TALLINN UNIVERSITY OF TECHNOLOGY
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Department of Technology

RESTORATION OF ARCHITECTURAL MONUMENTS WITH LOAD BEARING SOLID GLASS BLOCKS. SAMPLE DESIGN PROPOSAL FOR GLASS-STONE CONNECTION

EHITUSMÄLESTISTE RESTAUREERIMINE KANDVATE KLAASIST TÄISPLOKKIDEGA. LAHENDUSETTEPANEK KIVI- JA KLAASMÜÜRI ÜHENDAMISEKS

Master's Thesis
Civil and Building Engineering Focusing on Building Restoration

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Käesoleva töö põhieesmärgiks on ajaloolise looduskivimüüri näitel välja selgitada kandvate klaasist täisplokkide kasutamise võimalikkus ehitusmälestiste restaureerimisel, keskendudes kivi- ja klaasmüüri ühendamise problemaatikale. Uurimus käsitleb üldisemas mõttes kandva ehk konstruktsiooniklaasi *(structural glass)* kui kaasaegse ehitusmaterjali senist kasutust ja karakteristikuid, sealhulgas tugevusnäitajaid ning purunemiskäitumist. Töös on analüüsitud klaasi esteetilist sobivust ajalooliste hoonete ja üldtunnustatud mälestiste taastamise filosoofiaga.

Lääne-Virumaal asuva muinsuskaitse all oleva Toolse linnuse edelatorni looduskivist seinas paiknev ulatuslik pragu on võetud aluseks oletuslikule restaureerimiskontseptsioonile, mis näeb ette looduskivimüüri taastamist ja tekkinud lõhe täitmist kandvate klaasist täisplokkidega, eesmärgiga luua traditsiooniliste materjalide kasutamise kõrvale uus, läbipaistvust pakkuv lahendus. Töös on hinnatud linnuse varemete geotehnilise seisukorra mõju restaureerimismetoodika teostatavusele ja laiemalt käsitletud probleeme klaasmüüri ühendamisel ajalooliste kivipindadega, sealhulgas soojuspaisumise mõju ning sobiva adhesiivi valikukriteeriume.

Uuringus on põhinetud varasemalt Delfti Tehnikaülikoolis läbi viidud asjakohaste katsete tulemustele ja täiendavalt teostatud nihketeim klaasplokkmüüri ning kivipinna liimühenduse tugevuse hindamiseks, arvestades Toolse linnuse kui käsitletava objekti asukohast tulenevaid võimalikke mõjuvaid kliimategureid ning uurides polüuretaan- ja epoksüliimide tugevusomadusi. Kandvaid klaasplokke hõlmav pakutud restaureerimislahendus on täiendavalt analüüsitud, kasutades lõplike elementide meetodil (LEM) põhinevat modelleerimistarkvara, et välja selgitada klaasmüüri omakaalust tekkivad jõud ja hinnata nende mõju kivi ning klaasi ühendusele. Lisaks on teostatud esmased kontrollarvutused olemasolevate ja taastatavate kivimüüri osade soojuspaisumise mõju hindamiseks ning tehtud lahendusettepanek kivi- ja klaasmüüri ühendamiseks.

Testi tulemustest ja näidiskalkulatsioonidest selgub, et kandvatest klaasist täisplokkidest laotud müüri ühendamine ajalooliste kiviseintega on võimalik ettesüvistatud horistontaaltasapindade liimimisel epoksüliimiga. Tulenevalt joonpaisumistegurist on klaasmaterjali ühendamine kiviga antud kontekstis võrdsustatud oskusliku käsitööga, mille teostamine nõuab plokkide sobitamist, põhjalikku analüüsi ja eeltööd.

Märksõnad: epoksüliim, joonpaisumistegur, klaaskonstruktsioonid, klaasplokid, LEM modelleerimine, liimühendus, looduskivimüür, polüuretaanliim, restaureerimine, soojuspaisumine

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NOTATIONS AND ABBREVIATIONS

ASTM –	American Society for Testing and Materials
BS-EN –	British Standard European Norm
DIN –	Deutsches Institut für Normung (the German Institute for Standardization)
EEA –	Estonian Environmental Agency
EN –	European standard
EVS-EN –	Eesti Vabariigi standard (Estonian standard)
FEM –	Finite element method
IBC –	International Building Code
IGU –	Insulating Glazing Units
ISO –	International Organization for Standardization
MS polymer –	Silane modified polymer
NHBE –	National Heritage Board of Estonia
NHL –	Natural Hydraulic Lime
NRCME –	National Register of Cultural Monuments of Estonia
PVB –	Polyvinylbutyral
RH –	Relative humidity
TRAV –	Technischen Regeln für die Verwendung von ab sturzsichernden verglasungen (German technical rules for glass)
TRLV –	Technischen Regeln für die Verwendung von linienförmig gelagerten Verglasungen (German technical rules for glass)
TU Delft –	Technische Universiteit Delft (Delft University of Technology)
ULS –	Ultimate Limit State
VIG –	Vacuum Insulating Glass

PREFACE

The aim of the current study is to introduce load bearing glass to the restoration practices of architectural monuments by means of providing a feasible design concept of bonding solid glass blocks and historical stone masonry walls.

In Estonia, the use of structural glass has been relatively modest so far, since designing glass constructions is more complex than in case of traditional materials. Often, the use of glass is counted out of the consideration due to the lack of experts and building codes. However, as existing examples all over the world have shown, self-supporting glass can be effectively used both in new buildings and in architectural monuments, since it clearly distinguishes from other materials by its transparency. Historical monuments are hereby taken as a subject to the current study in order to find out the advantages and disadvantages of using load bearing glass in restoration.

Load bearing solid glass blocks are considered as the selected type of structural glass due to the aesthetical congruence with historic masonry. Also, the solid glass block masonry system is entirely novel field in glass engineering and therefore its behaviour and suitability with stone wall is yet unknown. In order to examine occurring problems in glass-stone connections, a specific case study of Toolse order castle ruins is taken as a basis to provide feasible design proposal. In more detail, the SW tower masonry will be inspected, since it accommodates an extensive crack that is selected as the main objective for the restoration concept that proposes replacing the missing parts of the castle walls to be built up by using solid glass blocks.

The technology of connecting glass block masonry to historic stone wall by means of suitable adhesives is taken as priority, since it holds the definitive significance of the proposal's feasibility. Therefore, the current study focuses on finding the proper adhesive for glass-stone connection under the circumstances of castle's location and its climatic data. For that, experiments for shear strength of the glass-stone composite specimens will be conducted and results compared to the strength requirements, determined by the proposed design.

Another obstacle when two different materials are designed to form a structurally safe and durable compound is their dissimilar thermal behaviour. Despite being both classified as ceramics and considered as brittle materials, glass and natural stone have different linear expansion coefficients due to their different chemical composition and microstructure. This can cause unwanted cracks when not being considered in the design phase. Skillful selection of the glass block type and precise dimensions can, however, lead to resistant glass restoration in the area of the observed wall. Therefore, sample calculations to estimate the thermal movement in the walls of Toolse castle are provided within the scope of the current work with a purpose to provide a feasible design proposal in terms of the glass masonry composition and location of dilation joints.

Nowadays, very complex-shaped structures can be rather easily analyzed with the help of computer software. One of the suitable options to determine inner stresses and support reactions of studied structures is FEM-based programs. In the current thesis, Scia Engineer 15, common 2D FEM modeling software for linear and non-linear calculations is used to determine how the designed glass masonry in the extensive crack of the SW tower of Toolse castle would affect the adhesive connection on the surface of historic stone masonry.

After the preliminary analysis of the strength of the connection and thermal behaviour, a proposed design is evaluated in terms of feasibility.

1. OVERVIEW OF BUILDING CONSERVATION AND STRUCTURAL GLASS

1.1 The Great Idea of Preserving Architectural Heritage

Every human activity leaves its trace. Architectural heritage, varying in age, style, condition and materials used, can be found from past civilizations. Regardless of different mentalities throughout the centuries towards preserving what is left, surroundings often include signs of history. In a way, landscape with distinguished architectural landmarks help humans preserve the connection between past and present, although means of interpretation have always been in constant change.

The care of cultural heritage has a long history. It was primarily aimed at mending and fixing objects for their continued use and aesthetic enjoyment [1]. In addition to praising classical civilization in renaissance time period, acknowledging ancestors' untouched heritage and attempts towards formalising conservation and restoration methodology became a question of issue already in 1717 when the Society of Antiquaries of London was founded, to encourage the study and knowledge of antiquities and history [2]. Following, believed to be established in 1734, Society of Dilettanti started to fund student's travel to ancient Rome and Greece mainly in order to support publications on the topic of interesting findings among historical monuments [3]. Although both foregoing organisations were found in purpose of spreading the ideas to value and protect cultural heritage, more specific unions with their main focus on concept-based preservation of architecture were about to be established afterwards. The history of organized building preservation goes back to 1877 when the first nonesuch association Society for the Protection of Ancient Buildings was founded in Victorian England by William Morris and Philip Webb. Their manifesto points out the importance of protection in the place of restoration to stave off decay by daily care as well as sustainability issue – 'to hand ancient buildings down instructive and venerable to those that come after us'[4]. Courtesy of great enthusiasts throughout the 18-20th century, the very idea of impartation is acknowledged at the present time worldwide by means of national standards and normative documents, such as nation-wide Heritage Conservation Act in Estonia, first taken into force in 2002.

The debate between ʹrestoringʹ and ʹnot restoringʹ has come to organise the narrative of conservation, structured around a dialectic between two diverging modes of practice; one that reconstructs in order to achieve a unity of style; the other, more antiquarian, that includes in the preservation all the changes and alterations that the building has suffered [5]. Often, the question whether unique predecessors' ruins should be protected has developed into a whole new level from ʹshould we or should we not?ʹ rather than to ʹwhy, how and to what extent?ʹ. When taking steps towards safeguarding, architectural heritage is constantly put at risk as threats caused by numerous physical factors act on the objects. Existing possibility of unexpected damage of monuments has contributed to the validation of preventive measures, for instance elaborated documentation of current situation and establishing vocational training and qualification criterions for practitioners dealing with buildings. The author hereby emphasises the belief that preserving cultural heritage has never been solely changing monuments appearance but paying respect to the past, therefore, it is, first and foremost, knowledge-based work that requires proper attitude.

Numerous codes of ethics have been published to provide guidelines for professional conservation and restoration. Perhaps world-renowned Venice Charter from 1964 is considered to be the main document and basis for appraisal. In the document, main principles and definitions are pointed out. However, chapter does not cover social and financial issues as well as the concept of reversibility in restoration. Key articles of ethics in conservation and restoration are described in many supplementary acts, such as World Heritage Convention (1972) to partly revise the Venice Charter and Nara Document on Authenticity (1994) to carry out the responsibility to clarify the authenticity related issues which were expressed in the articles 6 and 7 of the Venice Charter [6].

To prevent historical building from decay, different types of actions are required. According to the Estonian Heritage Conservation Act, conservation is described as a "complex of works which prevents the further destruction of a monument or structure located on a heritage conservation area by technically securing its structural and decorative elements by not altering them and preserving the historical layers" [7]. When conservation is done, the minimum effective action is always the best. Relying on Venice Charter, Sir Bernard Feilden, a well-known expert on conservation, has stated that if possible, the action should be reversible and not prejudice possible future interventions. He formulates standard of ethics to be rigorously observed in construction work, most importantly, the condition of the building must be recorded before any intervention and historic evidence must not be destroyed [8]. Regarding definition of restoration, Estonian Conservation Act proposes that restoration is 'a complex of works which ensures the authentic fixation of the historical and architectural condition of a monument or structure located on a heritage conservation area by removing elements of low value and elements and layers spoiling the appearance and by restoring the missing parts in scientifically justified form based on original documents and studies' [7]. Therefore, restoration is resurrection of the original concept and it is based upon respect for original material, archaeological evidence, original design and authentic documents [8]. 'Replacement of missing or decayed parts must integrate harmoniously with the whole and contributions from all periods must be respected,' states Feilden [8]. Aforementioned procedures seldom eliminate each other in a preservation process and often form a symbiosis with other necessary actions, such as consolidation, reproduction, or even reconstruction to obtain the maximum effect depending on the situation.

It is difficult, yet desirable to satisfy conditions presented from all parties when preserving architectural monuments. However, possible contradictions in values must always be settled before any action is put into effect. There is no absolute solution and fervent protection of heritage properties does not always empower itself, nevertheless, consistency of ethical and proficient treatment is desirable as ancient buildings carry fragments of history with themselves and sensing cultural background is beyond doubt essential for humankind.

1.2 Brief History of the Use of Structural Glass in Buildings

Glass has been used in buildings for centuries, dating back to 100 AD when Romans in Alexandria began to use it for architectural purposes. Cast glass windows with poor optical qualities then began to appear in the most important buildings in Rome and the most luxurious villas of Herculaneum and Pompeii [9]. Later on, in the Gothic cathedrals and churches stone walls and large window openings filled with stained glass were integrated. The realization of famous Crystal Palace of the Great Exhibition in Hyde Park, London from 1849 by Sir Joseph Paxton was definitely an eye opener for the world of modern building technology and glass architecture. Although visionary architects like Mies van der Rohe proposed complete glass envelopes around high-rise office buildings already in the early twenties, it took the Bauhaus period and the exile of its members in the USA to develop the all-glass facade office buildings which became a symbol of the 50's and 60's [10].

However, glass has been functioning as a transparent membrane isolating interior from exterior and offering protection from the weather while allowing daylight to penetrate inside the building. It used to transfer external actions (most notably wind) to the substructure, but did not carry any parts of the building except itself. This changed in the 1950's [11]. Nowadays, due to improvements in glass industry, the material is also being considered for its structural and protective capabilities. In other words – it has become a true load bearing element next to traditional concrete, timber, steel and masonry. Nevertheless, glass itself is unsafe as a material for structural applications and special care must be taken to design load bearing structures. Therefore, it is often used as a main article in combination of various materials. Special attention needs to be paid to fundamental weaknesses of glass, such as unpredictable failure behavior and brittleness.

The presented direction of structural glass is not entirely new. Hollow glass block, developed in the early 20th century [12] to be used most commonly in industrial buildings, similarly bears load from adjacent elements and is treated like masonry in application. The most common method for fixing blocks together is using Portland-cement based mortar and steel rods for reinforcement. Thus, the construction itself loses the aspect of pure transparency that architects nowadays strive to. Therefore, the use of hollow glass blocks with a rugged surface in modern construction has not shown any noticeable popularity.

Sir Norman Foster is considered one of the headmost to introduce structural glass in architectural projects, such as office building from 1975 for insurance company Willis Faber & Dumas in Ipswich, England. An innovative solution of internal glass fins were used to work in bending and provide necessary lateral stiffness to solar-tinted glass. The glass curtain wall was connected by using silicone sealant instead of traditional aluminum or steel mullions, resulting in a huge step towards full transparency with its novel technology (Figures 1 and 2) [11].

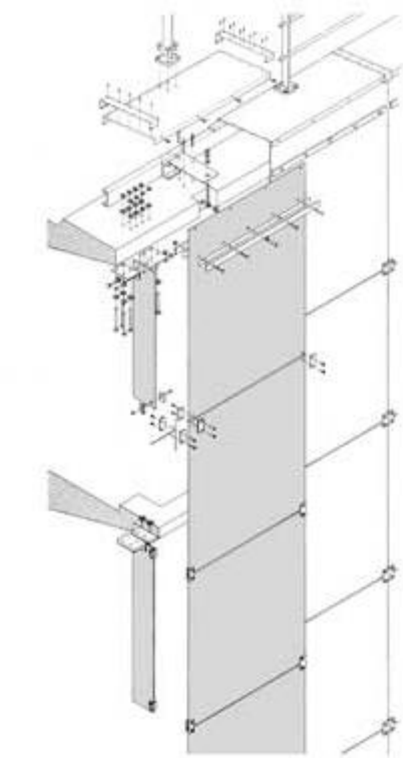

Figure 1. Technical drawing for glass fin technology used in Willis Faber & Dumas office building [13]

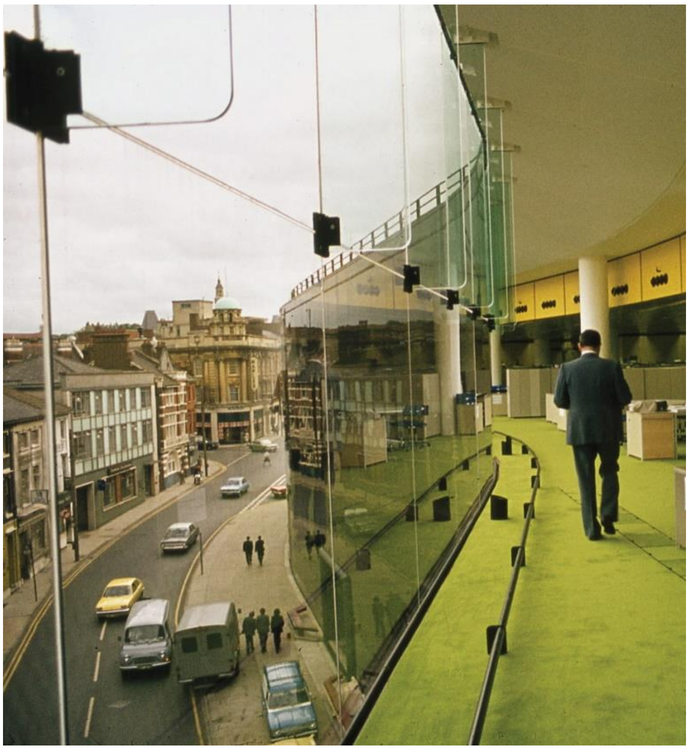

Figure 2. Willis Faber & Dumas office building, glass façade in Ipswich, England. Glass design by A. Hunt Associates [14]

Glass elements are capable of carrying loads even when holes are drilled in, although in this case, high [14]stress concentrations in glass pose a threat. Hole bearing connections were first developed in 1996 for Yurakucho underground entrance canopy at the Tokyo International Forum in Japan (Figure 3). It features a world-known 10.6 metres long cantilevered glass canopy designed by Dewhurst Macfarlane and Partners. The key to the design was the method of transferring force at the connections [15]. Construction consists of 9.2 metres long cantilevered glass fins, each made up of 4 component beams pinned at their middle and end points to form an arch (Figure 4). Connected with stainless steel pins and carrying self-weight and load from glass panels on top, the structure is also capable to resist seismic, thermal and wind loads. This unique and transparent world's largest free-standing glass structure subsequently inspired architects and engineers to use glass in structures in order to provide new innovative solutions.

Figure 3. Yurakucho glass canopy in Tokyo, Japan [16]

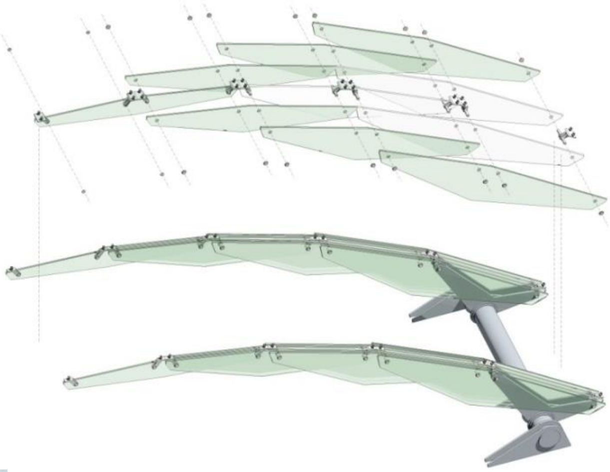

Figure 4. Detail drawing of Yurakucho load bearing structure by R. Hughes [17]

Another significant example of load bearing glass is the curved glass façade of Casa da Musica in Porto, Portugal designed by Rob Nijsse and ABT (Figure 5). The concert hall project (architectural design by OMA) was completed in 2005 by employing a rich variety of materials and new technologies, including design of the glass façade. On this particular occasion the glazing is made of waved glass, with the alignment of the ridges and valleys of the corrugations running in a vertical direction. The measures of the glass corrugation provide the necessary structural dimension to withstand wind loads. Aside from structural function, curved glass deflects sound waves and therefore supports acoustical diffusion [18].

Figure 5. Glass façade with corrugations in Casa da Musica (OMA) [19]

One of the most impressive examples of using structural glass in buildings in 21th century is perhaps the Apple Store in 5th Avenue, New York, USA by Bohlin, Cywinski and Jackson from 2006 (Figure 6). The box-shaped all-glass construction which measures 10x10x10 metres consists of frameless façade panels as well as load bearing structural framing with minimum use of steel [20]. In general, Apple Stores worldwide exhibit many interesting examples of load bearing glass, such as glass stairs, balustrades and aesthetically pleasing transparent facades.

Figure 6. Apple Store iconic glass cube entrance in 5th Avenue, New York [21]

Figure 7. Glass Concept Home all-glass construction [22]

Also, the promising vision and realistic renderings of Glass Concept Home by Ennio Arosio and Carlo Santambrogio (Figure 7) among many other innovative glass projects have caught public attention and started further discussions about numerous possibilities of structural glass. Furthermore, engineers and researchers throughout the world in the past 10-15 years have been working on efficient solutions using modern technology to bring out the potential of transparent glass.

1.3 Glass as a Load bearing Material

1.3.1 Glass Material Properties

Glass is an inorganic, amorphous solid material which is most often known by its transparency. It has found diverse applications, such as window and furniture industry, sculpture, optoelectronics, tableware and architecture in general. All flat glass that can be seen in buildings and cars, as well as bottles, vases and the most ordinary lamps is soda-lime silicate glass. In literature, soda-lime silicate glass is traditionally referred to as 'glass', unless noted otherwise. The production of the material comprises melting together quartz sand (SiO_2), sodium carbonate, also known as washing soda (Na_2CO_3), lime (CaO) and several minor additives. Average composition for soda-lime glass is presented in Table 1.

Table 1. Average composition in wt % for soda-lime glass [23]

Soda-lime glass	
Component	Composition (wt%)
SiO_2	71–73
CaO + MgO	9,5–13,5
Na_2O + K_2O	13–16
B_2O_3	0–1,5
Al_2O_3	0,5–3,5
Other	0–3

The main components can be divided into three groups in accordance with their objective:

1. **The former** is the main component of glass and is normally silicone dioxide SiO_2 (contained in sand). It has to be heated to relatively high temperatures to become viscous.
2. **Fluxes** are added to the former to lower the melting temperature of the silica. Soda (Na_2O) and potash (K_2O), both alkalis, are common fluxes.
3. **Stabiliser** keeps the finished glass from dissolving, crumbling, or forming unwanted crystals. Calcium oxide in the form of limestone is a common stabilizer [24].

