSIVE STRESS
110
100
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90 100 110
COMPRESSIVE STRESS AT FIRST DEFECT
5mm DATA
5mm REJECTED
5mm INCOMPLETE
9mm DATA
9mm REJECTED
hardened DATA
hardened REJECTED

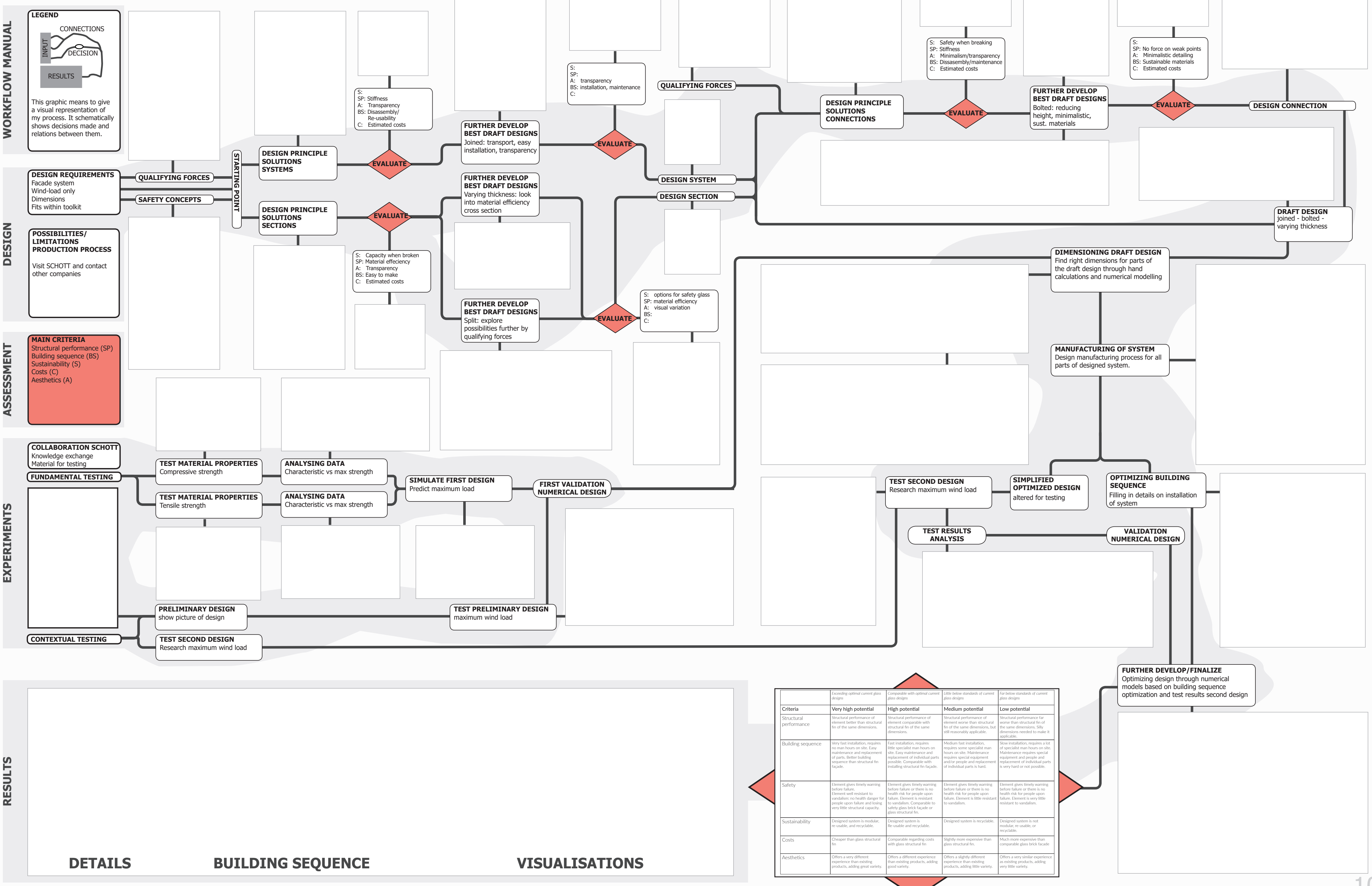

DURATAN®
D5







SCHENCK

WORKFLOW THESIS

WHAT IS THE POTENTIAL OF SECTION ACTIVE EXTRUDED GLASS STRUCTURAL ELEMENTS FOR ARCHITECTURE?