Glass is a unique material that can be processed in numerous ways. The continuous variation of viscosity with temperature allows a number of technologies to be applied, such as casting, bending, floating, rolling, soldering, cutting and blowing, all of which have a specific working point. A controlled cooling process, called annealing, produces a non-crystalline (amorphous) material which is solid at room temperature, even though the microstructure is similar to liquids (Figure 8). The faintly green color arises from small amounts of impurities in the glass from iron and chrome oxides.

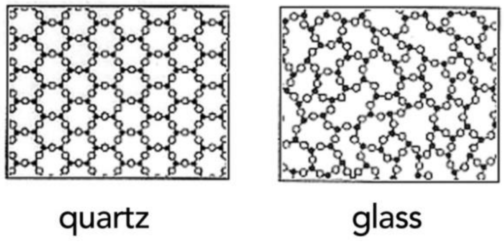

Figure 8. Molecular structure of SiO_2, crystalline structure on the left (quartz) and amorphous on the right (glass)

In architecture, the most common form of the material is glass sheets made using the float glass method that was invented in the 1950s by Sir Alastair Pilkington [14]. In addition, other glass products, such as glass blocks, glass fiber and bubble glass are used in buildings. During the float glass manufacturing process (Figure 9), molten glass, at approximately 1100 °C, is poured constantly from a furnace onto a bath of molten tin. It then floats on the tin, spreading laterally while being controlled by gravity and surface tension. The thickness is controlled by the speed of the flow at which the slowly solidifying glass ribbon is drawn through the tin bath. The continuous glass ribbon with virtually smooth glossy surface on both sides is cut after controlled cooling. Automatic cutters are used to trim the edges and to cut across the width of the moving ribbon. This creates sizes which can be handled for further processing (the most common maximum size is 3210x6000 mm with thicknesses ranging from 1 mm to 25 mm [25]).

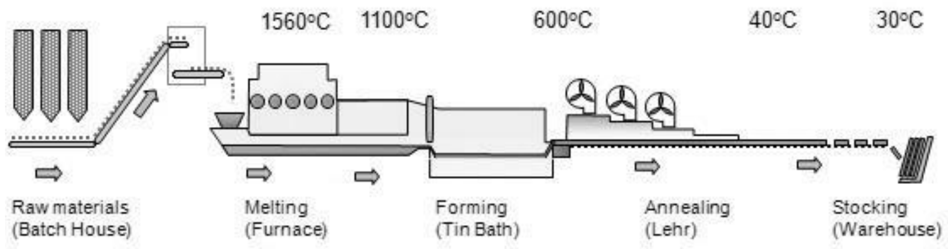

Figure 9. Float glass manufacturing process [25]

Soda-lime silicate glass has many beneficial qualities, such as relatively high hardness, compressive strength, chemical corrosion-resistance, zero water and vapour permeability and optical properties e.g. reflection, bending and transmittance of light. Fire protection properties can also be given to ordinary soda lime glass by toughening, reducing thermal expansion coefficient (by changing the glass composition) or by an additional reinforcement like a wire net [26]. However, glass failure behaviour is a complex phenomenon, despite the fact that its elastic stress-strain curve is linear (Figure 10) [11]. The high structural (theoretical) strength of glasses is without practical significance, because the strength of glass articles is determined by surface defects included by wear, such as tiny cracks (Griffith flaws), at whose tips critical stress concentrations may be induced by a mechanical load, especially if the load is applied perpendicular to the plane of the flaw [23]. Hence, failure probability instead of direct specification of failure load is often used when designing glass constructions. General properties of common glass types are presented in Table 2.

In order to reduce thermal expansion coefficient, chemical composition is changed in soda lime glass. Most common outcome is borosilicate glass, also known as Pyrex, which is used for chemical equipment in laboratories and for ovenware to sustain high temperatures without cracking. Borosilicate glass is soda lime glass with most of the lime replaced by boron trioxide (B_2O_3), providing high resistance to thermal shock [27]. It should be noted that borosilicate glass can also be successfully used in load bearing glass constructions, however, it is up to 5 times more expensive than regular, soda-lime glass. As the chemical consistence has been changed, borosilicate glass does not meet the maximum transparency condition when used in thick elements like solid glass blocks.

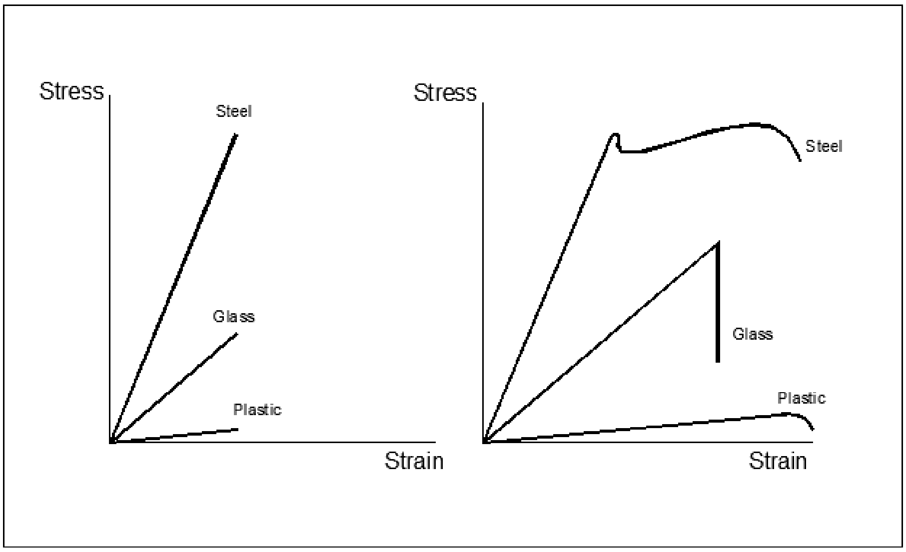

Figure 10. Stress-strain behavior of common materials

Table 2. General characteristic values of basic soda-lime and borosilicate glass according to Granta Design Limited CES EduPack 2014 [27]

Properties	Symbol	Soda-lime silicate glass	Borosilicate glass	Unit
Density	ρ	2500–2540	2200–2300	kg/m^3
Young's modulus	E	68–72	70–76	GPa
Poisson's ratio	ν	0,22 –0,24	0,19–0,21	-
Hardness – Vickers	H	439–484	83,7–92,5	Hv
Yield strength	σ_y	3600	22–32	MPa
Compressive strength (theoretical)	σ_c	360–430	264–384	MPa
Tensile strength	σ_t	31–35	22–32	MPa
Fracture toughness	K_c	0,55–0,7	0,5–0,7	MPa.m$^{1/2}$
Coefficient of thermal expansion	α	8,52–9,5	3,2–4	µstrain/C°

1.3.2 Types of Glazing

In order to provide greater resistance to thermal and mechanical stresses as well as to achieve certain break patterns for safety applications, *annealed* float glasses may be subjected to a heat-treating process. Heat-treating or toughening typically refers to the post processing of float glass products, although glass is annealed as a part of the float glass process and annealing itself is a form of heat-treatment [28]. There are two kinds of heat-treated glass, *heat-strengthened* and *fully tempered*. Furthermore, heat soaking is also used to reduce or eliminate spontaneous breakage. Heat soaking process involves exposing the toughened glass to elevated temperatures for a period of time (a typical heat soak process elevates the glass temperature to 290°C for two hours according to BS EN 14179-1) [29]. In general, the process is based on the assumption that any glass sheet with inclusions will break during the heat soak process. The term 'safety glazing' is used when reducing the risk of injury is required in buildings involving glass components. This is achieved by the characteristic break pattern of small pieces in case of toughened glass, and by the adhesion of the glass shards to the inner plastic layer in case of *laminated glass*. Different types of glazing are as follows:

<u>Annealed glass</u>

The term 'annealing' refers to the gradual cooling of manufactured glass for general purpose (incorporated into the float glass process). This type of glass is free of internal stresses that could result in breakage, influenced by such outside factors as wind or rapid thermal change [28]. Annealed glass can be cut without having any major damaging effect. Also, due to low residual stress, drilling and grinding are done on annealed glass.

<u>Heat-strengthened glass</u>

In heat strengthened glass production, glass is heated approximately 650 °C and then cooled to create compression on surface and edge. The cooling is slower and the resultant compression in the glass is lower than fully tempered glass yet higher than annealed glass. Heat strengthened glass cannot be safely cut after the heat-treating fabrication process [29].

<u>Fully tempered glass</u>

Fully tempered glass is produced in a similar fashion as heat-strengthened glass, using the same equipment for processing. It is by controlling the rate of cooling that determines whether the glass is either strengthened or tempered. In case of tempering, cooling is much more rapid, thus creating higher surface and edge compression in the glass. Fully tempered glass is designed to break into small cubical pieces and therefore qualifies as a safety glazing material rather than being a load bearing component [29]. In addition, all necessary cutting needs to be done prior the tempering process.

<u>Laminated glass</u>

Laminated glass consists of two or more layers of glass bonded together by an interlayer, typically of polyvinylbutyral (PVB). In the event of failure, thin interlayer prevents it from collapse by holding shattered glass in place. The process consists of compressing the layers and heating it in an autoclave. The translucent PVB becomes a transparent, tough material adhering to the glass surfaces and binding the pieces of glass firmly together [28]. Laminated glass is often used in security and acoustic applications.

Depending on the processing technology, glass material can achieve different characteristics. Comparative table of heat-treated glass types is presented in Appendix 1.

1.3.3 Potential of Glass

Within Europe, the production output of flat glass has shown an average annual growth in the order of 2–3 %. In 2008, the sector reached a production capacity of 12.7 million tonnes of float glass from 58 float tanks operating in the European Union. The global market for flat glass in 2009 was approximately 52 million tonnes [30]. However, demand for flat glass is particularly sensitive to economic cycles due to its high dependency on the building. Economic growth is in correlation with higher demand for flat glass, during economic downturns the flat glass sector has been hit badly.

In order to evaluate the role of glass in market, other construction materials production rates need to be compared to output of glass industry (Table 3). It is clear that from the discovery of glass thousands of years ago, glass has forgone its status of a luxury material and its production capacity in the beginning of 21st century is competing with other widespread materials. Therefore, a decline in simple float glass price can be acknowledged over the years.

Table 3. Comparative table of general characteristics of common materials [31]

Material	**Price*, EUR/kg**	**World production**, tonne/yr**	***Embodied energy, primary production*,* MJ/kg**	**Water usage**, l/kg**	***Recycle fraction *,* %**
Soda-lime glass	1,06–1,24	$80x10^6$–$82x10^6$	10,1–11,1	*6,8–20,5	22–26
Alumina	13,7–20,5	$1,19x10^6$–$1,2x10^6$	49,5–54,7	*29,4–88,1	0,5–1
Cast iron, ductile	0,42–0,46	$1,1x10^9$–$1,2x10^9$	18–22	*13–39	60–80
Brick	0,46–1,24	*$5x10^7$–$5,1x10^7$	2,2–5	*2,8–8,4	15–20
Concrete	0,03–0,05	$15x10^9$–$15,5x10^9$	1–1,3	*1,7–5,1	13–14,4
Softwood, pine	0,5–1	$9,6x10^8$–$9,7x10^8$	8,77–9,7	*500–750	8–10

* Estimated values from Granta Design Limited CES Edupack 2014 [27]

** Data according to Ashby, M.F. [31]

However, until this day, glass is not considered as a traditional load bearing material as it is relatively new in practice and has several disadvantages that need to be studied additionally. In comparison to other materials like concrete, timber, steel, plastic and brick, structural glass has proven itself as an equivalent material to bear loads, although great care should be taken when designing constructions due to brittleness and unexpected failure behaviour. Besides structural matters, depending on the complexity of a glass construction, economical issues and high price may come up as there is a lack of building codes and special design needs to be researched, tested and produced.

Along with examining chemical, mechanical and economical properties of glass, its ecological footprint and means of recycling should also be considered when introducing building materials. One possible way how to evaluate sustainability and energy consumption of a material is through the indicator of embodied energy. The embodied energy is the energy required to produce and maintain an object in use. The calculation is complex and varies in level of granularity, however, the main points of focus include primary resource extraction, transport, processing, recycling etc (Figure 11) [31]. However, sometimes the comparison of embodied energies per unit mass/volume (MJ/kg or MJ/m^3) is not proper when describing the whole building (as different construction types for carrying the designated load vary in shape and weight). Therefore, it is important to consider also the strength of a material when estimating embodied energy (materials embodied energies are graphically shown in Appendix 2).

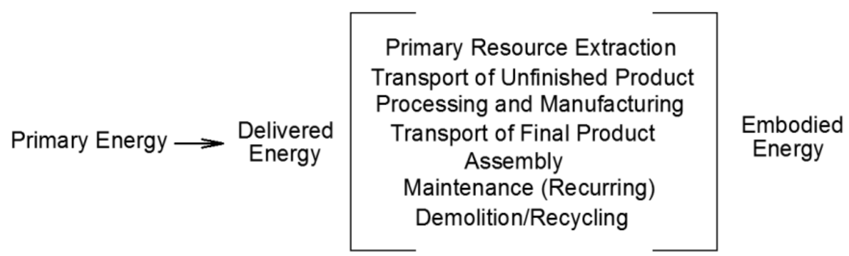

Figure 11. Breakdown of embodied energy calculations [31]

Considering the sustainability issue, key advantages of using glass as a construction material is that glass can be easily recycled, it has relatively economical manufacturing (compared to aluminum alloys for instance) and, more indirectly, due to the transparency it contributes to energy efficiency by exploiting solar energy. Nevertheless, it should be noted that glass has poor thermal performance as it is commonly used in a form of thin sheets and is not supposed to be covered with additional insulation layers in order to maintain transparency. Also, connecting glass sheets with other elements of a building is problematical due to thermal bridges.

Future energy regulations pose a real challenge in terms of glass energy performance. In practice, Insulating Glazing Units (IGU-s) instead of regular glass sheets are widely used in curtain walls and windows to contribute to energy efficiency of building envelopes. Insulating Glazing Unit consists of at least two separated panes kept along the edge by spacers that seal the cavity and are shear resistant (Figure 12). When higher thermal performance is required, triple glazing is used (most commonly in Nordic countries). The spacers are designed to provide good insulation, sound protection and to reduce small deflections. In recent years, new innovative options for windows and facades have been developed, such as Vacuum Insulating Glass (VIG), presented in Figure 12. Vacuum Insulating Glass can reach low u-values up to U_g= 0,4 W/m²K when typical Double-IGU has the same factor of U_g= 1,1 W/m²K [32].

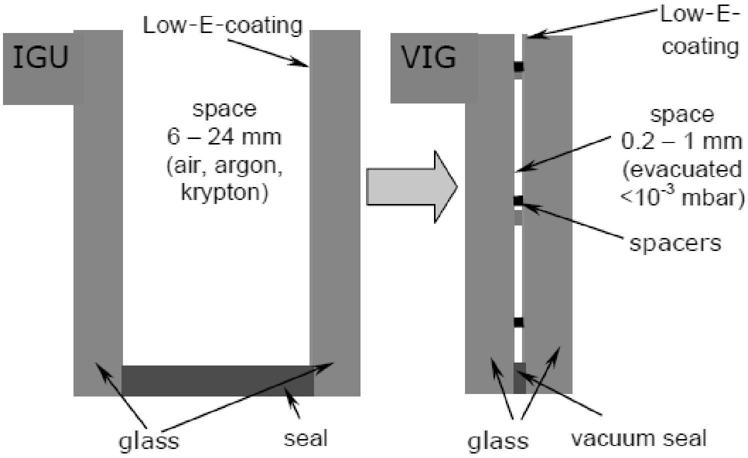

Figure 12. Comparison of VIG and IGU [32]

Glass panels can be given a unique architectural appearance with surface texture, decorative and functional coatings that can simultaneously improve energy performance or be self-cleaning. Similarly to toughened glass, chemical strengthening is possible by a surface finishing process. In this process, glass is submersed in a bath containing potassium nitrate at 300°C. By replacing ions, the surface will be in a state of compression when the core is in compensating tension. Therefore, it makes the structure stronger.

1.3.4 Structural Design and Safety of Glass

Similarly to other materials used in construction, the mechanical strength of glass can be prescribed as its resistance to loading. Despite the fact that glass is almost perfectly elastic and strong material that bears compression loads well, due to brittleness, it is vital to specify the correct type and thickness of glass for each individual application as it can still fracture without warning. Another thing to consider is situations where only the compressive load is present is rare – other factors are always acting upon simultaneously.

Just as in traditional engineering practice supported by building codes and standards, the idea of Safety Factors is used when glass elements are designed. The factor of safety is described as the ratio between the actual material strength and the maximum stress that is allowed for the structure to bear. Dealing with load bearing glass, there is no determined value regarding factor for safety. Main reasons for that are arisen unpredictable failure stresses and the lack of experience as structural glass is a relatively new engineering field. Instead, probability of failure in the case of specified designed stresses is taken into action. For example, commonly used standard ASTM E1300 for glass is not expressed in terms of safety factors, but probability of failure. Generally speaking, glass experts share the opinion that 8/1000 is acceptable for most purposes where no serious consequences follow after the possible breakage [33]. The number indicates the probability rate in which a critical surface flaw will develop into crack and result in a fracture of the glass in case of specified glass sheet geometry and uniform design load. Assigned stresses are modified for suitable type of glass and load duration. By this manner, engineers can designate the appropriate thickness of a glass for a given application.

In order to design structural glass as safe as possible, the probability of a complete failure of an element needs to be minimized. Primary solution in this case is heat-treatment or lamination. When glass is heat-treated, its strength increases, thereby, its probability of failure is lower. Using laminated glass with a supportive interlayer also makes the structure safer – in case one of the layers fails, the component is still able to carry load until safe replacement. The risk of total collapse can be avoided by achieving post-breakage ductile behavior of the structure. It has proved effective by using so-called reinforced glass beams – laminated heat-strengthened glass panes with a steel reinforcement running along the edge. In case of breaking, steel transfers the tensile forces, therefore, even if cracks develop, an element is still able to carry load [34]. Besides engineering, more simplistic methods are taken into action in architectural design process. For example, where transparent glazing may be mistaken for a doorway or path of travel it must be made visible by some form of marking. The marking may be in the form of decoration, company logos etc.

Load bearing, frameless glass can be used in many components of buildings: durable panels for facades and roofs, beams, staircases, fins, solid or hollow glass blocks and columns. Structural glass walls and roofs overcome the restrictions of ordinary steel or aluminum frames to provide the unique all glass façade. Glass panes are fastened to a support structure by different fitting options that are designed to cope with the unique requirements of the project. The purpose of fixings is to take acting forces when glass flexes under load and to provide a secure connection between the supporting structure and glass components. Most commonly, regular point fixing bolts, countersunk point fixing bolts and spider fittings made of steel are used in fastening glass panes (Figure 13).

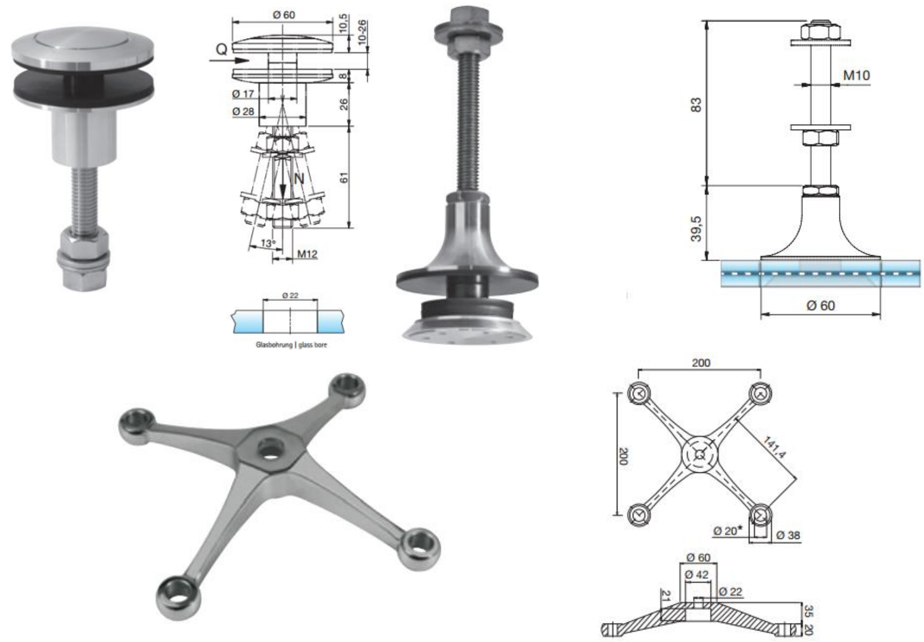

Figure 13. Sample steel fittings from Pauli + Sohn GmbH, regular point fixing bolt on the left, countersunk point fixing bolt on the right and spider fitting at the bottom [35]

Depending on the need and preferences, different supporting structures of structural facades are used. Morphological categorization of different types of frameless glass facades is presented as follows (Table 4). However, most typical solutions among engineers are glass fin, cable truss and cable net façade structures presented in Figure 14 and Figures 15 – 17.