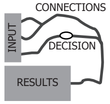
	Exceeding optimal current glass designs	*Comparable with optimal current glass designs*	*Little below standards of current glass designs*	*Far below standards of current glass designs*
Criteria	**Very high potential**	**High potential**	**Medium potential**	**Low potential**
Structural performance	Structural performance of element better than structural fin of the same dimensions.	Structural performance of element comparable with structural fin of the same dimensions.	Structural performance of element worse than structural fin of the same dimensions, but still reasonably applicable.	Structural performance far worse than structural fin of the same dimensions. Silly dimensions needed to make it applicable.
Building sequence	Very fast installation, requires no man hours on site. Easy maintenance and replacement of parts. Better building sequence than structural fin façade.	Fast installation, requires little specialist man hours on site. Easy maintenance and replacement of individual parts possible. Comparable with installing structural fin façade.	Medium fast installation, requires some specialist man hours on site. Maintenance requires special equipment and/or people and replacement of individual parts is hard.	Slow installation, requires a lot of specialist man hours on site. Maintenance requires special equipment and people and replacement of individual parts is very hard or not possible.
Safety	Element gives timely warning before failure. Element well resistant to vandalism: no health danger for people upon failure and losing very little structural capacity.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is resistant to vandalism. Comparable to safety glass brick façade or glass structural fin.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is little resistant to vandalism.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is very little resistant to vandalism.
Sustainability	Designed system is modular, re-usable, and recyclable.	Designed system is Re-usable and recyclable.	Designed system is recyclable.	Designed system is not modular, re-usable, or recyclable.
Costs	Cheaper than glass structural fin	Comparable regarding costs with glass structural fin	Slightly more expensive than glass structural fin.	Much more expensive than comparable glass brick facade
Aesthetics	Offers a very different experience than existing products, adding great variety.	Offers a different experience than existing products, adding good variety.	Offers a slightly different experience than existing products, adding little variety.	Offers a very similar experience as existing products, adding very little variety.

WORKFLOW THESIS

WHAT IS THE POTENTIAL OF SECTION ACTIVE EXTRUDED GLASS STRUCTURAL ELEMENTS FOR ARCHITECTURE?

WORKFLOW MANUAL

LEGEND



This graphic means to give a visual representation of my process. It schematically shows decisions made and relations between them.

DESIGN

DESIGN REQUIREMENTS
Facade system
Wind-load only
Dimensions
Fits within toolkit

QUALIFYING FORCES

SAFETY CONCEPTS

STARTING POINT

POSSIBILITIES/ LIMITATIONS PRODUCTION PROCESS

Visit SCHOTT and contact other companies

Safety concepts
Pieces glass falling down
Element fails

Laminated | Joined | Stringed

Joined best for sustainability reasons. This is the system easiest to assemble, repair and re-use. The price to pay for this is less minimalistic detailing, so extra attention should be paid to this.

S:
SP: Stiffness
A: Transparency
BS: Disassembly/ Re-usability
C: Estimated costs

DESIGN PRINCIPLE SOLUTIONS SYSTEMS

EVALUATE

Panel configuration
Transport
Easy installation
Connection

FURTHER DEVELOP BEST DRAFT DESIGNS
Joined: transport, easy installation, transparency

Many draft solutions have been found for building sequence optimization and criteria have been set up for maximum transparency for the system as a whole.

Minimalistic detailing is going to make or break this design.

This decision for the system will impact the design of the connection hugely, determining its requirements.

S:
SP:
A: transparency
BS: installation, maintenance
C:

EVALUATE

QUALIFYING FORCES

DESIGN SYSTEM

DESIGN SECTION

DESIGN PRINCIPLE SOLUTIONS SECTIONS

EVALUATE

Cross sections
Prelim. design
Laminated
Split
Varying thickness

S: Capacity when broken
SP: Material effeciency
A: Transparency
BS: Easy to make
C: Estimated costs

The varying thickness section seems most promising due to the material efficiency. It takes full advantage of the supposed benefits of the extrusion process. However the split option needs further research before it can be ruled out.