Table 4. Morphological categorization of façade structure types [28]

Closed Systems	**Open Systems**
Unidirectional Spanning	
Strongback	Cable Truss
Glass Fin	Cable Hung
Simple Truss with cable/rod bracing without cable/rod bracing	
Mast Truss	
Multidirectional Spanning	
Space Truss/ Space Frame	Cable Net flat surface geometry anticlastic surface geometry
Grid Shell (moment resistant)	Grid Shell with Cable Bracing
Tensegrity	Hybrid Tensegrity

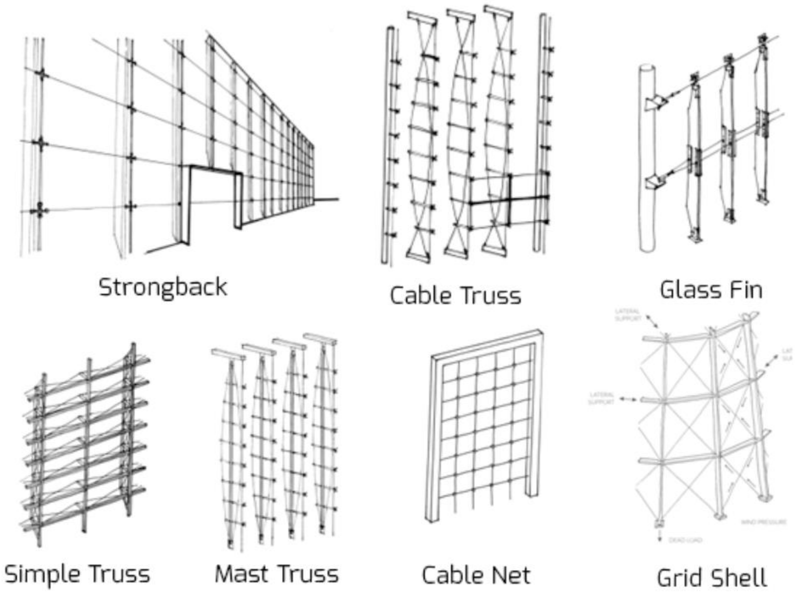

Figure 14. Common structural façade types according to M. Patterson [28]

Figure 15. Glass fin system in Tartu University College of Narva, Estonia [36]

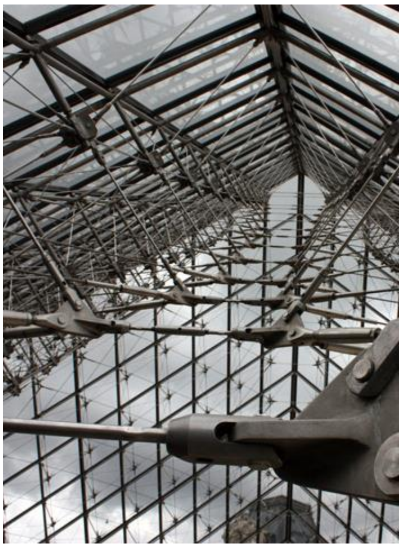

Figure 16. Cable truss system in Louvre Museum Glass Pyramid, France [37]

Figure 17. Cable net facade in Poly Plaza, Beijing, China [38]

It is necessary to carry out accurate calculations in glass design. Prevalent design principles are based on allowable stress method. However, in order to undertake structural glass design, engineers must have good knowledge of specific project and glass properties to select appropriate design methods. Often, glass elements with specified loads are additionally analyzed using Finite Element Method (FEM) software such as Mepla that is specially developed to provide as detailed estimations for glass design fidelity as possible.

Testing in laboratories has been a common practice in glass field, since overarching guides and building codes about calculating structural glass are yet absent.

Unlike other traditional building materials, Eurocode does not provide a subunit for glass design. European Normatives concerning glass design exist, however, despite being referred to as 'glass in building', they solely expand upon edge supported framed glass (such as prEN 13474 Glass in Building – Design of Glass). Similarly, the main glass standard in the United States, ASTM E1300, excludes glass with drilled holes and does not give any suggestions in case of load bearing glass. This has caused problems in design processes, such as overestimated safety factors (for example, International Building Code IBC 2407.1.1 for glass balustrades requires safety factor to be equal to 4.0) and inaccurate linking of probability of failure to the factor of safety. It can be assumed that relevant codes are being developed in committees and approaches towards structural glass design will be published in the near future. Furthermore, for example, German Standard DIN 18008 for design of glass elements, based on local technical rules like TRLV, TRAV and TRPV, have partially been published, including point fixed bearing design.

2. REPLACING MISSING PARTS OF HISTORICAL STRUCTURE WITH TRANSPARENT GLASS

2.1 Using Structural Glass in Building Restoration

Developments in the last decades have proven that glass is not only a material that fits to cover window surfaces. This transparent material that's structural properties have been researched in leading scientific centres worldwide, is ready by all means for wider innovative solutions, since qualified and proficient experts already exist and a sufficient amount of practical examples can be found. In spite of being uncommon in building preservation practices, glass can be an adequate material to find use in conservation or restoration chiefly because of its particular property – transparency. To secure a guaranteed performance of glass in protection of historic buildings, it is essential to analyze all the aspects concerning the given material's technical and aesthetical suitability with the authentic monument. In consequence, based on case study, current thesis aims to describe emerging issues and propose possible solutions with suggestions in questions of using load bearing glass as a technique in consolidation, conservation and restoration, focusing on the solid glass block masonry system and its advantages over other materials.

Beginning with the basics – the essence of restoration, is hereby important to elaborate on whether the use of structural glass is, if at all, well-grounded and essential. Also, it should further be examined if it would fall under restoration rather than conservation. The Venice Charter enacts: 'where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience' [39]. Respectively, the following can be concluded:

1. When glass (as previously researched material that complies with corresponding regulations) is used with the purpose of consolidation, it can be determined as conservation. Since conservation is, first and foremost, protecting the monument from surrounding environment's ravaging impact, if a simple glass roof is taken as an example, it would be classified under this term as it prevents precipitation from immersing into historic structure and in some cases, offer technical securing (when it is designed as stiffening element).

2. If preservation of a monument has an output of glass design solely on aesthetical purposes and some intervention is necessary for realisation, the action manifests itself rather as restoration. In this way, a part of the building, destroyed in war for example, can be restored with glass (in other words – built up once again by means of glass).

Generally speaking, as missing parts are restored often with the purpose of taking the object into use as a shelter or fully functioning building, the author finds that the usage of glass in context of historical buildings can simultaneously be determined as conservation, as well as restoration. Henceforth, for general descriptions in the current thesis, the term 'restoration' is used when referred to structural glass in architectural monuments. For example, decayed components of historic walls are re-built with glass to sense the authentic shape – load bearing glass, connected to old stone wall intends to work as a part of consolidation while also playing a role from aesthetical aspect. Furthermore, a glass roof can replace the historic roof of a monument that serves as a public building that responds to energy efficiency requirements. In this case, glass is used to conserve the walls from precipitation, however, its main idea is to modernise the environment and instead of an original cladding material, a glass structure is used.

Glass brings to present conservation and restoration practice an innovative approach – the aspect of perception. It is articulated as replacing missing parts of decayed monuments in a way that preserves its shape and form, but at the same time exposes the trace of ageing and introduces the discrete line between the old and new. Unique advantages such as natural light and solar energy also cannot be left out when talking about glass, since no other traditional material can provide it. Article 12 in the Venice Charter states that 'replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence' [39]. This disquisition supports the idea of using glass in restoration, as a discernable boundary indeed exists and glass details do not intend to falsify the monument.

Besides aesthetically significant transparency and aspect of sensing the old, glass as a restoration material can provide many extra qualities. It is favourable due to its sustainability as glass can easily be recycled by melting it up once again whereas no harmful waste matters are emitted. One of the main aspects that concerns glass, respected by current conservation principles throughout the world, is reversibility. When bonding glass elements, often modern sealants such as epoxy, silicone-based or acrylic adhesives are taken into use. Although showing good resistance to acting structural forces, they typically fail in extreme temperatures. Therefore, in theory, when a particular part of glass connection is temporarily subjected to certain level of temperature, the construction can be easily dismounted. In case of a monument, it means that in an ideal case without intervention, glass additions can be discarded from an object whereas the authenticity of the architectural heritage is maintained.

2.2 Existing Examples of Structural Glass in Historical Buildings

The concept of protecting architectural heritage has gone through a huge development throughout the years. Modern times have brought numerous ideas into practice with purpose to improve life quality of humankind. Like elsewhere, new materials have found usage in conservation and restoration and glass is perhaps one of the most upstanding examples, playing often an important role as a building material that protects and complements monuments. There has been an everlasting hesitation for the coexistence of glass constructions with historic structures due to the unsatisfied level of commanding paradoxes, cost and versatility. However, successful implementation of glass in recent years have extinguished these doubts [40]. More and more specialists in the field have used glass as a load bearing material when evolving restoration concepts and architectural projects. Outstanding examples can be found all over the world.

Victoria Memorial Museum Building in Ottawa (Figure 18), built in 1905–1912 as a part of Canadian Parliament Building development, is a proper example to describe the essence of glass in restoration of old buildings. A few years after completion, the main tower situated at the front was taken down on behalf of safety concerns as the building was built on unstable clay layers [41]. Being exploited for many decades as an incomplete building, as a result of major restoration in 2004– 2010, the glass structure was designed to take the place of the original tower. The new transparent construction offers a whole new interpretation of the past by bringing together the old and the new.

Figure 18. The rehabilitated Victoria Memorial Museum Building with new iconic hanging structural glass lantern[42]

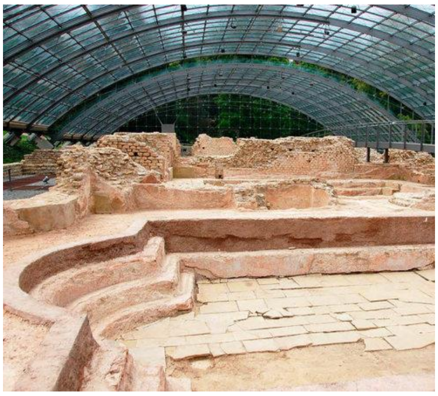

Figure 19. Roman Bath Ruins in Badenweiler, Germany [43]

Glass additions have also been welcomed in such well-known historic sites as Louvre Palace in France as a tourist entrance building and Roman Bath Ruins in Badenweiler, Germany, where glass takes the form of a large structural roof (Figure 19). The Reichstag building in Berlin, completed in 1894, today accommodates a modern glass dome that is designed as a replacement for the original dome which was destroyed in 1945 during the II World War (Figure 20) [44].

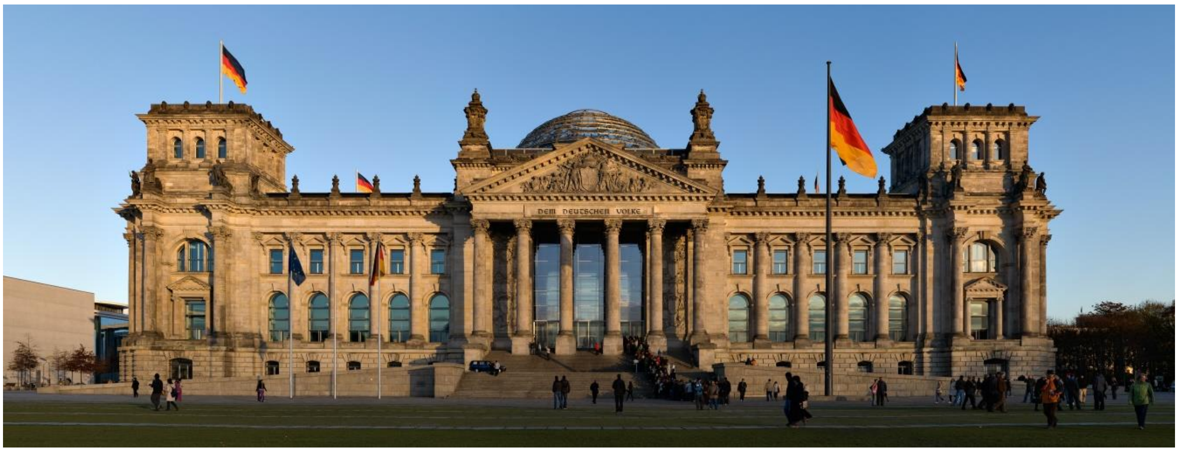

Figure 20. The Reichstag, German parliament building. The historic house is redesigned by using structural glass in façade and dome construction [45]

Another great example of structural glass being used in restoring an architectural monument is the medieval Juval Castle in South Tyrol, Italy (Figure 21). First known records of the building date back to year 1278 when the castle was built as a private residence. As the building is old, construction works for maintenance have continued throughout the years. The most prominent phase of restorations is the period from 1983, when current owner, Reinhold Messner became the owner of the castle. Since then, not only was the building restored with great care, respecting earlier phases of construction, the owner also 'filled the historic structure with new life' by introducing modern architectural details next to medieval walls. To prevent further decay of the desolate north wing, German architect Robert Danz designed a glass roof to cover the problematic area. It helps to protect old walls while the historical phases of constructions are still visible due to the use of transparent glass and the steel structure for the roof [46].

Figure 21. The Juval Castle in South Tyrol with its glass roof on the north wing [47]

In Estonia, restorations with glass structures have been relatively modest so far. It can be assumed that it is mostly due to insufficient knowledge of structural glass design, however, it cannot be excluded that innovative materials and modern tendencies are very difficult to be adapted in conservative fields such as protecting old heritage. Just as in many situations of life, the question of glass restoration always finds proponents as well as opponents. Some of the most outstanding uses of glass in Estonia include buildings such as Ajaveski Mill(Figure 22) in Harju county, where an old windmill has found a new architectural glass concept through replacing decayed walls with a framed polygonal glass façade and Fahle Building (Figure 23), 14-story apartment house in Tallinn that was originally an old cellulose factory building with walls of limestone, being extended with a glass section on top in 2006 and the main entrance of the British Embassy in Tallinn, where a point-fixed structural glass façade system is used. Furthermore, another framed glass construction can be found in the historic Estonian Traditional Music Centre building in Viljandi (Figure 24) in which the glass addition completes the old garner and is attached to existing stone wall.

Figure 22. Ajaveski in Harju County [48]

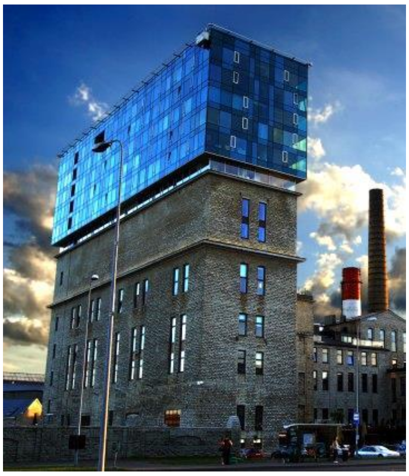

Figure 23. Fahle Building in Tallinn [49]

Figure 24. Estonian Traditional Music Centre glass extension[50]

The above-mentioned examples of glass structures in old buildings (except for British Embassy structural glass extension) are all in a form of standard glass sheets, supported to load bearing framing structures. On the other hand, when it comes to historical objects, an idea of imitating the traditional brick-laying technology is also possible by replacing missing parts of the structure with glass elements that somewhat copy the size of the original bricks used. This method can be even more preferable in restoration as the authentic building technology remains, but used material is modern.

In 2007, Greek sculptor and architect Costas Varotsos came up with permanent intervention and sculptural restoration concept of an old flourmill from the Byzantine period (Figure 25) in Geraki, Greece [51]. In this project, multiple layers of ordinary annealed float glass were used in areas of decayed wall in order to re-establish the original shape of the mill. Glass layers were attached on top of the building to correspond to the layered stone pattern (Figure 26), resulting in unique example of glass in restoration.

Figure 25. Sculptural restoration of an old flourmill using glass by C. Varotsos [51]

Figure 26. Multiple layers of float glass used to rebuild the ruined part of the mill [51]

Figure 27. Glass façade to cover the narrow crack in Maastricht, Netherlands [52]

Glass restoration has been used to replace the decayed wall as well in narrow areas, for example to form a window in a cracked area of the wall, but simultaneously fill up the surrounding envelope of the building. An example can be found in Biesland, Maastricht in Netherlands (Figure 27), where a small-scale glass façade is built behind the decayed brick masonry wall with thick window frames to imitate the historic appearance of the building.

Self-supporting glass block structures have been used previously in several architectural projects such as the Maastricht Academy of Arts in Holland (1993, design by Wiel Arets Architects), Maison Hermes in Tokyo, Japan (2001, architect Renzo Piano), the Optical Glass House in Hiroshima, Japan (2012, Hisohi Nakamura & NAP) and Atocha Memorial in Madrid, Spain (2007, Estudio FAM). Commonly, glass blocks are produced in a hollow form, whereas air gap is needed in order to provide thermal and acoustic insulation. Maison Hermes and Maastricht Academy of Arts are appropriate examples to illustrate the exploitation of transparent load bearing hollow glass blocks in buildings. The technology of hollow glass is widely known and described in building codes (for example in Estonian standard EVS-EN 1051-1:2003), on the contrary the production of solid glass blocks can be very complex. Yet, it can be successfully accomplished as Optical Glass House and the Atocha Memorial have been realized. In both cases, casted borosilicate glass blocks were used, although in Optical Glass house, blocks were connected to the steel structure by metal plates embedded into the block [53] and Atocha Memorial's structural stability was achieved by colourless adhesive as well as the geometry of the blocks and circular laying pattern [54]. The visual material regarding the examples mentioned above, are of self-supporting glass blocks, presented in Appendix 3.

2.3 Steps towards the Methodology of Restoration Using Solid Glass Blocks

At present, fully load bearing glass is rarely used in monument restoration. Most existing examples involve glass as panes that form a roof or façade construction or as hollow glass blocks, commonly being laid using thick, opaque mortar or adhesive and embedded steel sheets as supporting elements. The methodology of using transparent solid glass blocks as a masonry unit or component of glass columns that plays a complete structural role is still absent at present. Therefore, aforementioned approach is suggested to be taken into consideration as it could lead to respectful, elegant restoration or conservation that preserves the aesthetic and historic value of a monument.

Prerequisite of using load bearing glass in restoration is the technical capability of a material. This has generally been proved repeatedly in recent past by various engineers and material scientists. Also, using glass in historic structures complies well with basic conservation and restoration principles by acknowledged institutions and world-renowned charters. Glass, because of its exceptionally high compressive strength, forms an appropriate and safe choice for load bearing walls and columns. Recent developments in solid glass block element technology can make the replacement of the missing parts of a historic structure with transparent structural components considerable.

As a result of substantial study, novel solid glass block masonry system with colourless adhesive between, is expected to be completed in June, 2015 on the Crystal House in Amsterdam, designed by MVRDV and Gietermans & Van Dijk architecture firms. This is considered as the first known example of the use of self-supported solid glass blocks in commercial building. Located in the historic area in Pieter Cornelisz street, the design proposal of 10 x 12 m façade was required to meet strict planning regulations including maintaining the same organization, rhythm and composition as in surrounding buildings from 19th century. To conform limiting conditions, but at the same time suggest a transparent façade solution, the solid glass block system was designed to replace the traditional clay brick masonry. As glass design involves only ground floor, gradient transition to traditional masonry on top floor is provided with intermixing alone-standing clay bricks between the glass blocks. 3D impressions of the designed solid glass block façade for Crystal House can be seen in Appendix 4. In the research phase of the façade, numerous tests were conducted in Delft University of Technology to provide reliable data for structural engineering and therefore to comply with building codes [55].

In order to develop and propose a proven methodology that uses glass for the replacement of missing elements in damaged monument, further research and detailed analysis in specific cases need to be conducted. Additionally, problematical aspects such as bonding glass to existing surfaces, determining inner stresses of a historic structure and allowable range of intervention need to be reviewed.

Basing on the above-mentioned, the main focus of the current thesis is selected to be the complexity of connecting two dissimilar substrates to provide safe structural behaviour of the composite. A specific case of an extensive crack in the wall of Toolse order castle has been introduced as the object of study to propose an applicable sample design of the glass-stone connection with the speculative aim to replace the decayed structure of the monument with load bearing solid glass blocks. For that, an architectural concept is proposed and by following the proposed design criterions, finding a suitable adhesive and intermediaries, estimating the thermal movements as well as local forces in the glass-stone connection constitute the main programme of the current thesis.

3. CASE STUDY: TOOLSE ORDER CASTLE RUINS

3.1 Introduction

3.1.1 Location and Weather Conditions

Toolse order castle, also referred to as *Tolsburg* in German and *Торчь-Бор, Толчбор, Толщебор* or *Толшебор* in Russian [56], thought to be one of the most recent strongholds of the Livonian Order, is located in Toolse village, Lääne-Viru County, Estonia with a picturesque sight to the sea and surroundings. Built on overconsolidated Cambrian blue clay layers, the castle is situated on a narrow strip of land along the Gulf of Finland, exposed to breezes and humidity throughout four seasons (Figure 28). Therefore, Toolse encounters maritime climate that is relatively mild in spite of its northern latitude. Detailed geographical location of Toolse order castle is presented in Appendix 5.

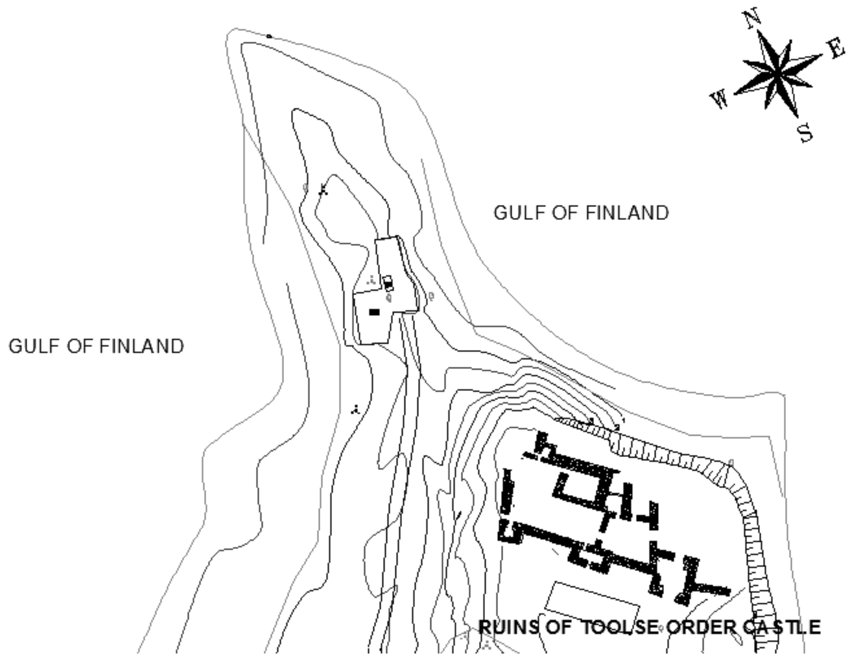

Figure 28. Situation scheme of Toolse order castle ruins

In order to analyze weather conditions affecting the stronghold, parameters of harbour city Kunda (from aerial perspective 4,5 kilometres away) are taken into consideration as the city accommodates the closest weather station. According to the weather data provided by the Estonian Environment Agency, the temperature, humidity, wind speed and precipitation curves measured in the past 10 years follow similar path every year. Relevant weather data by the EEA is presented in Table 5. It can be seen that temperatures reach peaks during the summer months of June, July, August and minimums in winter period (January, February and March). The average temperature of Kunda in the last 10 years has been +5,2°C.

Extreme minimum was measured in February 1956 and December 1978 when absolute minimum was –34,9 °C. The absolute maximum temperature has reached as high as 34,4 °C in August 2010.

Table 5. Average weather data of Kunda over the last 10 years [57]

Kunda Weather Data				
Month	Precipitation (mm)	Temperature (°C)	Wind Speed (m/s)	Humidity (%)
January	35,1	–3,3	3,4	72,3
February	21,9	–4,7	2,9	70,8
March	25,1	–1,4	3,1	67,4
April	16,2	3,7	2,8	61,5
May	47,3	8,7	2,7	61,2
June	62,9	12,1	2,6	63,1
July	49,1	15,3	2,4	63,8
August	61,4	13,9	2,6	67,0
September	49,9	10,5	2,9	68,6
October	50,0	6,0	3,3	69,8
November	47,7	2,5	3,6	72,9
December	37,9	–0,8	4,0	72,8

In coastal areas, short-term wind speed can easily reach 25 m/s. In general, it is stated that the coast of Estonia hosts approximately 20–30 days per year in which wind is considered to blow more than 15 m/s [58]. Dominating wind directions have been SW and S throughout the years [59]. According to the National Annex of Eurocode, snow load value equals 1,5 kN/m² in Toolse region, meaning that extreme rainfall conditions can also be considered present during the winter season.

From all the data introduced above it can be concluded that the following main climatic factors can pose a threat to the structural composition of the castle: wide temperature amplitude (minus degrees in winter and high temperatures during summer), blasting wind and permanent moisture with content of salt in the air due to nearby sea. Based on the above-mentioned information, a preliminary assumption is made that the high level of degradation and erosion have been affecting the structure of the ruins and their strength capacity must be evaluated lower than the currently accessible similar building materials.

3.1.2 Brief History of Toolse Order Castle

The history of building the castle of Toolse is still not thoroughly investigated, however, it is assumed to date back to 1471 when Wolthus von Herse, master of the Livonian Order organized construction works to begin. It was built on the territory owned by Wrangler family where previously existing feudal residence presumably lied. Toolse order castle is built in many stages. To be more precise, historians have ascertained at least five different phases of construction [60].

The fortified stronghold was probably oblong OW-directional building with three rectangular towers on the S side and a round-shaped turret at the NW corner (Figure 29). The oldest part is thought to be a 3-story residential tower from the 15th century located behind a massive W wall. Also the SW flanking tower, separated from the W wall through joint, belonged to this initial complex that was meant for living. Later on, extensions were added along with adjustments for firearms in different phases until the middle of the 16th century [56].

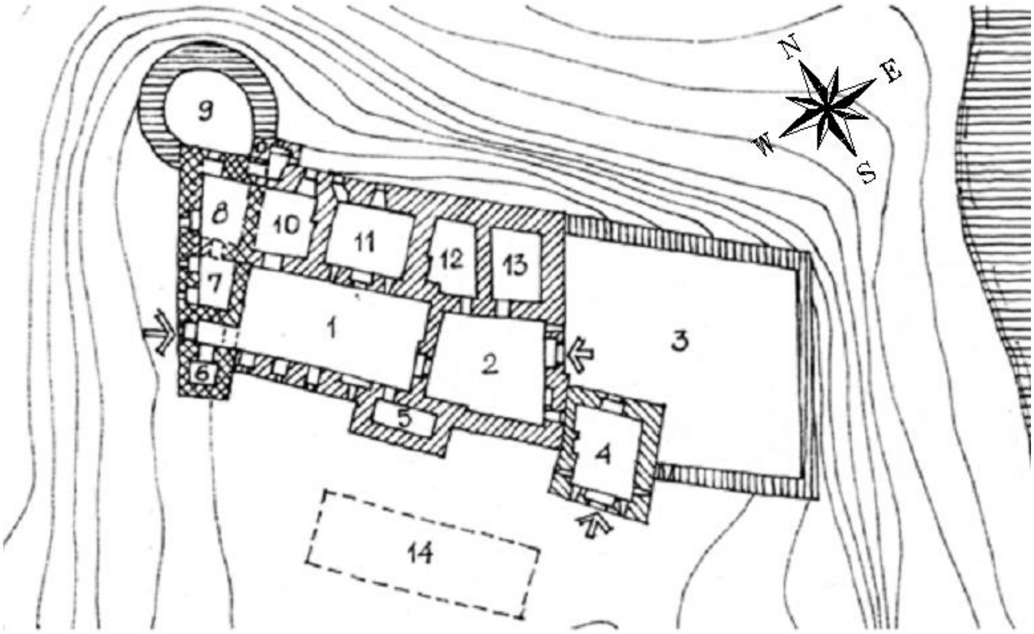

Figure 29. Ground plan of Toolse order castle by K. Aluve; 1 – courtyard from building stage II, 2 – stage II front yard, 3 – stage III forecourt, 4 – tower from stage III, 5 – tower from stage II, 6,7,8 – stage I residential quarters, 9 – bombard tower from stage V, 10,11,12,13 – stage II rooms, 14 – ruins of tavern, built later [60]

Currently, experts share the opinion that the castle was built next to harbour and trading routes in order to give greater protection against the enemies from the sea. It has been partially destroyed three times during wars and restored twice. Exact data from the last destruction of the residence is missing until this day. One of the versions suggest bombing during Russo-Swedish war (1656–1661) [56], however, unintentional collapse due to insufficient soil resistance is also feasible [61]. One is sure, in the chronicles of Karl Johann von Blomberg from 1701, Tolsburg was already mentioned as ruins of the castle [62], although it was exploited afterwards until 20th century despite the poor condition of the building [56].

As for today, the ruins of medieval Toolse order castle are taken under protection by the National Heritage Board of Estonia as a national monument. Situated in a beautiful location by the sea (Figure 30), it is often visited by tourists as the authentic walls of the castle offer divine architectural sights as well as legends of long-gone settlers.

Figure 30. Toolse order castle ruins today [63]

3.2 Pathology of the Castle. Previous Preservation and Conservation

The 500 years old ruins of Toolse castle mainly consist of massive masonry walls, about 1,3–1,5 metres in thickness, laid as a homogenous mixture of local limestone and rubble stone, whereby limestone is clearly dominating. Stones are bound to the masonry wall using lime-based mortar. The maximum height of the walls is approximately 15 metres, although it varies, depending on the construction stage. As the archaeological excavations have revealed, foundations of the stronghold are built of large scale granite stones and possible log-wall that initially surrounded the castle area leaned on a foundation made of small pebbles joined with abundant lime mortar [64]. Despite the human factor leading to decay, harsh weather conditions and exposure to the sea, causing possible erosion, walls of Toolse castle have remained in a good condition up till now. That conclusion is also verified by NHBE which states the ruins status to be satisfactory, as referred in the National Register of Cultural Monuments of Estonia after the last inspection in October, 2014 [65].

Apparently, the current fine situation of the walls is provided by frequent conservation works that started already in 1934, suggested by U. Trumm [56],when doorway of the S tower was repaired using improper cement mortar and fired clay bricks. Except for the period from II World War to 1964, the ruins of Toolse castle have been regularly inspected and to guarantee safety through compounded wall structures, local smaller scale conservation works along with archaeological excavations have been conducted up until 2014, greatly based on the elaborated conservation project from 2004 by H. Uuetoa.

Another point of consideration that could indirectly contribute to the good performance of the 500-year-old massive walls is relatively good properties of the stone and mortar. Regarding origin, the stone used in Toolse falls under Lasnamäe Construction Limestone grouping [66]. This type of limestone is considered to be relatively strong due to minimal porosity with bulk density of approximately 2660 kg/m^3 [67]. Furthermore, density of granite is considered 2550–2700 kg/m^3. According to C. Groot, an experienced specialist in mortars from Delft University of Technology, when a sample specimen of historic mortar was initially analyzed in the laboratory, it was found that besides silica sand, crushed limestone was added to the mix as a binder (author hereby directs attention to the fact that sample specimens were collected from detached parts on the object with great care and respect to maintenance of the monument). Thus, the quality of the mortar used, in terms of strength and durability, can be assumed to be clearly higher than a pure air lime mortar. Furthermore, its strength as well as composition characteristics can be taken similar to natural hydraulic lime mortars.

Nevertheless, neither the quality of historic wall structures nor amount of small scale conservation works of masonry has guaranteed the sustainability of the construction. At present, the situation is far from ideal. Walls of the monument are not under a protective roof, rainwater and wind factors that provoke erosion of the stone wall will remain. The top of the walls is not thoroughly conserved with weather persistent lime-cement mortar and plants still grow on parts of the ruins. Therefore, it cannot be eliminated that detaching pieces of stone debris could pose a threat to human life.

The true fate of the monument is highly dependant on the soils that reside under the foundations of the castle. From the geotechnical aspect, the castle of Toolse lies on relatively strong soils: gravel, sand and layers of overconsolidated Cambrian blue clay. However, exact strength characteristics of the overconsolidated clay layers depend on the water content W_n. M. Mets, one of the leading experts in geotechnical engineering in Estonia, being involved in the study of geological structure under the castle, has stated that cracks occurred in the walls straight after the completion of the building and developed ever since [61].

Overconsolidated clays are delusive. Being strong, dense and difficult to dig in ideal conditions, as soon as the moisture content increases, the strength, correspondingly, is negatively affected. Under the direct influence of seawater and weather, strength of the clay may decrease even more, mostly due to the growth of micro cracks in the structure. Hence, the strength of the decomposed upper clays, regardless of their hard consistency, does not differentiate from the strength of weak soils. The result – in case of Toolse castle, due to the inclination towards the sea (inclination 1:5), the W and N walls have been creeping horizontally since geotechnical analysis from 1989 shows that occurring shear stresses in the soil,

$\tau = 25 - 30\ kPa$ is higher than the creep limit $C_{uy} = 20\ kPa$, but smaller than maximum shear strength C_{uf} of the upper layer of Cambrian clay [61]. Positioning of weather-affected overconsolidated clay layers and their properties are presented in Table 6 and on Figure 31.

Table 6. Geotechnical parameters of the soils in Toolse according to M.Mets [61]

Nr.	Soil layer	W_n, %	C_{uy}, kPa	C_{uf}, kPa
1	Fill			
2	Sand and gravel			
3	Cambrian clay layer 1 (0 – 1,0m)	29 –31	20	40
4	Cambrian clay layer 2 (1 – 3,0m)	24 – 25	30	55
5	Cambrian clay layer 3 (over 3,0m)	20 – 21	40	70

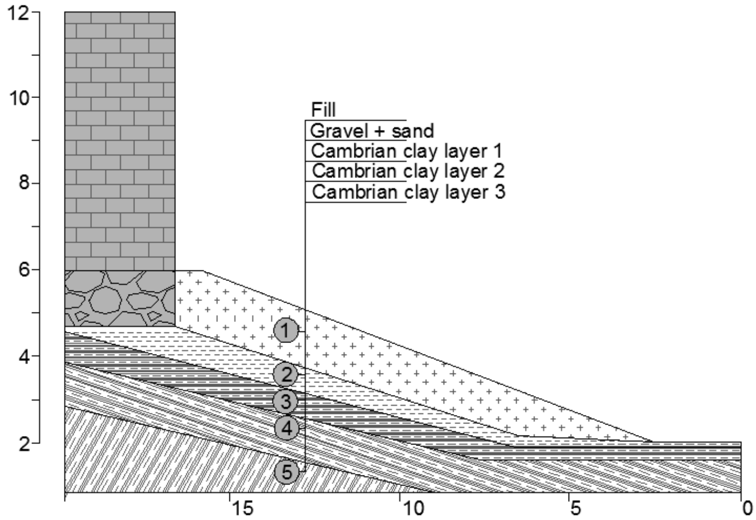

Figure 31. Geological section of Toolse castle [61]

As mentioned above, soil movements have affected W and N walls most of all and tilting of the ruins is visible. Furthermore, the SW tower is torn into two and a wide crack, approximately 0,3–1,0m wide, separates the western side of the tower from the eastern side (Figure 32).

Figure 32. Extensive crack in the SW tower. Location of the tower

Consequently, solutions for the arisen situation have been proposed by experts in the field. In 1936, the first two steel anchors were installed to problematic SW tower that had been drifting apart for many years. As they did not eliminate the issue of increasing crack in the tower, another 3 tension rods were added crosswise to the same tower in 2008 to support the walls and prevent them from collapsing (Figure 33).

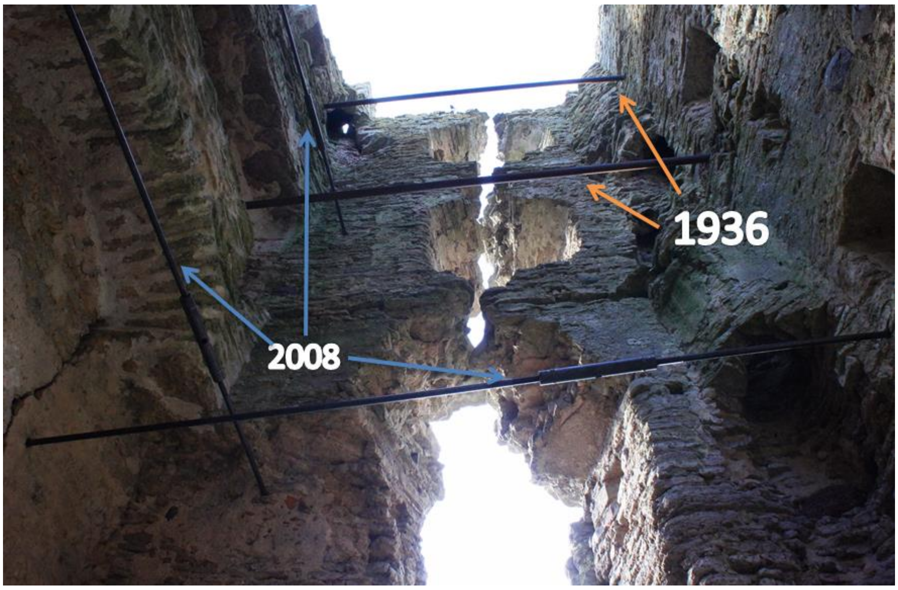

Figure 33. Steel anchors mounted into the SW tower to stabilize the wall movement

What concerns W and N wall, conservation project from 1992 by H.Uuetoa in collaboration with M.Mets [68] clearly suggests three steps in order to stop the crucial degradation process of the monument:

- Mounting tension rods (4 to W wall, 2 to N wall) with concrete slabs or pile foundations in the ground of courtyard of the monument;
- Placing the fill of extra soil as counterbalance (at least 1200 m^3) against the main direction of soil movement;
- Construction of the drainage system further away to reduce water content in the gravel and sand.

According to U. Trumm [56], in 1999 the tension rods were fixed to the W and N walls. However, it was the only measure out of three taken into action. The drainage system and filling soil have never been realised as a result of lacking financial funds. Furthermore, no additional studies have been performed to evaluate the effectiveness of steel rods in stabilizing the structure. Therefore, it is suggested by the author that before any aboveground big-scale preservation activity could take place, the movement of the walls should be examined and stability of the structure secured.

3.3 The Concept of Restoration by Using Solid Glass Blocks

3.3.1 Main Points of Focus

The current case study focuses on hypothetical restoration of the SW tower of Toolse order castle ruins with a transparent, adhesively bonded soda-lime or borosilicate glass block masonry system. As the stronghold is an architectural monument and under the protection of the National Heritage Board of Estonia, all hypothetical construction work is planned with respect to widely acknowledged preservation principles and the best current practices. Henceforth, the proposed design project is referred as restoration rather than conservation, since the scope of work comprises of replacing missing parts of a historic wall with monolithic glass blocks that differ from the authentic material – natural stone. However, the proposed glass reconstruction is expected to work also as a structural element since it works as a rigid masonry unit that connects two separate parts of stone wall and prevents the stone wall from further decay due to the exposure to weather. The nature of the concept is limited with following key figures:

1. Proposed glass design is fully speculative. Thus, no real actions towards the construction are planned. Toolse order castle as the object under observation was decided upon due to exceptional suitability for research as the criterions like the status of the national monument, historic stone wall with decayed parts and high exposure to weather were satisfied.

2. As emphasized previously, a glass restoration proposal can become possible only if detailed expertise of structural stability in walls and soils is done prior to it. To analyze the geotechnical situation, modern computer software such as PLAXIS can be recommended. If it turns out to be necessary, additional measures like a drainage system, counterbalancing soil fill, strengthening of foundations or similar need to be considered. When any of these mentioned would happen, archaeological excavations are important to be carried out.

3. Aspect of diversity in used restoration or conservation measures should be looked at. Since the monument serves as a whole and decorously represents the national heritage, partial supplementary construction works that use different materials and technologies – therefore disunify the complex, cannot be agreed on from a professional point of view. The restoration concept should follow a continuous line in its style to form a compound. Therefore, redundant local fixings out of wood, steel, improper stone and glass need to be avoided.

4. The glass restoration concept in frames of this current study involves mainly the SW tower and indirectly the top part of the W wall. The cause of this adap-

tation is the continuous crack throughout the height that is convenient in terms of magnitude and necessity to protecting the exposed stone surfaces. The bottom area, the footing (up to 760 mm from the ground) of the tower is assumed to be conserved and laid up using traditional rubble stone (granite) and mortar similar to the authentic mortar type. Also, the top part of the W wall is partly counted in as a secondary phase of the restoration concept as it mostly adds only architectural value to the monument. Thus, although considered to be essential, the granite stone footing and glass blocks on top of the W wall receive somewhat less attention.

5. Load bearing glass can be designed in many forms such as hollow or solid blocks, laminated panels, fins, working as single structural elements or cladding systems, also uniquely shaped cast moulding. In the current case, the output of structural glass is selected to be solid glass blocks and further consideration of the glass is referred to the form of load bearing solid block units, if not mentioned differently. The sample design proposal aims to re-lay the crack area with adhesively bonded solid glass blocks that have similar measurements and thermal behaviour alike the historic stones in the rest of the tower wall. This type of approach was opted to retain the most similar forms of historically used material with respect to authenticity of the monument and traditional building manners.

6. Low-iron soda-lime glass is preferred in production of blocks to refill the masonry. The determinative advantages of soda-lime glass over the borosilicate are lower price and bigger transparency, although the final solution of the glass type in the restoration concept is determined by the analysis of the thermal movements.

7. The main objective and anticipated end result of the case study is an elegant glass restoration proposal using self-supporting solid glass blocks and designing an effective connection between the glass masonry and historic stone wall. The preliminary design process is to a great extent driven by minimal total cost of the potential project as well as transparency and aesthetic impression. The outcome is an extremely unique type of monument restoration that would serve as a popular tourist attraction or subject of discussions in architectural communities. Furthermore, it could be used as an existing example in the future methodology of solid glass block restoration in order to realise similar projects around the world.

Taking into account all the moments submitted above, the technology of adhesively bonded solid glass block masonry, selection of the proper bonding element and design of the connection between historic stone wall and monolithic glass block masonry system is henceforth taken as priority, since it holds the definitive significance of the restoration proposal's feasibility.

3.3.2 Arising Challenges

Besides problematic soil situation, other challenges appear that need to be reviewed before proposing an appropriate design for re-laying the extensive crack area with glass. The most critical aspects to consider include:

1. Unknown strength properties and structure of the historic stone wall that mainly consists of limestone and granite stones, assumingly bonded with hydraulic lime mortar. Without laboratory analysis or further testing it is difficult to evaluate the quality of laying technology, existence of dilation joints and strength of the masonry as no codes are targeted for old structures. It should be noted that Eurocode 6, commonly used as a design guide for masonry constructions, is directed merely to designing new constructions. In case of a historic masonry, only indirect assessments and conjectural calculations can be done and often the evaluations are based on the experience of engineers.

2. Glass is a brittle material and its failure behaviour is difficult to predict. Thus, it expects extra caution in the mounting process to avoid micro cracks in the structure that could later on lead to loss of bearing capacity. Other problematical aspects that come along with the use of glass are vandalism and unexpected point loads (bird action, windstorms to cause object impact), thermal shock behaviour and non-resistance to strong alkalines (pH of 13-14).

3. Without previous large-scale testing, precise estimation of the behaviour of the connections between stone and glass is unlikely to be achieved, although attempts towards it can be done as thermal expansion and other general characteristics of materials are known. However, it is impossible to predict climate conditions and their influence as well as ageing of specific adhesives since it is a fast developing field in material science and it is yet unknown for how long the developed glues can last.

4. The glass part on top of the tower might pose a threat to the W wall as heavy counterbalancing from the SW tower may cause a rupture in the large wall surface (in the area of axis I in Drawing 1, Appendix 8), since occurring tension and movements caused by creeping soils as well as shear strength of the authentic masonry are unknown.

5. The economic issue can be posed. Due to innovative characteristics, using solid glass blocks to reconstruct the masonry wall is far not the most cost-efficient method. At present, limited glass manufactories in Europe have the experience

of producing solid glass blocks that meet the required quality and tolerances. Thus, transport expenses would be reflected in the total cost. Also, to avoid the introduction of residual stresses, the production of soda-lime glass blocks is very slow (it takes 3-4 days for one 10 kg glass block that meets tolerances in measurements to become ready for construction) and requires special equipment. Similarly problematical is the possible usage of traditional and natural hydraulic lime mortars in monuments – technically they have been proven to fit with the old structures, but their price can be up to 10 times more expensive than industrial mortars, since the production process is not mechanised. Additionally, using modern adhesives and laying the glass blocks are considered as handicraft and successful results cannot be achieved through low budget strategies.

6. Another concern is the attitude of the public towards this type of restoration, as it is, beyond doubt, exceptional. At this moment it is difficult to predict if wider interest in the glass restoration technology is guaranteed to continue the research and look for the most cost-efficient but high-quality solutions.

3.3.3 Technology of Glass Block Masonry System

The prerequisite in the case study was to find architecturally exclusive and transparent, but simultaneously a structurally feasible solution that could be used in historic monuments. As soda-lime solid glass blocks were already researched in TU Delft (by Research Group of Structural Mechanics in the Department of Structures, the Faculty of Architecture and the Built Environment) and found that the blocks a have sufficient resistance to occurring stresses and other harmful influences such as extreme temperature fluctuation, impact loads and chemical contact, particular type of structural glass is preferred first of all due to lower price and higher transparency as well as higher compressive and tensile strength than borosilicate glass. Despite the preferences, structural design designates the final type of the chosen blocks since both of the glass blocks can be estimated to work similarly. Evolved technology and scientific data of the glass block masonry system, researched in TU Delft by F. Oikonomopoulou, T.Bristogianni, F.Veer, R.Nijsse and K.Baardolf is taken as the basis of current case study of the glass restoration concept. Assumptions as well as suggestions are made, considering outcomes of the thorough study of the glass blocks by the above-mentioned research group.