FURTHER DEVELOP BEST DRAFT DESIGNS
Varying thickness: look into material efficiency cross section

Diana results

FURTHER DEVELOP BEST DRAFT DESIGNS
Split: explore possibilities further by qualifying forces

EVALUATE

S: options for safety glass
SP: material efficiency
A: visual variation
BS:
C:

The split variants in theory may use the full structural potential of the material used, but in practice are hard to realize due to surface quality, connection design, safety issues and/ or building sequence related inefficiencies. This is why for this thesis an optimized ellipse shape is chosen. This shape will further be fine-tuned in the numerical stage where its performances will be simulated accurately. The split variants are not to be forgotten completely however and forms options for further research.

Connections
A: Screwed | B: Bolted | C: Glued/Welded
D: Click-system | E: Interlocking

DESIGN PRINCIPLE SOLUTIONS CONNECTIONS

EVALUATE

The bolted variant is best overall. It is easy to install, easy to dis-assemble and can can create a stiff connection.

The requirement for success of this variant is keeping the detailing minimalistic. This is what will be focused on in the further development.

S: Safety when breaking
SP: Stiffness
A: Minimalism/transparency
BS: Dissasembly/maintenance
C: Estimated costs

FURTHER DEVELOP BEST DRAFT DESIGNS
Bolted: reducing height, minimalistic, sust. materials

EVALUATE

A detail has been designed where the bolts will mostly be loaded if the force is straight up. For all other directions the steel takes part of the load because of the tight elliptical fit. It has been designed for decreased connection height and 'hides' a lot of material in the sections themselves. A universal connection to for example a spider system has also been designed to attach the facade panels to the column.

S:
SP: No force on weak points
A: Minimalistic detailing
BS: Sustainable materials
C: Estimated costs

DESIGN CONNECTION

Decreasing seams/connections in sight
Developing the ring/references
Mini assembly

DRAFT DESIGN
Joined - bolted - varying thickness

DIMENSIONING DRAFT DESIGN
Find right dimensions for parts of the draft design through hand calculations and numerical modelling

MANUFACTURING OF SYSTEM
Design manufacturing process for all parts of designed system.

ASSESSMENT

MAIN CRITERIA
Structural performance (SP)
Building sequence (BS)
Sustainability (S)
Costs (C)
Aesthetics (A)

EXPERIMENTS

COLLABORATION SCHOTT
Knowledge exchange
Material for testing

FUNDAMENTAL TESTING

TEST MATERIAL PROPERTIES
Compressive strength

ANALYSING DATA
Characteristic vs max strength

TEST MATERIAL PROPERTIES
Tensile strength

ANALYSING DATA
Characteristic vs max strength

SIMULATE FIRST DESIGN
Predict maximum load

FIRST VALIDATION NUMERICAL DESIGN

RESEARCH PROPOSAL

RESEARCH PROPOSAL

Diana results

PRELIMINARY DESIGN
show picture of design

TEST PRELIMINARY DESIGN
maximum wind load

RESEARCH PROPOSAL

CONTEXTUAL TESTING

TEST SECOND DESIGN
Research maximum wind load

TEST SECOND DESIGN
Research maximum wind load

RESEARCH PROPOSAL

SIMPLIFIED OPTIMIZED DESIGN
altered for testing

OPTIMIZING BUILDING SEQUENCE
Filling in details on installation of system

TEST RESULTS ANALYSIS

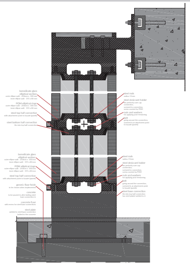
VALIDATION NUMERICAL DESIGN

RESEARCH PROPOSAL

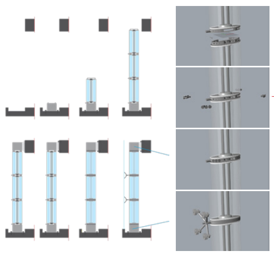
FURTHER DEVELOP/FINALIZE
Optimizing design through numerical models based on building sequence optimization and test results second design

RESEARCH PROPOSAL

RESULTS



DETAILS



BUILDING SEQUENCE

VISUALISATIONS

	Exceeding optimal current glass designs	Comparable with optimal current glass designs	Little below standards of current glass designs	Far below standards of current glass designs
Criteria	**Very high potential**	**High potential**	**Medium potential**	**Low potential**
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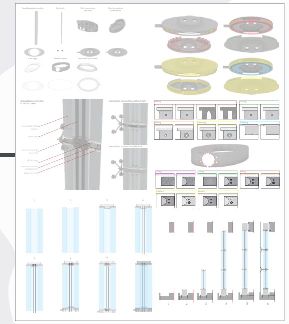
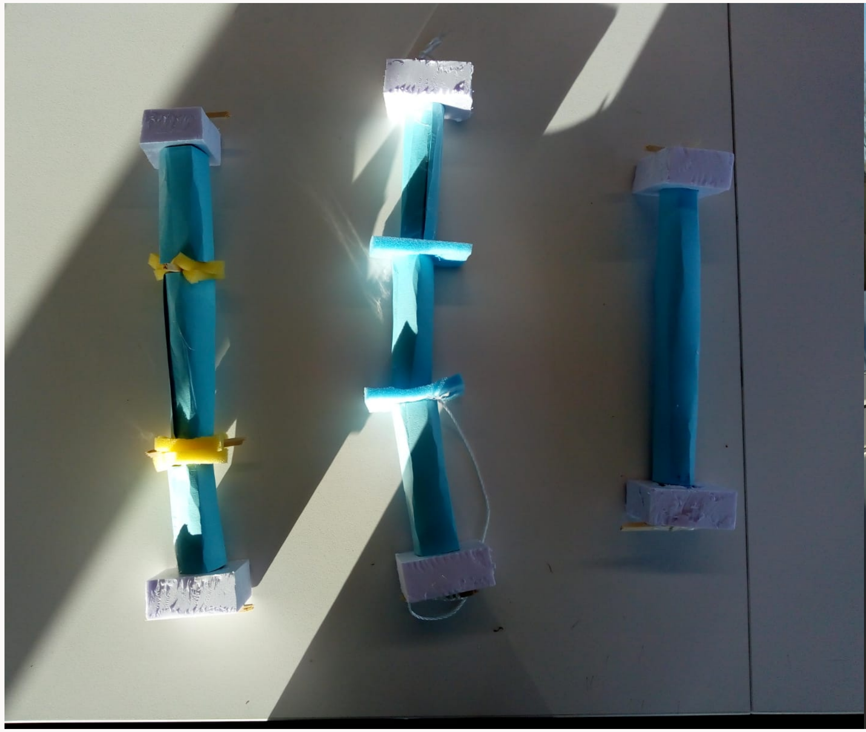
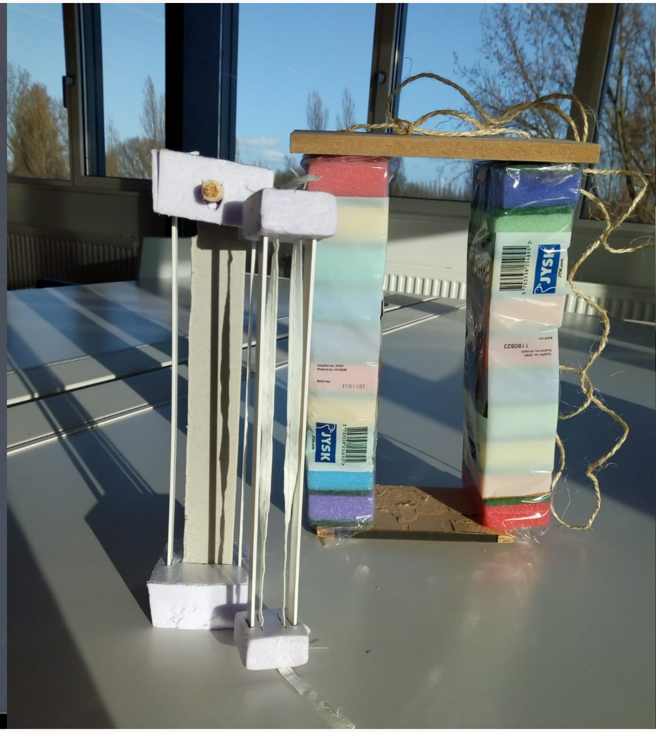
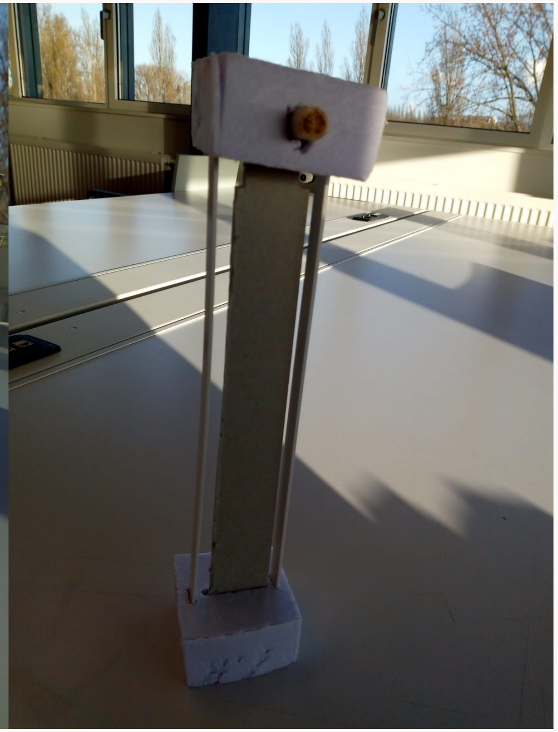
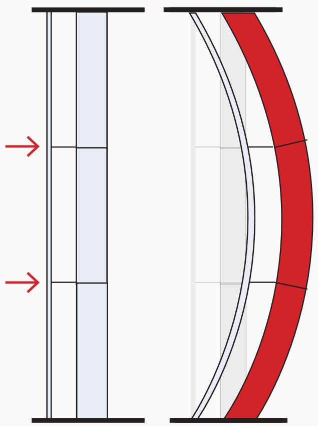
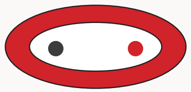