Innovative, custom-made solid glass blocks that were used in the Crystal House in Amsterdam (see paragraph 2.3) are produced by POESIA® Company in Italy. As manufacturing requires special technology and equipment, this factory is also a possible provider for glass blocks required in Toolse glass restoration project due to their experience that competing companies do not have yet, although technically it is possible to produce solid glass blocks in Estonia as well.

In the process, monolithic, low-iron glass blocks are manually cast in specially designed precision moulds coated with nickel in order to produce components with smooth surfaces and to remove elements out of the mould more easily. Viscous glass, melted at approximately 1200 °C is shed into steel moulds and left to naturally cool down as far as 700 °C. During the process, the convex surface appears on top of the block due to gravity. Following, the element in 700 °C is removed from the mould and placed to the oven as a controlled process to slowly cool it down to room temperature. This process, lasting from 8 to 36 hours depending on the block size, avoids thermal cracking and internal residual stresses. Then, the fabricated block is placed in a CNC machine that removes the slope on the top and processes the element to a required precise height. Lastly, horizontal faces of the blocks are polished to smooth flat surface (Figure 34) [55].

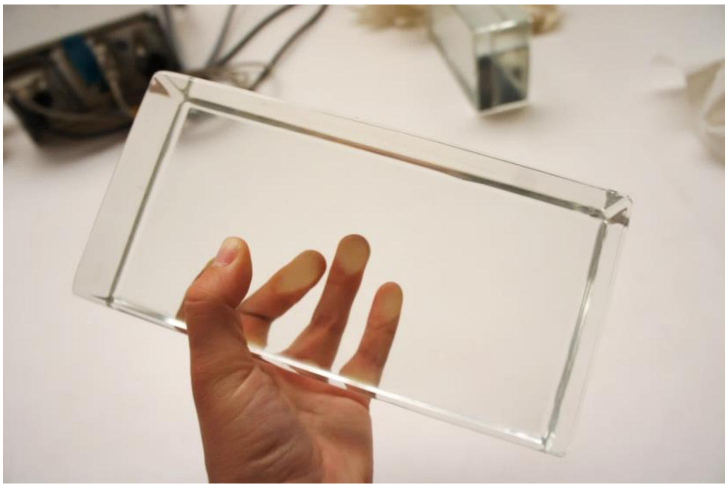

Figure 34. Low-iron completely transparent soda-lime glass block

In order to qualify as an appropriate construction material, correspondence to strict tolerances, ±0,25 mm is required in size, rectangularity and flatness. Compared to borosilicate glass, soda-lime glass blocks have significantly more shrinkage on cooling and therefore they need post-processing to attain dimensional accuracy. In this, the blocks are controllably and slowly cooled in order to limit defects such as slopes and air bubbles in the viscous molten glass, although elevated risk for defects is always present as cast objects have considerably larger thickness in comparison of float-glass production. Furthermore, the strength is also expected to be somewhat less than standard values (see Table 2) of soda-lime glass.

To form a masonry unit from glass blocks (Figure 35), colourless adhesive is desirable to obtain maximal transparency. At the same time the bonding material must provide structural performance and durability in time so that the glass block system could safely work as a single rigid unit when exposed to loads and climate

factors. Since opaque supporting structures such as steel reinforcements will affect transparency, in case of large-scale slender structures, the adhesive and the geometry of the structure must guarantee the resistance to lateral loads and buckling. Only by this, a transparent self-supporting glass block unit can be realised. It is critical that the bonding substrate would similarly meet all the required mechanical properties as the glass blocks, because their interaction as one structural unit defines the performance of the entire system.

Figure 35. Glass block masonry system with transparent adhesive on horizontal surfaces and sealings on edge joints.

Based on the study of glass research group in TU Delft, photocatalytically cured transparent one-component acrylate (specific products Delo Photobond 4497 and 4468 were used in experiments) meets all the requirements concerning suitability for glass-glass connection: necessary strength (tensile strength according to producer circa 14 MPa), water resistance, resistance to ageing, suitable and safe application procedure (to provide maximum strength, optimal layer thickness of 0,1 – 0,3 mm is prescribed by the producer). Strict tolerances are required both from the adhesive and glass blocks – the biggest difference between the acrylate adhesive and a traditional mortar is that latter can allow for variations in brick dimensions, while thin layer of adhesive cannot. Due to viscosity issues, the vertical joints of the blocks are impossible to be homogenously bonded, therefore, the monolithic structure is formed only via horizontal connection surfaces (Figure 36). To add extra resistance in time, vertical and horizontal joints are additionally sealed with UV-curing colourless sealant) [55].

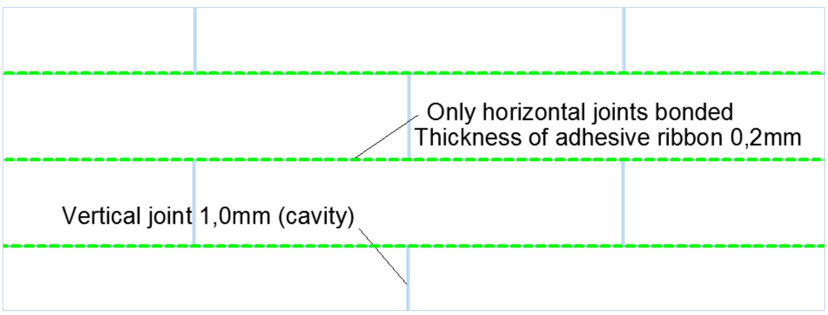

Figure 36. Structure of the glass block masonry system

Various tests have been conducted to determine the strength characteristics of the blocks and the glass masonry structure. Experiments have proven that glass block masonry works as monolithic structure. Single glass blocks have compressive stress capacity minimal from 20 MPa up to 135 MPa or more depending on the base surface (respectively, higher strength was achieved when a soft base – wood was used; exact capacity unknown due to limits of hydraulic compression machinery). Custom made columns made of glass blocks and acrylate adhesive show average failure stresses in compression ranging from 50–114 MPa. Four-point bending strength of the masonry wall specimens with horizontal adhesive surfaces (similar to the measurements and laying technology of proposed block system in case of Toolse) reach up to 9 MPa. Glass masonry system with cavities in vertical joints has been analyzed in FEM modeling software as well. Results show that even in case of relatively large masonry wall working as monolithic plate (0,65x0,65x0,21 m), internal stresses near supports do not exceed critical stresses that the glass and adhesive can take. Also, good behaviour in vandalism and thermal shock tests has been demonstrated. Furthermore, it can be concluded that glass block system with specified adhesive technique can work efficiently under regular structural loads from buildings, although strict tolerances and proper bonding play a critical role. Also, the replacement of the single block in the system has been studied and it is claimed possible by local heating with a hot air blower above 120 °C.

3.3.4 Architectural Design

A fully transparent load bearing glass block masonry system is proposed in restoration project of Toolse order castle ruins to reconstruct a wide existing crack in the SW tower. Glass construction involves monolithic transparent blocks that are bonded with strong colourless adhesive. The desirable outcome in current case is a system that works structurally without any support by opaque substructure and effectively performs as a wall unit, connected with the existing limestone and granite masonry to unite the tower that historically compounded a whole but now is decaying. The design solution of the glass-stone bonding is expected to be aesthetically pleasing, structurally safe and durable through time. Architectural drawings (Drawings 1–4) of the proposed design for restoration are presented in Appendix 8.

Typical measurements for authentic limestone blocks used in stronghold walls are as follows: height 40–50 mm, length 23–25 mm, width (depth) 30–35 mm. To follow the same style in restoration, it is important to use similar measurements as well in glass blocks. Respectively, the main basic dimensions of glass blocks for Toolse castle are designed to be 250x50x300 mm and 230x50x300 mm. However, as the crack of the SW tower varies from 161 mm up to 1364 mm and intervention to the old structure must be minimal, assisting blocks with secondary measurements

120x50x300 mm and 80x50x300 mm are assigned to the design proposal in order to help fitting the glass elements to various crack lengths. The necessity of different glass block types is defined by thermal expansion of the materials. More detailed argumentation of the selected block dimensions with analysis of thermal behaviour of the structure is presented in section 4.2.

Blocks need to be joined into the masonry through bonding element. Besides glass-glass bonding technology described in previous section, there are two other connections that need to be reviewed: vertical glass-stone connection and horizontal glass-stone connection. Connecting glass to stone, the bonding can be opaque as it will not be clearly visible, however, natural tones are expected. Also, mechanical properties of the glues are important when choosing the right type of bonding element, since it is the combination and interaction of blocks and adhesive that defines the structural performance of the system. Specifically in current case study, taking into account the climate conditions, in addition to being environmentally friendly and safe for the applier, adhesives and sealants are required to meet following criterions:

- UV resistance;
- resistance to salt and constant moisture;
- temperature tolerances from –35°C to +35°C;
- durable through time;
- resistance to shear and tensile stresses;
- flexible behaviour to allow thermal movements;
- suitable curing time in construction situation;
- proper viscosity to enable accurate application.

An important difference between adhesive system and mortars in stone masonry is that mortar can compensate for small deviations in brick dimensions while adhesives cannot. Therefore, when the right glue is decided upon, its recommended thickness should be followed to provide optimum strength of the material. Also, the application procedure of adhesives and sealants must comply with guidelines from producers. More detailed analysis and selection of suitable adhesives to connect glass surfaces with stone is presented in section 3.4.1.

The solid glass block masonry system is designed to fill the crack area in SW tower of Toolse castle in depth of one block layer (300 mm; see sections in Drawing 3, Appendix 8). The range of reconstruction also involves historic windows/loopholes to be left open as they were historically. As a result of wide analysis of photo materials and archive files, it can be assumed that 4 authentic windows in the tower were with dimensions approximately 530x770 mm similarly to the extant window in the W wall. Therefore, 4 holes with measurement mentioned above are included in the design proposal.

All glass surfaces that are exposed to rain (inner and outer vertical surfaces, window sills and cheeks) must be covered with a self-cleaning surface layer to keep the glass free of dirt and grime to maintain the transparency. Self-cleaning coatings are offered in wide range by numerous producers, however the main idea remains the same – to allow glass to clean itself through the action of water either by rolling droplets (hydrophobic coatings) or by sheeting water that carries away dirt and chemically breaking down absorbed dirt in sunlight (titanium oxide based hydrophilic surface coatings). Additionally, bottom sills of windows are designed with an outwards inclination to avoid stagnant water congregation that could freeze and thereby pose a threat to glass microstructure and possibly cause cracks in the blocks. Therefore, the bottom rows of windows will be laid using special shaped glass blocks that have the height of 70 mm inside and 50 mm outside (Figure 37).

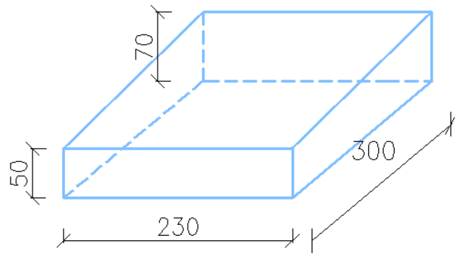

Figure 37. Special shaped glass blocks with inclined top surface for windows

Besides structural glass reconstruction in crack area, an idea of restoring the shape of the original tower is suggested in order to serve an architectural aspect and to present historical proportions for the viewer. Currently, up to 2 metres in height has been decayed as a result of weathering from the top of the W wall and SW tower. The exact appearance of the top extension cannot hereby be determined as it is not clear, until this day, if the edges of the tower were cogged or not. In preliminary drawings (Figure A in Drawing 1, Appendix 8), top edge of the glass construction has been left straight. In order to design structurally working glass block walls to replace the decayed walls on top of the tower, buttresses need to be considered to take lateral loads on top of the tower. However, the calculation and stability check of the upper part is not in the scope of the current restoration concept and it needs to be reviewed additionally. Similarly, possible shear stresses in the W wall caused by self-weight from the glass on top need to be evaluated additionally.

A granite masonry footing with suitable mortar, about 0,8 m high is designed to be restored in the footing of the SW tower. Traditional stone is selected in this region due to structural and aesthetical matters, since the footing is a very important part of the tower and maximal suitability with the existing walls is essential. Therefore, evaluation of the compressive strength and stresses in the stone masonry are excluded from the current restoration project as the main focus falls solely on glass restoration. However, the top surface of the granite footing as the contact region for the glass masonry is designed to be processed even with natural hydraulic lime in optimum thickness of 15–30 mm. This type of mortar is considered suitable for historic structures as well as flexible and strong enough to encounter possible compressive stresses from the glass above, therefore it is suggested to be used throughout the full scope of the glass-stone connection design.

Glass and stone have different thermal behaviours and probable vertical movements along with imperfections in laying tolerances can be compromised via designed dilation joints. The frequency and height of the joints are determined by the upper edge of the 4 windows designed to the glass unit, since it is aesthetically and technologically the best location to separate glass structure and therefore avoid critical deformations. 5 sections of the glass block masonry system lean on historic walls and each segment is laid on prefabricated vertically glued lintel that forms a bottom part of the section and matches with the historical brick laying technology on top of the windows. In order to create the support surface for parts of the formed sections, possible hollows need to be cut at some parts of the existing masonry walls, although minimal intervention must be taken as an objective. As dilation joints do not conduct loads, instead of adhesives, commonly used flexible window and façade sealants can be used to seal the joint and therefore, prevent water to enter the narrow joint strips. To maintain transparency, colourless sealant must be used.

Regarding construction technology, following measures must be taken into consideration:

- Sealants and adhesives have a fixed working temperature range and time for drying. When using such materials, producer's guidelines must be strictly followed.
- Appropriate transmission of forces in glass structure must be provided. As dilation joints cannot take any stresses from above, each segment must be built separately. Therefore, glass lintels/bottom rows of glass block masonry should be prefabricated and then mounted to the even horizontal surface to work as one piece, followed by regular masonry laying technology.
- All horizontal natural stone surfaces must be cleaned and polished to provide even surface area in bonding glass structure to the stone. Before construction, detached pieces of stones and old redundant mortar must be removed and edge surfaces cleaned. When polishing particular regions of the surface manually or with special milling cutter, extra care should be taken to leave rest of the historic structure untouched.
- Thin elastic layer of traditional lime mortar suitable for monuments is used to even the surface, fill the gaps and minimise possible micro cracks in the glass structure that can be caused by hard and uneven stone surface or juts. Howev-

er, it should be noted that the shape of the layer between the glass and natural stone is complex and partial compressive loads in the form of glass structure's self-weight may be affecting the mortar. Thus, lime mortar with good strength characteristics must be selected.

- In special areas where the stone wall surface is extremely uneven and include hollows or juts, natural stone is used to replace it and therefore reduce the size of the crack in order to create proper row width and more straight stone surfaces.

The order of the construction is as follows (after the bottom granite footing construction is complete and intermediary mortar layer applied and let to dry): removal of detached parts of historic wall, careful cleaning, polishing and carving horizontal stone surfaces and where rigid connection is designed, applying first layer of lime mortar to smooth the rough edges of the crack and simultaneously replacing natural stone units where necessary, cleaning the glass surfaces, laying glass blocks to required height (each row will be connected to stone from the edges through injected lime mortar/ fixing adhesive), partial prefabrication of glass lintels, mounting glass lintels and proceeding with masonry laying technology until the top, preparing (cleaning from loose stone and mortar and plants, polishing) top surfaces of the tower and finally laying glass masonry with buttresses (phase 2).

3.4 Methodology and Testing

3.4.1 Design Principles

The fundamental idea of the glass-stone connection design is taken under review in terms of structural stability. Preliminary estimation of the feasibility to use glass block masonry in the SW tower of Toolse castle has been taken as main consideration, focusing indirectly on the Ultimate Limit State by observing only the most critical – load from material's self-weight. Therefore, within the scope of current design proposal, no wind or snow action as well as impact and seismic loads etc. have been examined. Also, possibly existing harmful influence from tension stresses in the soil has been abandoned in order to find out the principal load distribution pattern from dead weight of the glass structure on historic natural stone walls, since the design complying with criterions of the ULS is essential to guarantee structural safety. For that, simplified 2D FEM model has been created, using special modeling software (see section 4.3).

The crack in the tower will be re-laid and filled with glass blocks that in principle hold the same magnitude with limestone masonry in terms of density. This can be taken as an advantage, because when designing a structure, using materials with similar characteristics is always preferred. It is known that Lasnamäe type limestone that was used in Toolse walls has the density of 2660 kg/m³ [67], soda-lime glass respectively 2500 kg/m³ and borosilicate glass 2300 kg/m³ [27]. Natural stone masonry with lime mortar is estimated to be as dense as 2250 kg/m³, since circa 20 mm thick mortar joints compose a structure consisting 60% limestone and 40% lime mortar with an average density of 1800 kg/m³ and some loss in stone density can be counted in due to the age of the walls. The estimated density of the limestone masonry fits best with borosilicate glass' density. Also, their thermal expansion behaviour is similar, therefore, it can be concluded that this combination of materials will be used to fill the crack area. However, it should be noted that in areas where granite stones are used (lower third of the tower, see Figure B, Drawing1 in Appendix 8), soda-lime glass blocks give better results as they are considered more similar to granite stone structure. As a result, skillful assembling of the right type of the glass in different areas is expected. More detailed analysis of the thermal expansion behaviour and sample selection of the blocks to form a row is discussed in section 4.2.

The glass masonry system in the crack area, in case of only soda-lime glass blocks with higher density compared to borosilicate, weighs about 11,47 tonnes or 112,5 kN according to FEM model data, although it is divided into 5 segments, each weighing about 10 kN and the topmost part is about 70 kN. The load is distributed on stone structure by following very complex pattern, since the historic wall has been cracking naturally and has left the edges rough. In an ideal case, glass blocks would be connected to the stone structure only from sides using strong adhesive so that the connection could carry the load of the whole glass masonry system. However, as it is unthinkable for stone wall to take dead loads from glass despite of the surface alignment, some intervention to the historic structure needs to be done to provide even, horizontal connection surfaces where bonding adhesive takes horizontal component of the self-weight load and works therefore to the shear. Current design proposes small horizontal support areas to be cut in in pace of p = 250 mm or every 5th glass block row on both sides. Vertical loads are generally taken by the strong stone masonry (also the adhesive will be under compression in this case), although specific calculation to estimate the local strength of the historic wall is counted out from the current case study. At some regions (such as the area around axis 2 and F in Drawing 2, Appendix 8), as the surface of the existing masonry is very uneven, stone juts are currently threatened by collapsing due to critical bending moments, glass block system could offer a support and therefore balance the inner stresses in old stone wall. Drawing 4 in Appendix 8 describes the design of the connections between glass and stone.

Critical bonding surface area is dependant on acting loads at specific connection, therefore, the depth of the hollows that need to be cut into the historic structure is determined by the stress values in the region (derivable from FEM model). By default, the model was created taking into account that the glass surface is supported on the stone structure in 20 mm of width.

Due to building technology, hollows for lintels must be cut into a depth that when mounting the glass element, the geometry of the stone wall should not interfere with the process (estimated reserve value for both in vertical and horizontal directions is 40 mm). Minimal support area width in case of lintels is taken similarly 20 mm, although the final area depends on the lintel design.

Besides horizontal and vertical load components from dead load of the glass that in connection areas do not exceed respectively $F_x = 0{,}82\ kN$ and $F_z = -1{,}69\ kN$ in most critical regions in the crack area, thermal movement poses a threat to the glass-stone contact surface by causing shear stresses when the structure moves vertically and tensile or compressive stresses when horizontal movements occur. It should be noted that hydraulic lime mortar is not expected to carry loads (although some stresses at minimum level may still encounter) and is primarily designed as an elastic intermediary between hard stone and glass to balance thermal movements of both of the materials and make the connection air-tight.

What concerns internal stresses in the glass masonry, its behaviour can be estimated more similar to the point supported rigid plate than a beam, since normal stresses do not develop in straight line and neutral axes move close to the bottom. Also, probable loss of bearing participation in the upper part of the structure occurs. However, due to the complex shape and numerous supports in the edges, the exact internal stress distribution is unknown and must be subjected to further analysis. As the glass masonry has no vertical adhesion surfaces, partly prefabricated lintels with vertically bonded glass blocks are designed take potentially evolving tensile stresses at the bottom of the segmented glass structure.

In the selection process of the adhesives, weather and age resistance as well as the best possible adhesion and cohesion to stone and glass was expected. Most commonly in glass constructions, silicone, polyurethane, epoxy and acrylic based adhesives are used. Since the variety of adhesive materials is wide, only two of the most suitable bonding substrates for current case study were examined and taken as the subject of experiments – epoxy and MS polymer (polyurethane) based glues. Epoxy glues have very high strength (evaluated up to 30 MPa to shear stresses [69]) and excellent performance under harsh weather conditions as well they have already been proven to be long-lasting in time. However, epoxy is very rigid and allows elongation only about 10% before fracture. This is considered as the biggest disadvantage of the adhesive, because in glass and stone masonry movements, the connection needs not only the strength, but as well as some flexibility to balance the movements of the dissimilar structures. On the other hand, MS polymer, modified silane adhesive from polyurethane or sometimes polyether family is much more elastic and can similarly show good resistance to extreme weather conditions. In this case, long curing time in thick layers, short durability and relatively lower strength characteristics are present – typically, tensile strength is evaluated between 1 and 4 MPa.

During the construction phase, glass blocks, mortar, sealants and adhesives should be mounted by following special principles of building technology to ensure a working structure. For example, in areas where larger horizontal stone surfaces take compression forces from glass (such as region between axis C and D in Drawing 1, Appendix 8), soft wooden or polypropylene sheet supports need to be used at first to lay the glass block row and then, after connecting the glass masonry into precut stone hollows with adhesive layer, the wooden support can be discarded and the hole injected as the rest of the gaps between two masonries. Also, polypropylene sheets can be suggested as intermediate invisible layer in the precut hollow on stone structure's horizontal surface (connected similarly on two sides with load-transferring adhesive), so that the glass would be supported on softer surface to prevent micro cracks. As the plastic sheet layer can be produced in various thicknesses, it can help to provide demanded tolerances and horizontal rows of the glass blocks, especially when the technology of cutting hollows into the stone is complex and imprecisions are easy to come up. Although showing relatively good behaviour in compression, in the described case flexible lime mortar does not qualify as a suitable intermediary due to the mismatching elastic modulus with non-porous natural stone. Polypropylene, on the contrary, is rigid enough to provide even surfaces under the glass blocks.

3.4.2 Testing Glass-stone Bonding for Shear Strength

Shear properties of two adhesives between stone (fired clay brick) and glass (soda-lime) were determined by mechanical testing of the material under varying temperature conditions – room temperature (+21 °C; RH 40–60 %) and possible highest encountering temperature in Toolse (+40 °C; RH 40–60 %). Testing in low temperatures was left without attention since generally, the strength of the chosen adhesive types becomes more critical when temperature rises according to experiments conducted by F. Nicklisch [70]. Tests were conducted in Delft University of Technology, Faculty of Mechanical, Maritime and Materials Engineering, using Zwick universal testing machine Z100 type BTC-FR100TL.A4K with maximum capacity of 100 kN and environmental chamber Instron SFL model EC75-1010. The loading speed was determined as v = 10 mm/s. Failure stresses and strain of composite connection were investigated by means of computer software testXpert® II by Zwick Roell Group. Small-scale composite specimens were tested for shear strength by following well-established test routines, using a special set-up made of steel and softening rubber layers (presented in Figure 38).

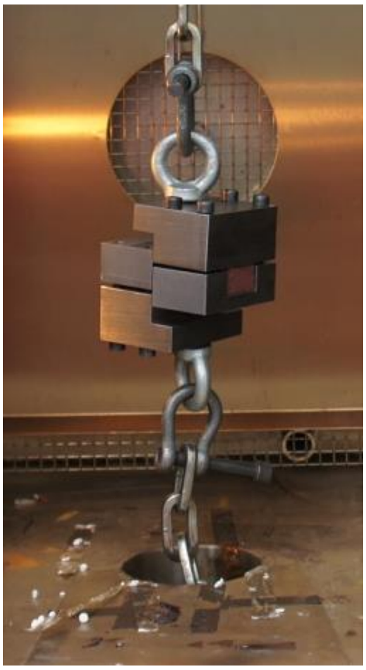
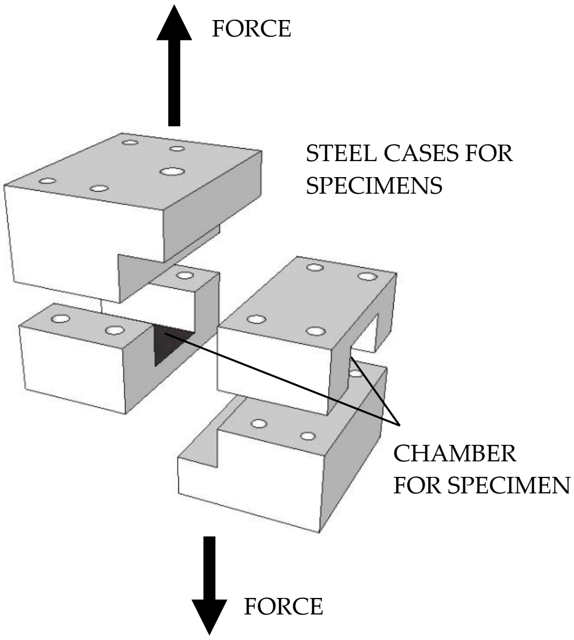

Figure 38. Design of the test set-up

Specimens (25 in total, divided into 4 test sets) comprising stone and glass substrates (Figure 39) were bonded with either polyurethane based MD-MS Polymer by Marston-Domsel GmbH© or epoxy adhesive Araldite® 2013 by Huntsman Advanced Materials. General dimensions of the tested specimens, both for ceramic stone and glass were 50x50x20 mm and 50x35x20 mm. Specific geometry of the shear-specimens were chosen in order to fit the testing equipment and simplify the preparation process.

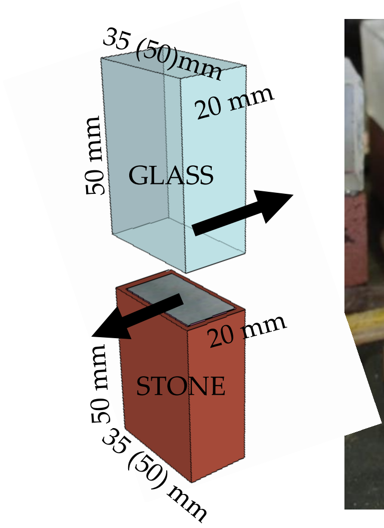

Figure 39. Specimen design

The comparative table of used adhesives and their properties and technical data is presented below. The information is assembled from producers' technical data sheets available on the internet. Following guidelines, adhesive layer thicknesses were taken approximately equal to 1 mm (MD-MS Polymer) and 0,1 mm (Araldite® 2013) and glued to the stone surface using gluing guns. In both cases, the curing lasted six days before the specimens were tested.

Table 7. Characteristics of tested adhesives according to technical data sheets [71] & [72]

Descriptive Data	MD-MS Polymer	Araldite® 2013
Basis	Polyurethane (modified silane)	Epoxy
Colour	Translucent	Grey
Picture		
Working temperature	+5/+30 °C	Room temperature
Density	1 g/ml (DIN 53479)	1,4 g/ml
Hardening time	3 mm/24 h	27 h
Temperature resistance	–40 to +100 °C	–60/+100 °C
Maximum joint width	25 mm	0,05–0,10 mm
Breaking strain/Elongation	250% (DIN 53504)	10%
Strength characteristics	Tensile strength (DIN 53504): 2,2 MPa	Shear modulus 2,5 GPa (25 °C) Flexural strength 46 MPa (23 °C) Lap shear strength: 20 MPa (40 °C) Shear strength 20 MPa

Common fired red clay brick (bulk density of 1800 kg/m^3), belonging to the first category according to Eurocode 6 was chosen as a substrate of cut specimen in connections to represent historic stone in the walls of Toolse. Although it has lower bulk density than original limestone, clay bricks were used as they have possibly more comparable properties to 500-year old limestone in terms of brittleness and shear strength compared to Lasnamäe type construction limestone. Base glass material was soda-lime glass block cut into appropriate size. Adhesive was applied to the polished, glossy surfaces of the specimen to imitate conditions of restoration. All surfaces were cleaned prior to gluing. Glass was thoroughly processed with propanol (routine of 3 cycles of cleaning), in case of bricks, stainless steel detail brush and pressure air was used. A certain amount of the specimens were kept underwater for 4 hours before testing. Specimens that were tested in the environmental chamber were preconditioned at the test conditions for at least 30 minutes. Table of specific data for specimen properties and connection details is presented in Appendix 6.

4. CALCULATIONS OF CONNECTIONS AND TEST RESULTS

4.1 Shear Test Results

Test data was analyzed by averaging strain values obtained from testXpert® software recordings so that $\varepsilon = \Delta L / L_0$. The strain data cannot be defined as the strain of the sole bonding, since the difference in length was calculated for the whole test set-up including metal clamps and fixators. Therefore, strain values play no significant role in following data analysis and stress values are taken as top priority. Stress was determined by taking into account specified cross-sectional area of the bond, resulting in $\sigma = F / A_0$. Testing was conducted until complete failure of the adhesive or the substrate materials. For both cases (specimens bonded with MD-MS Polymer or Araldite 2013), the stress-strain diagrams at room temperature and at +40 °C as possible highest encountering temperature in Toolse are presented in Figures 40, 41, 42 and 43 (descriptive data for test specimens are presented in Appendix 6).

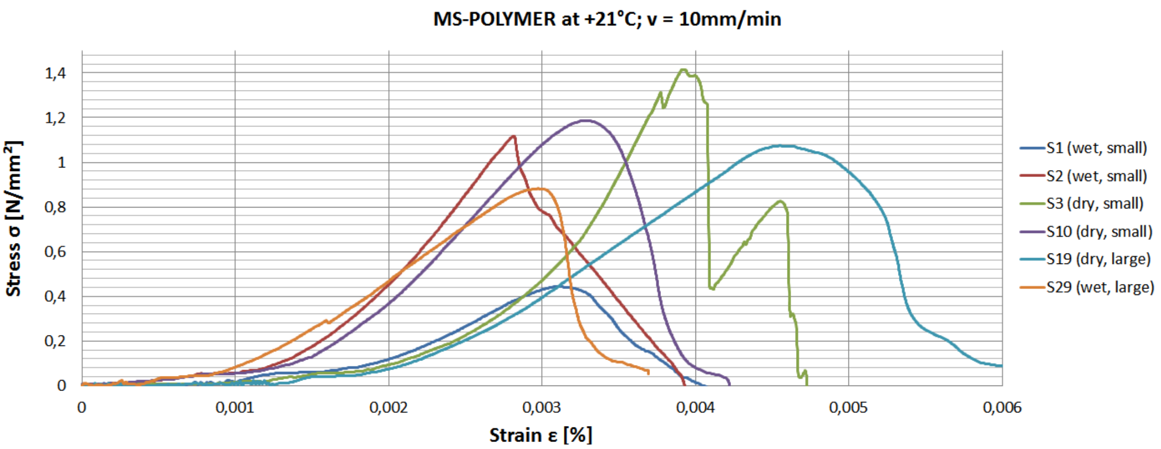

Figure 40. Stress-strain relationships for ms-polymer bond at +21°C

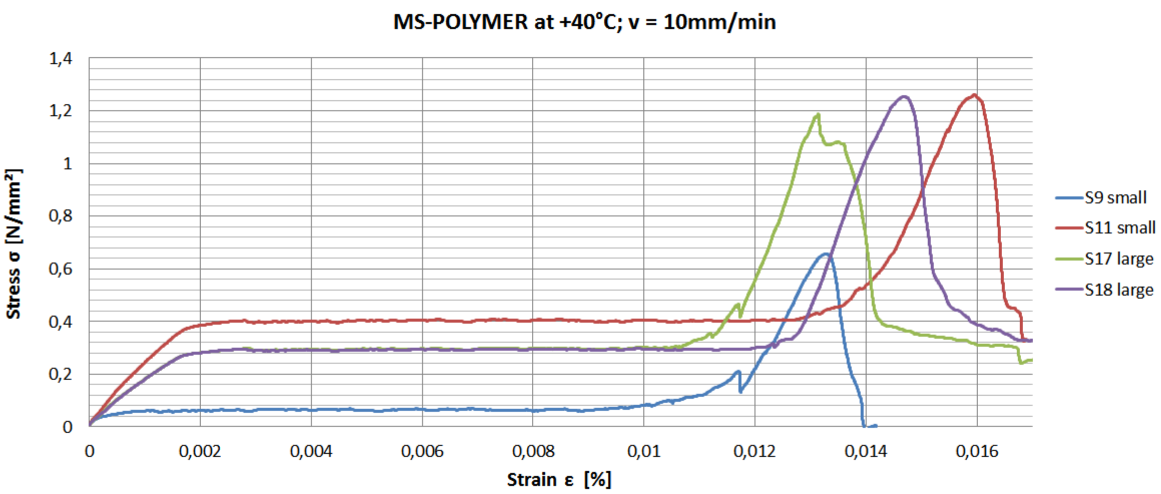

Figure 41. Stress-strain relationships for ms-polymer bond at +40°C

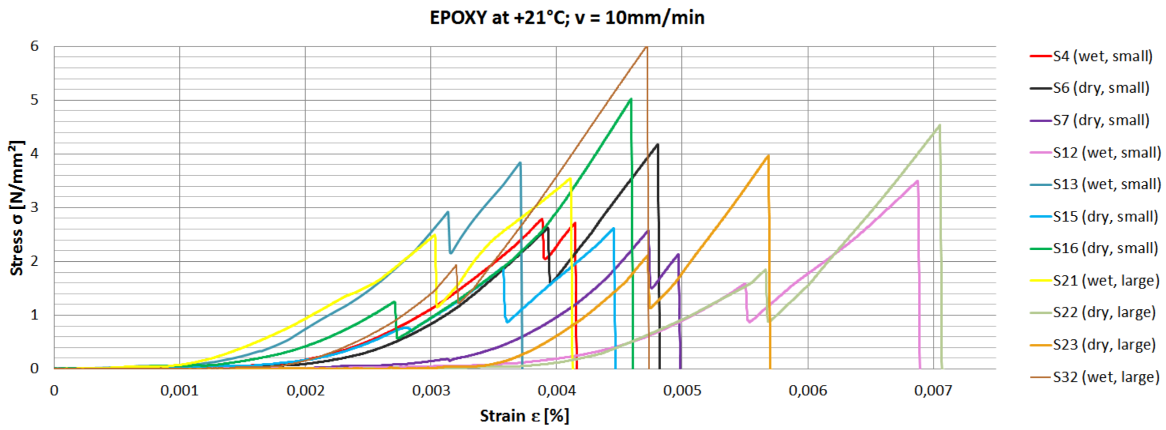

Figure 42. Stress-strain relationships for epoxy bond at +21°C

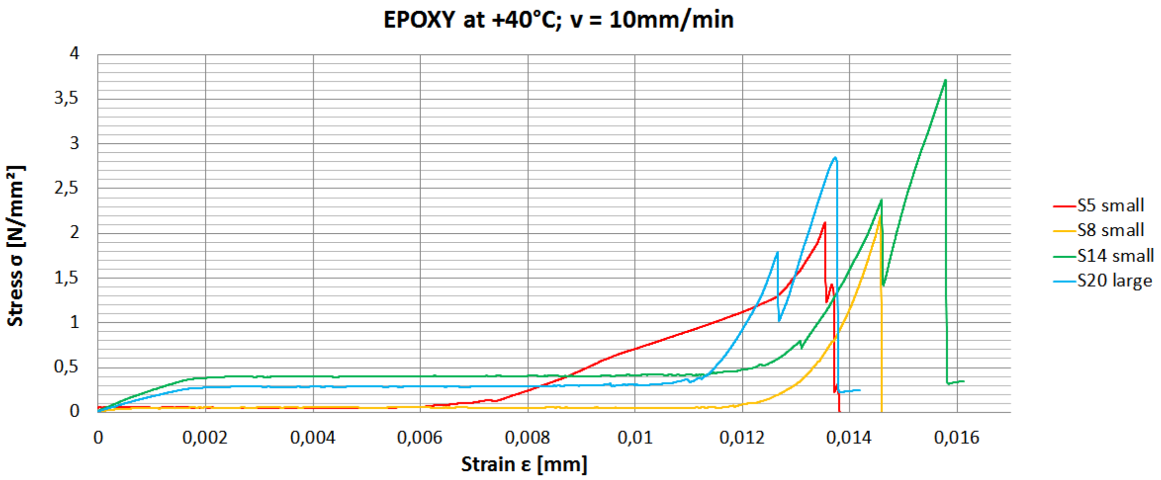

Figure 43. Stress-strain relationships for epoxy bond at +40°C

Results indicate that epoxy based adhesive Araldite 2013 show better resistance in glass-stone connection to shear stresses compared to modified silane based MD-MS Polymer bonding in both applied temperature conditions. Out of all tested specimens with modified silane polymer bonding, the most typical failure stress in shear can be estimated roughly three times weaker than specimens with epoxy adhesive connections. Therefore, it can be concluded that generally, as expected, stiff epoxy adhesives show better failure behaviour in chosen temperature conditions than elastic MS bonding materials when glass is connected to stone.

Failure behaviour of modified silane adhesive MD-MS Polymer is relative to soft bonding material and shows approximate linear stress-strain relation. Failure of the MS based connection most commonly resulted in complete delamination of the glue, in case of high temperature conditions, the delamination was more ductile than at room temperatures (although some ductility can be met at room temperatures also, since the stress drop is expressed as a smooth curve). Attention should be paid to Figure 41 and 43 that show strain in constant stress – this indicates the behaviour of steel members in the test set-up that have become ductile in +40 °C (full length of the test assemblage was 1260 mm). Elastic MS adhesive shows no weakening in higher temperatures as in both temperature cases the average stress values are comparable. Another thing to note is that wet specimens possess smaller strain values. This may be explained by the behaviour of water molecules that enter the adhesive and interfere with the attraction between the molecular chains.

Diagrams on Figures 42 and 43 describe how test specimens connected with stiff epoxy adhesive Araldite 2013 failed under loading. The curve stands for brittle material failure as most of the cases the adhesive itself could not be tested until failure – the first distinctive maximum indicates the failure of a stone substrate, second tip of the line describes final breakage of the bond close to the connected surface area, however, also located in brick. Since second failure expresses possible behaviour at realistic situations in connections under shear stresses, the values are taken as failure maximums for epoxy adhesive (although it is estimated that glue can take about 30 MPa in shear). Glass in the composite failed only in rare cases (information regarding breaking pattern presented in Annex 6). Similarly to MS polymer glue, destructive influence are absent when temperatures reach +40 °C and epoxy glue can be effectively used in higher temperature ranges, although stress capacity is somewhat lower in that instance. Moisture content does not play a role in specimens connected with epoxy adhesive as no recognisable pattern can be ascertained.

As a result, adhesives with an epoxy basis can be justifiably selected for more suitable bonding material because of the higher resistance to shear stresses. Additionally, other advantages like lasting serviceability in age, relatively thin optimal thickness and weatherproof characteristics support the selection in favor of epoxy adhesives. On the other hand, stiffness of the chosen material is the biggest negative aspect and needs to be taken into account when using the glue in filling the contact area when connecting glass to historic stone wall surfaces.

To propose the usage of epoxy adhesive in current restoration concept, the characteristic shear strength of the bonding material working between similar stone and glass is taken equal to $\sigma_{connection.k} = 2{,}12\ MPa$, adapted from the poorest result (specimen S5 respectively) after the results of defective specimens are abandoned. It can indirectly reduce the risk of application quality and insufficient cohesion of the adhesive on a construction site since outdoor environment is not as consistant as laboratory conditions. To ensure safe shear behaviour of the bonding, safety factor $\gamma_m = 2{,}0$ is used in the design proposal, although more precise stress value and safety factor require long term creep testing. In current design, the design shear strength of the epoxy basis connection $\sigma_{connection.d}$ is taken equal to

$$\sigma_{connection.d} = \frac{\sigma_{epoxy.k}}{\gamma_m} = \frac{2{,}12}{2{,}0} = 1{,}06\ MPa. \qquad (1)$$

Attention should be paid on the circumstance that the derived value does not describe the strength of the epoxy adhesive layer, but rather shear strength of the brittle ceramic material that in the current case was fired clay brick.

4.2 Evaluation of Thermal Expansion Influence on Glass-stone Connection

4.2.1 Considering Thermal Movements

Building materials change in volume in response to changes in temperature – most important are increases in length. To avoid cracks and critical thermal stresses in connection of two different materials, glass elements should be designed in such a way to minimize the movements or accommodate differential movements between materials and assemblies. It is complicated to predict exact movements of building elements as the volume changes depend on climate conditions and material properties that in case of old walls are unknown. Furthermore, there are several examples of large-scale historic masonry structures that have become damaged through thermal cracking but still serve as a whole without any noticeable signs of dilations.

As in traditional masonry technology, to avoid stresses from vertical movements, dilation joints are designed into the glass structure. However, in the case of relatively narrow horizontal gaps, the appropriate length of glass masonry needs to be reviewed in more detail as every small region of the glass block row plays an important role in the extension or contraction of the whole composite structure consisting of historic walls and the crack area filled with glass blocks. Significant differences in the movements of two materials may result in failure of the connection. Furthermore, each glass block type is selected to have a thermal expansion coefficient similar to the historic structure to provide maximally balanced behaviour of the composite wall. It is impossible for two materials with different dimensions to act exactly the same way under temperature influence, yet, thermal stresses can be reduced by selecting the right glass types.

The linear thermal expansion coefficient α is described as a degree of expansion in dimensions of the element divided by the change in temperature. Coefficients α of observable materials according to CES Edupack 2014 [27] (most critical values applied):

Granite $\alpha = 12{,}00\ \mu strain/C°$
Limestone $\alpha = 6{,}30\ \mu strain/C°$
Soda-lime glass $\alpha = 9{,}50\ \mu strain/C°$
Borosilicate glass $\alpha = 4{,}00\ \mu strain/C°$

Regarding climate data provided by EEA, determined temperature conditions to evaluate maximum extension of glass blocks and natural stone are:

Minimum $t_0 = -35°C$ taken as initial temperature; Maximum $t = 35°C$.

To fill the crack in the SW tower completely without the need of intervention, different sizes of glass blocks need to be produced and then fitted as handicraft work similar to natural stone masonry laying technology – each row is unique. Proposed dimensions for glass blocks are as follows: 250x300x50 mm (type 1), 230x300x50 mm (type 2), 120x300x50 mm (type 3) and 80x300x50 mm (type 4). The prototype block sizes are also presented in Figure 44. First two prototypes in the list are selected with respect to historic stone elements in the walls of Toolse castle, type 3 and 4 are necessary to fill smaller gaps that possibly evolve in the crack area. Smaller block sizes are chosen to meet overlapping criterions determined in Eurocode 6 section 8.1.4.1 – glass blocks with the height less than 250 mm are required to have minimal overlap of 40 mm per block, therefore, the minimum dimension for width is taken equal to 80 mm.

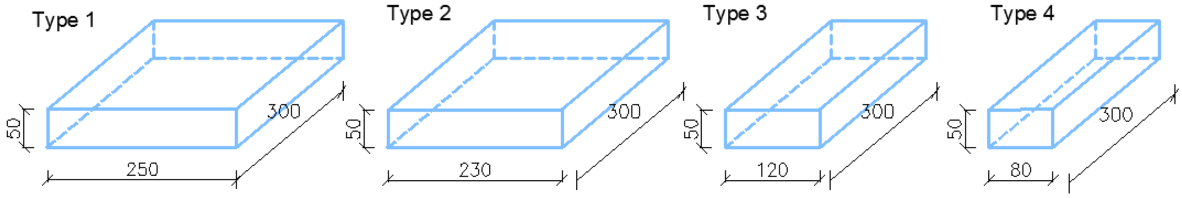

Figure 44. Prototype glass blocks to fill the crack in the tower

Flexible lime mortar is suggested to seal the very end of a glass row that faces the stone surface to seal the small air gap and take the movements of half the glass row and stone that is in direct contact with the sealer. Mortar needs to be strong enough to carry possible compressive self-weight from glass in certain areas, but also resistant to climate conditions occurring in Toolse and injectable as it is applied as a last step after the glass walls have been laid and horizontally connected to the stone surface with epoxy adhesive. In architectural monuments, traditional lime mortars should be used as it has proven to be much more suitable in restoration compared to industrial mortars that are produced in mechanized processes at higher burning temperatures, although their chemical composition is similar.

The key to good cohesion characteristics with old stone walls in traditional lime mortars lies in lower burning temperatures and manual slacking, resulting in oblong crystals in the microstructure, while modern industrial mortars form from oval shaped crystals that have a lower ability to bind in comparison with traditional lime mortar [73]. However, it should be noted that mortar does not bond to the glass as it is not a porous material. To improve the mechanical connection, manufactures of hollow glass blocks have suggested coating the block edges with polyvinylbutyral (PVB) or latex paint. It can easily be used as well as in case of Toolse castle glass restoration concept. Also, the larger the masonry unit and mortar contact area, the better connection can be obtained.