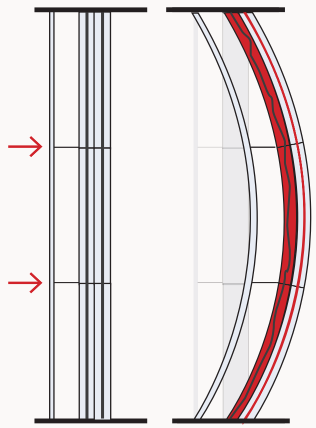

JYSK

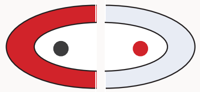






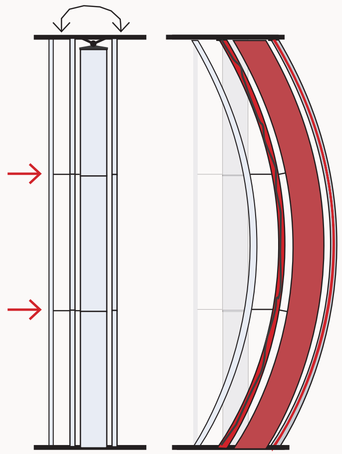
The entire section is working here to convey the moment. A major disadvantage of this is that half of the section is conveying tension and glass doesn't hold up that well in tension. This can be avoided by not loading it eccentric. This can be done by splitting the ellipse.

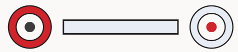




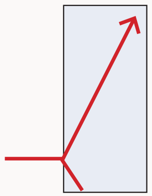
Compression only half, glass takes all forces of moment, cable tension releases

Tension only half, glass takes no forces of moment because cable tension increases

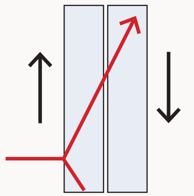




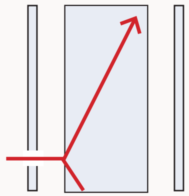
The same principle as for the split section is true here. But in this section the forces are split up even more as the middle part cannot convey any forces of the moment because of the rotation connection on top.



Shear force is conveyed through the section as it would through any section and material. The amount of material parallel to the direction of the shear force is very important for the stress in the material.



Shear force is conveyed through both halves. Connection has to allow for this passing on of forces. However, elements must also be able to slide over one another.



Shear force in this section is not conveyed by the outer tubes, just by the main section. This main section is clamped on one end of the column and connected with rotational freedom on the other. This allows it to still convey shear.