For restoration with glass blocks, natural hydraulic lime mortar NHL 3,5 with compressive strength 3,5 N/mm² or similar is proposed. The soft mortar will absorb and evaporate the moisture from the surrounding masonry to allow it to breathe. It will also accommodate movements of thermal expansion and therefore not damage the masonry by exerting pressure (detailed product data of leading producer St. Astier's NHL 3,5 mortar is presented in Appendix 7).

As Estonian limestone has the required clay content, it has also proven possible to produce traditional natural hydraulic lime locally. In Lümanda, Saaremaa, necessary limekiln and old technology currently exist, although problems may occur with sufficient level of knowledge since natural hydraulic lime mortars have not been widely used before in Estonia [74]. The possibilities of producing NHL mortar in Saaremaa need to be specified in order to propose its usage in glass-stone connection of Toolse SW tower as an alternative. Initially, well-known St.Astier, a company based in the UK, one of the leading companies in Europe to produce natural hydraulic lime mortars suitable for restoration and conservation is selected.

4.2.2 Horizontal Thermal Expansion

Borosilicate and soda-lime glass blocks will be used in a certain pattern depending on the crack width and specific stone (granite or limestone) when connected to stone walls. The three most problematic areas were selected for analysis in terms of horizontal thermal expansion to find a suitable glass block pattern of soda-lime and borosilicate. Visual inspection reveals 3 critical sections marked as 1-1, 2-2 and 3-3 in Appendix 8 (Drawing 2, Figure B). Since the calculations are based on presumptive, not fully precise values, it serves as an informative example and correct values are required to be specified prior to construction. As a result, the most suitable assessment of the glass blocks is proposed, taking into account the type and dimensions of the blocks.

<u>Horizontal linear thermal expansion of prototype blocks</u>

$\frac{l-l_0}{l_0} = \frac{\Delta l}{l_0} = \alpha(t - t_0) \;\rightarrow\; l = l_0(1 + \alpha\Delta t)$, where (2)

l – length of the element in temperature t, mm;
l_0 – length of the element in initial temperature t_0, mm;
Δl – expansion of the element, $\Delta l = l - l_0$,mm;
α – linear thermal expansion coefficient;

Δt – temperature difference, $\Delta t = t - t_0$, °C.

1) Block with dimensions 250x300x50 mm

Borosilicate:

$l = l_0(1 + \alpha\Delta t) = 250(1 + 4{,}00 \times 10^{-6} \times [35 - (-35)]) = 250{,}070\ mm$

Expansion $l_{B,250} = \Delta l = l - l_0 = 250{,}070 - 250 = 0{,}070\ mm$

Soda-lime:

$l = l_0(1 + \alpha\Delta t) = 250(1 + 9{,}50 \times 10^{-6} \times [35 - (-35)]) = 250{,}166\ mm$

Expansion $l_{SL,250} = \Delta l = l - l_0 = 250{,}166 - 250 = 0{,}166\ mm$

2) Block with dimensions 230x300x50 mm

Borosilicate:

$l = l_0(1 + \alpha\Delta t) = 230(1 + 4{,}00 \times 10^{-6} \times [35 - (-35)]) = 230{,}064\ mm$

Expansion $l_{B,230} = \Delta l = l - l_0 = 230{,}064 - 230 = 0{,}064\ mm$

Soda-lime:

$l = l_0(1 + \alpha\Delta t) = 230(1 + 9{,}50 \times 10^{-6} \times [35 - (-35)]) = 230{,}153\ mm$

Expansion $l_{SL,230} = \Delta l = l - l_0 = 230{,}153 - 230 = 0{,}153\ mm$

3) Block with dimensions 120x300x50 mm

Borosilicate:

$l = l_0(1 + \alpha\Delta t) = 120(1 + 4{,}00 \times 10^{-6} \times [35 - (-35)]) = 120{,}034\ mm$

Expansion $l_{B,120} = \Delta l = l - l_0 = 120{,}034 - 120 = 0{,}034\ mm$

Soda-lime:

$l = l_0(1 + \alpha\Delta t) = 120(1 + 9{,}50 \times 10^{-6} \times [35 - (-35)]) = 120{,}080\ mm$

Expansion $l_{SL,120} = \Delta l = l - l_0 = 120{,}080 - 120 = 0{,}080\ mm$

4) Block with dimensions 250x300x50 mm

Borosilicate:

$l = l_0(1 + \alpha\Delta t) = 80(1 + 4{,}00 \times 10^{-6} \times [35 - (-35)]) = 80{,}022\ mm$

Expansion $l_{B,80} = \Delta l = l - l_0 = 80{,}022 - 80 = 0{,}022\ mm$

Soda-lime:

$l = l_0(1 + \alpha\Delta t) = 80(1 + 9{,}50 \times 10^{-6} \times [35 - (-35)]) = 80{,}053\ mm$

Expansion $l_{SL,80} = \Delta l = l - l_0 = 80{,}053 - 80 = 0{,}053\ mm$

Critical Section 1-1: Limestone and Granite (Window Area)

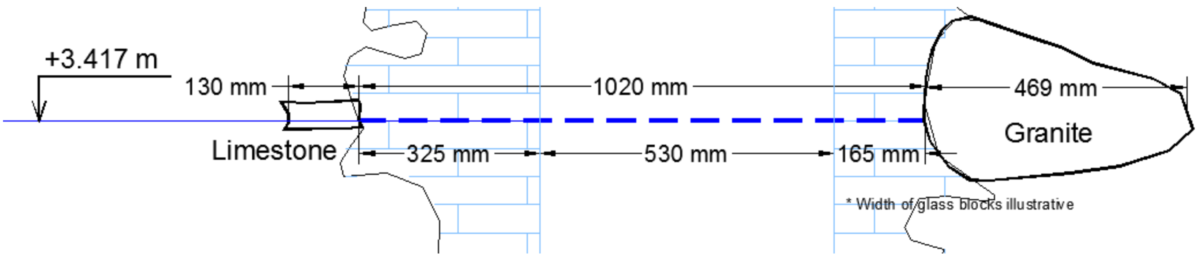

Figure 45. Schema of section 1-1

Crack width (Figure 45) $b_{crack} = 1020\, mm$ whereas left side of the window $b_{crack,l} = 325\, mm$ and right side $b_{crack,l} = 165\, mm$. Both sides of the window are observed separately. Due to possible uneven surfaces of limestone at the crack edges, minimal thickness of mortar $b_{min} = 15\, mm$ is taken into account.

- Determination of suitable glass blocks to the left side of the window:

One block with dimensions 230x300x50 mm and a block with dimensions 80x300x50 mm will be taken, since optimal width of glass

$b_{opt} = 230 + 80 = 310\, mm.$

Mortar thickness is therefore $b_m = 15\, mm,$

$b_m = b_{crack,l} - b_{opt} = 325 - 310 = 15\, mm \ \geq b_{min} = 15\, mm.$

Connection between limestone and glass will be affected by both materials. The horizontal measurement l_0 of the uttermost limestone is $l_0 = 130\, mm$. Joint area filled with mortar will be influenced by the expansion of half of the stone as there are flexible mortar joints in two horizontal edges of the block.

- Determination of expansion of limestone by Formula (2):

$l = l_0(1 + \alpha\Delta t) = \ 130(1 + 6{,}30 \times 10^{-6} \times [35 - (-35)]) = 130{,}057\, mm$

Expansion $\ l_{L,130} = \Delta l = l - l_0 = 130{,}057 - 130 = 0{,}057\, mm$

Horizontal expansion of limestone $l_{limestone}$ must be as similar as possible with expansion of a glass block row l_{glass} to provide balanced thermal behaviour in composite structure of glass masonry and historic stone walls.

- Horizontal expansion taken by observable joint from limestone:

$$l_{limestone} = \frac{l_{L,130}}{2} = \frac{0{,}057}{2} = 0{,}028\, mm$$

Due to similar thermal expansion coefficients, in case of limestone, borosilicate glass blocks are chosen instead of soda-lime glass to lay parallel part of the row in section 1-1 as it provides more comparable thermal expansion behaviour to stone.

- Horizontal expansion taken by observable joint from borosilicate and soda-lime glass:

$$l_{borosilicate} = \frac{1 \times l_{B,230} + 1 \times l_{B,80}}{2} = \frac{1 \times 0{,}064 + 1 \times 0{,}022}{2} = 0{,}043\, mm \rightarrow l_{glass}$$

$$l_{soda-lime} = \frac{1 \times l_{SL,230} + 1 \times l_{SL,80}}{2} = \frac{1 \times 0{,}153 + 1 \times 0{,}053}{2} = 0{,}103\, mm$$

Mortar in connection of glass and limestone need to be flexible enough to cope with thermal movement of both materials. Since the materials will expand as well as contract, the balance point can be determined as 0 °C. Therefore, values of full movements can be divided by two.

- Necessary thermal movements that the mortar connection need to accommodate:

$l_l = \frac{l_{limestone}}{2} = \frac{0{,}028}{2} = \pm 0{,}014\ mm$

$l_{gl} = \frac{l_{glass}}{2} = \frac{0{,}043}{2} = \pm 0{,}022\ mm$

l_{gl} constitutes 157% of l_l since $\frac{l_{gl} \times 100}{l_l} = \frac{0{,}022 \times 100}{0{,}014} \cong 157$.

Conclusion: In section 1-1 the left side of the window, borosilicate glass is used: a block with dimensions 230x300x50 mm and a block with dimensions 80x300x50 mm are assigned to the specific part of the row. Possible movement differences (evaluated maximally 157% of stone structure expansion/contraction) are balanced by air gap filled with elastic hydraulic lime mortar between glass and stone with estimated thickness of $b_m = 15\ mm$ that will assumably act as a dilatation.

- Determination of suitable glass blocks to the right side of the window:

One block with dimensions 120x300x50 mm will be taken, $b_{opt} = 120\ mm$.

Mortar thickness is therefore $b_m = 45\ mm$,

$b_m = b_{crack,l} - b_{opt} = 165 - 120 = 45\ mm\ \geq b_{min} = 15\ mm.$

Mortar thickness is therefore 45 mm,

$165 - 120 = 45\ mm\ \geq 15\ mm.$

- Determination of extension of uttermost granite stone ($l_0 = 469\ mm$) by Formula (2):

$l = l_0(1 + \alpha\Delta t) = 469(1 + 12{,}00 \times 10^{-6} \times [35 - (-35)]) = 469{,}394$

Expansion $l_{G,469} = \Delta l = l - l_0 = 469{,}394 - 469 = 0{,}394\ mm$

Horizontal expansion of rubble stone $l_{granite}$ must be as similar as possible with expansion of glass block row l_{glass} to provide a balanced thermal behaviour in composite structure of glass masonry and historic stone wall.

- Horizontal expansion taken by observable joint from granite:

$$l_{granite} = \frac{l_{G,469}}{2} = \frac{0{,}394}{2} = 0{,}197\ mm$$

Due to similar thermal expansion coefficient, in case of granite, soda-lime glass blocks are chosen instead of borosilicate glass to lay the horizontal row as it provides more comparable thermal behaviour with granite.

- Horizontal expansion taken by observable joint from glass block masonry:

$$l_{borosilicate} = \frac{1 \times l_{B,120}}{2} = \frac{1 \times 0{,}034}{2} = 0{,}017\ mm$$

$$l_{soda-lime} = \frac{1 \times l_{SL,120}}{2} = \frac{1 \times 0{,}080}{2} = 0{,}040\ mm \rightarrow l_{glass}$$

- Necessary thermal movements that the mortar connection need to accommodate:

$$l_{gr} = \frac{l_{granite}}{2} = \frac{0{,}197}{2} = \pm 0{,}099\ mm$$
$$l_{gl} = \frac{l_{glass}}{2} = \frac{0{,}04}{2} = \pm 0{,}020\ mm$$

l_{gl} constitutes 20% of l_{gr} since $\frac{l_{gl} \times 100}{l_{gr}} = \frac{0{,}020 \times 100}{0{,}099} \cong 20$.

Conclusion: In section 1-1 the right side of the window, soda-lime glass is used: a block with dimensions 120x300x50 mm is assigned to specific part of the row. Possible movement differences (evaluated maximally 20% of stone structure expansion/contraction) are balanced by air gap filled with elastic hydraulic lime mortar between glass and stone with an estimated thickness of $b_m = 45\ mm$ that will assumably act as a dilatation.

Critical Section 2-2: Limestone and Limestone

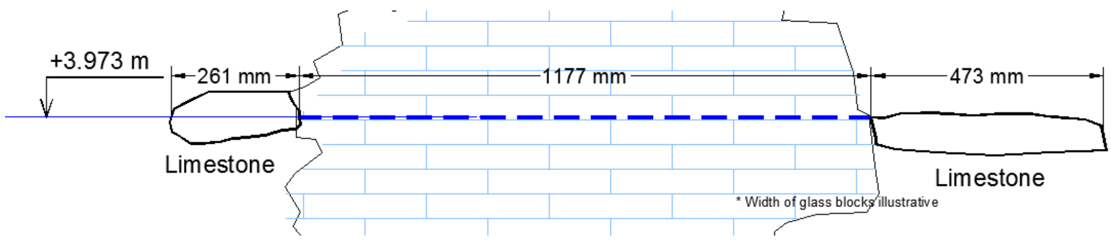

Figure 46. Schema of section 2-2

Crack width (Figure 46) $b_{crack} = 1177\ mm$.
Minimal thickness of mortar $b_{min} = 15\ mm$ is taken into account.

- Determination of suitable glass blocks:

Three blocks with dimensions 250x300x50 mm, one block 230x300x50 mm and two blocks with dimensions 80x300x50 mm will be taken,

$b_{opt} = 3 \times 250 + 1 \times 230 + 2 \times 80 = 1140\ mm.$

Mortar thickness is therefore $b_m = 17\ mm$ on one edge,

$b_m = \frac{b_{crack} - b_{opt}}{2} = \frac{1177-1140}{2} = 18{,}5\ mm \ \geq b_{min} = 15\ mm.$

- Determination of expansion of limestone on the left ($l_0 = 261\ mm$) by Formula (2):

$l = l_0(1 + \alpha\Delta t) = \ 261(1 + 6{,}30 \times 10^{-6} \times [35 - (-35)]) = 261{,}115\ mm$

Expansion $l_{L,261} = \Delta l = l - l_0 = 261{,}115 - 261 = 0{,}115\ mm$

- Determination of expansion of limestone on the right ($l_{0,R} = 473\ mm$) by Formula (2):

$l = l_0(1 + \alpha\Delta t) = \ 473(1 + 6{,}30 \times 10^{-6} \times [35 - (-35)]) = 473{,}397\ mm$

Expansion $l_{L,473} = \Delta l = l - l_0 = 473{,}397 - 473 = 0{,}397\ mm$

Horizontal expansions of limestone in the edges of the crack $l_{limestone,L}$ and $l_{limestone,R}$ must be as similar as possible with expansion of glass block row l_{glass} to provide balanced thermal behaviour in the composite structure of glass masonry and historic stone walls.

- Horizontal expansion taken by joint from limestone on the left:

$$l_{limestone,L} = \frac{l_{L,261}}{2} = \frac{0{,}115}{2} = 0{,}058\ mm$$

- Horizontal expansion taken by joint from limestone on the right:

$$l_{limestone,R} = \frac{l_{L,473}}{2} = \frac{0{,}397}{2} = 0{,}199\ mm$$

- Horizontal expansion taken by edge joints from borosilicate and soda-lime glass blocks:

$$l_{borosilicate} = \frac{3 \times l_{B,250} + 1 \times l_{B,230} + 2 \times l_{B,80}}{2} = \frac{3 \times 0{,}070 + 1 \times 0{,}064 + 2 \times 0{,}022}{2}$$
$$= 0{,}159\ mm \rightarrow l_{glass}$$

$$l_{soda-lime} = \frac{3 \times l_{SL,250} + 1 \times l_{SL,230} + 2 \times l_{SL,80}}{2} = \frac{3 \times 0{,}166 + 1 \times 0{,}153 + 2 \times 0{,}053}{2}$$
$$= 0{,}379\ mm$$

- Necessary thermal movements that the mortar connection need to accommodate:

On the left, $l_{l1} = \frac{l_{limestone,L}}{2} = \frac{0{,}058}{2} = \pm 0{,}029\ mm$

On the right, $l_{l2} = \frac{l_{limestone,R}}{2} = \frac{0,199}{2} = \pm 0,100\ mm$
$l_{gl} = \frac{l_{glass}}{2} = \frac{0,159}{2} = \pm 0,080\ mm$

l_{gl} constitutes 276% of l_{l1} and 80% of l_{l2} since $\frac{l_{gl}\times 100}{l_l 1} = \frac{0,080\times 100}{0,029} \cong 276$ and $\frac{l_{gl}\times 100}{l_l 2} = \frac{0,080\times 100}{0,100} = 80$.

Conclusion: In section 2-2, borosilicate glass is used: three blocks with dimensions 250x300x50 mm, one with 230x300x50 mm and two blocks with dimensions 80x300x50 mm are assigned to the row. Possible movement differences (evaluated maximally 276% on the left and 80% on the right higher from stone structure expansion/contraction) are balanced by air gaps filled with elastic hydraulic lime mortar between glass and stone with an estimated thickness of $b_m = 45\ mm$ that will assumably act as a dilatation.

Critical Section 3-3: Limestone and Granite

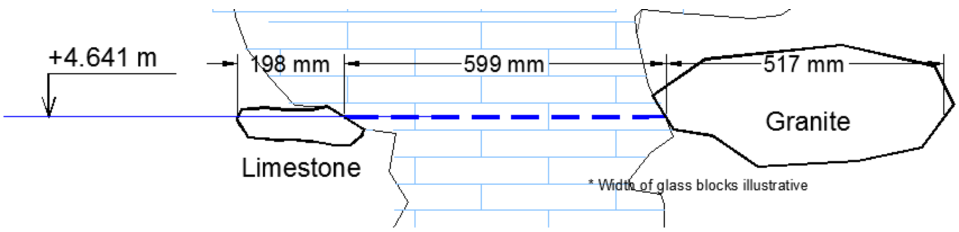

Figure 47. Schema of section 3-3

Crack width (Figure 47) $b_{crack} = 599\ mm$.
Minimal thickness of mortar $b_{min} = 15\ mm$ is taken into account.

- Determination of suitable glass blocks:

Three blocks with dimensions 250 x 300 x 50 mm, 230 x 300 x 50 mm and 80 x 300 x 50 mm will be taken,

$b_{opt} = 1 \times 250 + 1 \times 230 + 1 \times 80 = 560\ mm.$

Mortar thickness is therefore $b_m = 17\ mm$ on one edge,

$b_m = \frac{b_{crack} - b_{opt}}{2} = \frac{599-560}{2} = 19,5mm \geq b_{min} = 15\ mm.$

- Determination of expansion of limestone on the left ($l_0 = 198\ mm$) by Formula (2):

$l = l_0(1 + \alpha\Delta t) = 198(1 + 6,30 \times 10^{-6} \times [35 - (-35)]) = 198,087\ mm$

Expansion $l_{L,198} = \Delta l = l - l_0 = 198,087 - 198 = 0,087\ mm$

- Determination of expansion of granite on the right ($l_{0,R} = 517\ mm$) by Formula (2):

$l = l_0(1 + \alpha\Delta t) = 517(1 + 12,00 \times 10^{-6} \times [35 - (-35)]) = 517,434\ mm$

Expansion $l_{G,517} = \Delta l = l - l_0 = 517{,}434 - 517 = 0{,}434\ mm$

Horizontal expansions of limestone in the edges of the crack $l_{limestone,L}$ and $l_{granite,R}$ must be as similar as possible with the expansion of the glass block row l_{glass} to provide balanced thermal behaviour in the composite structure of glass masonry and historic stone walls.

- Horizontal expansion taken by joint from limestone on the left:

$$l_{limestone,L} = \frac{l_{L,198}}{2} = \frac{0{,}087}{2} = 0{,}044\ mm$$

- Horizontal expansion taken by joint from limestone on the right:

$$l_{granite,R} = \frac{l_{G,517}}{2} = \frac{0{,}434}{2} = 0{,}217\ mm$$

- Horizontal expansion taken by edge joints from borosilicate and soda-lime glass blocks:

$$l_{borosilicate} = \frac{1 \times l_{B,250} + 1 \times l_{B,230} + 1 \times l_{B,80}}{2} = \frac{1 \times 0{,}070 + 1 \times 0{,}064 + 1 \times 0{,}022}{2}$$
$$= 0{,}078\ mm$$

$$l_{soda-lime} = \frac{1 \times l_{SL,250} + 1 \times l_{SL,230} + 1 \times l_{SL,80}}{2} = \frac{1 \times 0{,}166 + 1 \times 0{,}153 + 2 \times 0{,}053}{2}$$
$$= 0{,}186\ mm$$

For best suitability with both stone types in the edges, the row is expected to be laid by combining both glass types. Respectively, l_{glass}:

$$l_{glass} = \frac{1 \times l_{SL,250} + 1 \times l_{B,230} + 1 \times l_{B,80}}{2} = \frac{1 \times 0{,}166 + 1 \times 0{,}064 + 1 \times 0{,}022}{2}$$
$$= 0{,}126\ mm$$

- Necessary thermal movements that the mortar connection need to accommodate:

On the left, $l_{l1} = \frac{l_{limestone,L}}{2} = \frac{0{,}044}{2} = \pm 0{,}022\ mm$

On the right, $l_{l2} = \frac{l_{granite,R}}{2} = \frac{0{,}217}{2} = \pm 0{,}109\ mm$

$l_{gl} = \frac{l_{glass}}{2} = \frac{0{,}126}{2} = \pm 0{,}063\ mm$

l_{gl} constitutes 286% of l_{l1} and 58% of l_{l2} since $\frac{l_{gl} \times 100}{l_l 1} = \frac{0{,}063 \times 100}{0{,}022} \cong 286$ and $\frac{l_{gl} \times 100}{l_l 2} = \frac{0{,}063 \times 100}{0{,}109} = 58$.

Conclusion: In section 3-3 both, borosilicate and soda-lime glass are used: three blocks, one soda-lime with dimensions 250x300x50 mm, one borosilicate with measurements 230x300x50 mm and one borosilicate block with dimensions 80x300x50 mm are assigned to the row. Possible movement differences (evaluated maximally 286% on the left and 58% on the right higher from stone structure expansion/contraction) are balanced by air gaps filled with elastic hydraulic lime mortar between glass and stone with an estimated thickness of $b_m = 19{,}5\ mm$ that will assumably act as a dilatation.

4.2.3 Vertical Thermal Expansion

Dilation joints are essential to prevent thermal stresses from causing cracks in glass and natural stone connection since the characteristics of thermal behaviour between limestone, granite, soda-lime and borosilicate glass are all different (values presented in 4.2.1). In the design phase of horizontal gaps to allow vertical movement in glass masonry system, historic appearance and building technology will be taken into account.

As different vertical expansion values of the glass blocks connected with acrylic UV-curing adhesive DELO Photobond 4497 (thermal expansion coefficient $\alpha = 250\ \mu strain/C°$) and historic masonry binded with traditional lime mortar inevitably cause small thermal stresses in mortar joints between two structures, it is significant to provide more than one dilation joint to divide the 15 m high glass structure into segments to keep the shear stresses from thermal movements minimal. Also, the risk of exceeding tolerances of glass blocks and adhesive layer thickness is distributed if horizontal joints appear in the structure.

With respect to historic arcs above the windows, vertically laid prefabricated glass block lintels can be used for dividing the structure and creating independent glass segments with dilation joints between them. As there have been four windows in the SW tower of Toolse castle historically, lintels are designed above each window similarly. Thermal joints with width of 20 mm are planned below the lintels (Figure 48). To prevent congregated water in narrow slots, flexible silicone sealants that are commonly used in structural façade design can be used to make joints waterproof. For instance, Dow Corning as one of the leading providers of silicone solutions for structural facades in the world offers a wide range of suitable, translucent sealants (for example Dow Corning® 756 SMS, 790 SBS or 791 SWS). It should be noted that silicone based sealants are not resistant in time and most of the products offered in market do not exceed warranty period of 20 years. Therefore, maintenance and regular check-ups need to be planned in order to keep the joints waterproof.

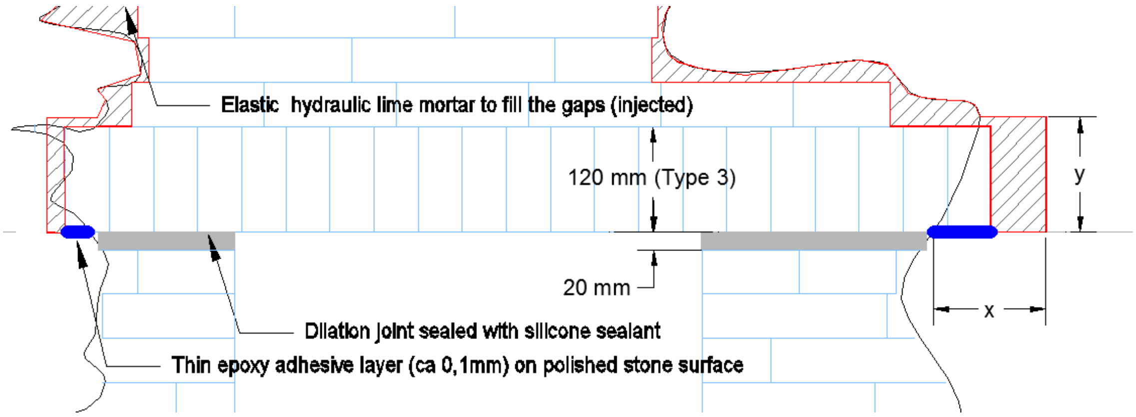

Figure 48. Dilation joints to allow vertical movement of the glass structure

The biggest disadvantage of the solution is that in order to support the lintels, authentic walls need to be intervened to make a support area for vertical glass plates. This brings forth the necessity of controlling local compressive stresses under the support areas in old masonry. This type of analysis requires further research on historic walls' strength, therefore it is counted out from the scope of this current case study, although it can be indirectly estimated that bearing capacity of historic walls is sufficient due to large dimensions and the existing possibility to enlarge the support area in order to lower local stresses.

In order to prevent separate glass structures from transferring loads and creating a proper dilation joint, building technology requires prefabricated lintels to be mounted in precut hollows in the stone wall. To realise this, hollows need to be horizontally and vertically somewhat wider than the lintel itself (marked as x and y on Figure 48) to balance the possible imprecision due to rough edges. On one edge of the lintel, x and y are determined to be 20 mm wider than required support area width or height of the lintel respectively. In the case of second edge, the x must be double the size of support area width plus extra 20 mm due to building technology issues. The value y is similarly 20 mm higher than the height of the lintel (120 mm). Support areas must be polished smooth or processed with epoxy adhesive that can take necessary compressive shear and compressive stresses. After the installation, lime mortar is injected to the gaps in the walls, also the seals between glass are tightened with silicone to be able to lay another segment of glass, following the typical horizontal routine.

For example, in axis C and section B-B in Drawing 3 (Appendix 8), a partly prefabricated lintel must be mounted to range crack width of b = 1000 mm. As support area width was determined by minimum of w_{min} = 20 mm, the entire area would be $A_c = w_{min} \times l = 20 \times 300 = 6000\ mm^2$, where the length of the glass block l = 300 mm. Blocks with measurements 120x50x300 mm are used to design a lintel (w_h = 50 mm is the width value as the element is prefabricated and bigger surfaces are adhesively bonded). Since required length $l_{lintel.min}$ must be at least:

$l_{lintel.min} = b + 2 \times w_{min} = 1000 + 2 \times 20 = 1040\ mm,$

the designed length of the lintel must be greater than the minimal, $l_{lintel.d} \geq l_{lintel.min}$. Due to the predetermined dimensions of the glass blocks, taking into account the above-mentioned criteria, the lintel requires N amount of glass blocks:

$N = \frac{l_{lintel.min}}{w_h} = \frac{1040}{50} = 20{,}8 \rightarrow 21.$

Therefore, designed length of the lintel in the current case equals

$l_{lintel.d} = 21 \times 50 = 1050\ mm$

and the support width x_{req} is therefore

$x_{req} = \frac{1050-1000}{2} = 25\ mm.$

Depending on the exact location and lintel, the length values of the crack vary, therefore, each support area value is unique and must be clarified furthermore.

4.3 Finite Element Analysis of the Connection

In order to determine local stresses in the adhesive connection and natural stone wall, evolved forces from self-weight of the glass blocks were examined with the help of FEM modeling software Scia Engineer 15.0.115. The program for load dissection was selected as the most suitable option since very complex shaped bodies can easily be analyzed using finite element method in terms of load transfer mechanisms of in-plane stress fields. The FEM modeling, where the examined material can easily be described in the program by determining shape, elastic modulus and density, is commonly used in case of glass constructions.

In the current case, 5 segments of the glass block masonry system were separately entered in the program as 2D plates with thickness of 300 mm (Appendix 9.1 Figure 70). Despite of being not considered in the scope of the current thesis, segment 1 intentionally involves the top part of the glass block masonry wall in the plane of SW tower in order to provide more accurate results in load distribution. The glass masonry system was described as a rigid material with E modulus of 50 GPa and Poisson's ratio ν equal to 0,22, assuming that whole structure is made of soda-lime glass with unit mass 2500 kg/m^3 and its behaviour is elastic. In selection of glass type, more critical material was taken as the base component of the whole system. In comparison with borosilicate, soda-lime glass has bigger bulk density, therefore, it was applied into the program as the glass block material. Elastic modulus of 50 GPa was opted due to the vertical joints in the masonry that are left unglued (E modulus for solid soda-lime glass is normally taken ca 70 GPa). Rigid supports were inserted under surfaces where adhesively bonded connections between glass and stone are located (in the edges with pace of every 5th glass block row, although some offsets can be found due to the variable shape of the stone wall. In longer horizontal areas where glass is possibly leaning on the stone wall, support slabs were inserted. Support reactions (Appendix 9.1 Figure 71), horizontal and vertical components from self-weight (Appendix 9.2) were found by linear analysis, taking into account the mesh width to match with glass block dimensions of 230 mm on average. The analysis of the inner stresses in the glass masonry was abandoned, since scientific research and previous FEM analysis have proven the masonry system to have sufficient bearing capacity.

Subsequently, a natural stone masonry 2D FEM model was created with thickness of 1350 mm and mesh average width of 250 mm, loaded with point loads. What concerns characteristics of the material, bulk density of 2250 kg/m^3, elastic modulus 2550 MPa and Poisson's ratio ν equal to 0,19 was used, based on experiments conducted by G. Magenes [75]. Supports for the masonry model were inserted in a way to copy the realistic situation in the tower. Horizontal and vertical force components were applied to the same horizontal surfaces where rigid adhesive layer was assigned (matching with rigid support locations in glass masonry FEM analysis). Linear calculation was done, taking into account the self-weight from the stone structure and eccentrically applied point loads (glass central axis offset 425 mm outwards from the stone wall central axis) from glass block masonry in order to evaluate stresses in the connection areas and stone masonry wall.

Results of the FEM analysis show maximum vertical and horizontal components to occur between axis I and J where glass blocks lean horizontally on the stone structure. The most critical horizontal load in length of the crack area is $F_x = 0{,}82\ kN$ (Section 1, axis I-J) in structural node Sn7 and vertical load $F_z = -1{,}63\ kN$ (Section 1, axis I-J) in structural node Sn6 respectively. Firstly, the stone wall in depth of glass masonry (300 mm) is subjected under observation to study the evolved stresses in the adhesion area. Adhesively connected rigid bonding between glass and natural stone needs to take shear forces as big as 0,82 kN and compression forces 1,63 kN.

As the default surface area of the adhesive layer was determined as

$A_c = w_{min} \times l = 20 \times 300 = 6000\ mm^2$,

stress values would be respectively:

$$\sigma_{v.k} = \frac{F_x}{A_{epoxy}} = \frac{0{,}82 \times 10^3}{6000} = 0{,}14\ MPa$$

$$\sigma_{c.k} = \frac{F_z}{A_{epoxy}} = \frac{1{,}63 \times 10^3}{6000} = 0{,}28\ MPa.$$

If these results are multiplied by the factor of safety $\gamma_{G,sup} = 1{,}20$ (adapted from EVS-EN 1990:2002), final stresses in the connection are determined as:

$$\sigma_{v.d} = \gamma_{G,sup} \times \sigma_{v.k} = 1{,}20 \times 0{,}14 = 0{,}17\ MPa$$

$\sigma_{c.d} = \gamma_{G,sup} \times \sigma_{c.k} = 1{,}20 \times 0{,}28 = 0{,}34\ MPa.$

The experiment result, shear strength of the adhesively bonded glass-stone connection $\sigma_{connection.d} = 1{,}06\ MPa$ is used to evaluate the critical shear stress in the connection area. Strength criterion is therefore fulfilled, as:

$\sigma_{v.d} = 0{,}17\ MPa \leq \sigma_{connection.d} = 1{,}06\ MPa.$

Considering roughly estimated compression capacity of the historic masonry similar to $f_d = 2{,}00\ MPa$ and flexural strength of the used epoxy adhesive $\sigma_{flex.e} = 46{,}00\ MPa$, compressive strength of the connection is conclusively evaluated to be minimum of $\sigma_{comp.connection.d} = 2{,}00\ MPa$. Thus, the criterion is fulfilled, as:

$\sigma_{c.d} = 0{,}34\ MPa \leq \sigma_{comp.connection.d} = 2{,}00\ MPa.$

Safe behaviour of the glass-stone connection in terms of compressive and shear stresses caused by self-weight of the glass block masonry is thereby assured.

In current design proposal, the glass masonry is designed to refill the crack area eccentrically, so that the central axis of the glass is located 425 mm outwards from the centre of the stone wall for aesthetical purposes. Local stresses in the stone masonry, caused by the self-weight of the glass cannot exceed bearing capacity of the stone structure to provide safe structural design. Also, self-weight of the massive stone wall itself needs to be taken into account to provide accurate results. Current 2D FEM model of the tower shows equivalent peak stresses of 1,61 MPa in sharp-edged corner areas (for example above C-axis in Appendix 9.1 Figure 73) from a load combination of self-weight and force components from glass structure. The equivalent stress σ_E, also known as von Mises stress is a result magnitude of stresses from all 6 dimensions (3 tension/compression stresses and 3 shear stresses). It is commonly used for ductile materials to evaluate failure behaviour of the structure by comparing determined yield strength of the material with subjected equivalent stress. However, in the current case, the structure itself is brittle, therefore, detailed stress analysis by means of von Mises stress is out of consideration and the created 2D FEM model (Appendix 9.1 Figure 72) serves only the illustrative purpose to reveal the critical stress areas in the length of the tower. It needs to be pointed out that the eccentric load from the glass structure, transferred to the stone masonry is distributed, therefore, it has low impact on the general stability of the historic wall. The most critical values of the equivalent inner stresses in the stone structure arise from the self-weight, dimensions and the shape of the wall. In Appendix 9.1 Figures 73–75, informative magnitudes of the inner stresses by load type are presented.

It is essential from the structural design point of view that before any glass restoration could take place, current inner stresses in the historic walls need to be compared with the strength of the historic wall. The bearing capacity of the brittle structure is traditionally estimated by using Mohr-Coulomb criterion that expresses the idea of the shear value to be the most critical. However, due to high complexity, detailed calculations of the strength capacity of the historic masonry walls are out of the scope of the current thesis. Nevertheless, conclusion can be made that relying on the data of linear FEM analysis, the connected glass structure's dead weight would not influence the stability of the historic structure significantly. Inner stress concentrations in the stone masonry evolve in the sharp-edged corners due to the self-weight of the wall and areas with local stresses from the glass structure generally stand separately.

5. DISCUSSION

5.1 Conclusions on the General Feasibility of Proposed Restoration Concept

The current study shows that in case of historic stone walls, missing parts or extensions can be laid up by using solid glass blocks to provide a unique and transparent restoration or conservation solution. Basing on the study, it becomes evident that connecting two dissimilar substrates is problematical due to different chemical composition, density and thermal behaviour. Since previously mentioned factors are inevitable to consider when designing safe structures, glass and stone connection require detailed analysis prior to construction. When the glass masonry system is designed as an infill between two stone masonry wall elements (crack in the structure), extra attention must be turned on thermal expansion to fit the prescribed widths. The partly decayed SW tower of Toolse castle with its uneven rough-edged historic walls adds extra complexity to the restoration concept because the edge shape varies in length and every glass block row must be analyzed separately. Therefore, a conclusion can be made that the more complex is the crack edge, the more complicated is the technology and design of the glass restoration. Also, when bonded materials have space for movements (in case of an extension instead of an infill), the design simplifies significantly, since thermal behaviour estimations must not meet strict tolerances and load distribution is easier to predict.

Another thing to bring forth is that glass restoration, to some degree, must come along with the use of traditional masonry materials. Mortars, matching with the historic stone wall's strength and composition are necessary to fill the cavities between glass block unit and the old stone structure. Also, in the scope of the current design proposal, glass is not designed for restoring the footing and foundation of the SW tower due to aesthetical reasons, unknown behaviour in terms of freeze-thaw cycles and higher risk of impacts loads. Therefore, granite stone masonry is proposed to restore the footing prior to glass additions. Also, loose debris and fallen pieces from natural stone wall might be subjected to reassembling in order to provide fixed and proper measurements of the crack where the glass masonry is designed.

Although being theoretically feasible in terms of glass-stone connection strength, the proposed restoration concept in Toolse can be problematical in terms of funding. The main articles that form a remarkably higher final cost of the project are exhaustive preliminary research, technologically sophisticated fitting of suitable glass blocks, usage of traditional, hydraulic mortars and borosilicate glass blocks and UV-curing transparent acrylate that have relatively higher price compared to other construction materials. Since the construction market and developments in the field are highly dependant on the total cost of the projects, it becomes questionable if the restoration is realistic at all, taken from the financial aspect. The author hereby shares the opinion that the concept is, beyond doubt, exceptional, but due to its exclusiveness it can provide unique architectural outcomes. Moreover, the first real example of such innovative glass block masonry façade is currently being built in Amsterdam, the Netherlands.

Another point of issue in the realization of the proposal is the aspect of maintaining the authenticity of the ruins. It is clear that the intervention and glass restoration cannot take place without any modern chemical substrates and precut hollows in the stone wall to create support surfaces for glass, but the question is the well-grounded extent that is morally and professionally unthinkable to surpass. The current proposal requires epoxy and acrylate adhesives to connect respectively glass with stone or glass blocks to form a masonry system. Also, although not visible, PVB coat or latex paint between the glass and mortar as well as polypropylene sheets for balancing the tolerances and providing straight horizontal glass block rows (although not visible) may become necessary inside the stone structure. Since the hollows and adhesives in current design proposal are inevitable, the only recommendation to give is extra care in mounting process and further research on the topic of how to connect the glass masonry to the stone wall without the necessity of making cuts into the authentic walls.

The most important thing to consider as the first step towards the realization of the concept is practical experience, as often, unexpected problems occur when building novel constructions and the behaviour of the old masonry is unknown. It is pointed out that the trial re-laying of the crack in the historic masonry wall with glass blocks would start from laboratories or small-scale objects that do not serve as architectural monuments and are located in non-prominent areas, such as historic limestone fences that can be found in rural areas.

5.1.1 Thermal Movement and Block Pattern Calculation

In the current design proposal for the SW tower of Toolse castle, the glass masonry is laid to fill the existing crack, taking into account thermal movements. Therefore, to balance horizontal movements, each row must be observed separately in order to determine suitable block in terms of its consistence (soda-lime or borosilicate) or dimensions (different prototypes proposed). Possible vertical movements are balanced by designing dilation joints with the height of 20 mm in the glass structure, dividing the whole unit into 5 sections. The existence of joints between glass segments can additionally help to meet the tolerances in order to provide precisely horizontal glass block rows.

Following conclusions can be made after preliminary analysis of the thermal movement:

1. Presented calculations are informative and not conclusive as following factors remain unclarified at the stage of design proposal: thermal expansion coefficient of old natural stone and glass blocks, exact width of uttermost stone and crack itself.
2. Laying glass blocks is complicated handwork. Good care needs to be taken when fitting suitable, predefined blocks in the crack area, paying attention to strict tolerances.
3. To simplify the construction process, first phase of the design is processing the crack edge surfaces with mortar to create an even surface for future glass connections.
4. After applying mortar, exact crack width needs to be measured (current method of measuring distances straightly from image is indirect, therefore not suitable).
5. Possible combinations of dimensions of glass blocks need to be reviewed to find out the most suitable solution (current proposed dimensions 250x300x50 mm, 230x300x50 mm, 120x300x50 mm and 80x300x50 mm). Measures similar to authentic limestone and granite blocks should be preferred. Also, smaller dimensions should be considered to fill minor gaps. This needs to be decided prior to production. To meet overlapping criterions determined in Eurocode 6 section 8.1.4.1, glass blocks with the height less than 250 mm should have minimal overlap of 40 mm per block, thus, minimal dimension for width must be 80 mm. The criterion from Eurocode 6 is taken as recommendation and it should be acknowledged that the guide expands upon stone masonry with mortar, not glass blocks and adhesives.
6. In the production process, both borosilicate and soda-lime glass blocks need to be manufactured – mostly borosilicate as it is confirmed to match better with dominating limestone in terms of thermal expansion. The lower part of the tower where glass is likely to be connected to granite, soda-lime must be used to create a glass structure that is as similar as possible to the historic stone wall from the thermal movement point of view.
7. When laying glass bricks, lime mortar needs to be injected into cavities between old walls and glass masonry to prevent gaps that are opened to rainfall and pose a threat to the structure due to weathering. Altogether, a mortar layer between authentic stone and glass is suggested to be 15-30 mm wide in order to provide maximal strength of the connection.
8. On special areas where fabricated glass block sizes are unsuitable to match with stone walls, natural stone as well as mortar should be used to reduce crack width and provide proper row size that can easily be filled with glass.

5.1.2 Structural Design

At present, the experiments with the intention to prove solid glass blocks to be structurally safe choice for construction have been successful. The blocks have shown a relatively good behaviour while being tested separately as well as in the role of the masonry system element. Proper adhesives to bond blocks together also show good characteristics in forming a fully transparent monolithic masonry. Although there are no relevant design rules or codes for such a branch of study, basing on reliable test results and structural analysis, solid glass blocks can be taken into consideration as qualifying masonry units.

The current design proposal, focusing on Toolse order castle with a specific crack in the SW tower, finds a possible method how to solve the connection issue between two dissimilar substrates – glass and stone. The proposed solution – skillful brick laying with predefined type and size of the block, adhesively connected to the stone through horizontal adhesion surfaces – is elaborated by considering thermal movements, requirements for bonding material and inner forces acting upon the connection area. The final conclusion that the connection will serve as designed can be made, relying on the results of conducted experiments of adhesive's shear strength and further FEM analysis of glass masonry dead load distribution pattern. Neither the weak resistance of the selected epoxy adhesive nor excessive values of dead loads from the glass structure to the connection surface pose a threat to the structural feasibility of the proposal. Furthermore, to minimise the degree of intervention with respect to the authenticity of the monument, the support areas that are required to be cut in the stone structure can be corrected, depending on the magnitude of acting load in specific location, determined in FEM software.

Nevertheless, the most critical and fundamental aspect of the structural safety of the whole design concept is the strength capacity of the historic walls that was, due to high complexity, counted out from the scope of the current thesis (only the rough assumption of compressive strength to be minimum of 2,00 MPa was adopted). Without detailed and well-grounded calculations to evaluate the structural strength of the historic natural stone masonry in terms of compressive, shear, tensile and equivalent stresses, no final conclusion can be made whether the stone structure in the specific tower of Toolse castle could be structurally safe to accommodate the solid glass block masonry to fill up the crack.

What concerns load distribution, it can be assumed that despite the rigid adhesive connections that are designed as surfaces to transfer loads from the glass to the stone, longer horizontal surfaces of stone masonry will have an impact on the glass due to gravity. As the stone structure is possibly supported on the glass blocks and hydraulic lime mortar layer, reallocation of measured force components may occur and glass-stone connection with epoxy bonding is subjected to somewhat bigger loads. Since the general distribution of dead loads from the glass is well-diffused, it can be estimated that the change is insignificant and need no further consideration. Simultaneously, when beetling stone masonry is supported by glass blocks from the bottom, it could lead to the relief of stresses and moments that currently act upon the stone masonry juts. That being the case, re-laying the crack with glass blocks can have homogenizing effect on the whole structure of the SW tower. Due to the eccentricity of the designed glass masonry system, thick stone wall with uneven surfaces might be exposed to extra shear forces when, for example, one third of the beetling wall part becomes supported by glass and the rest is left to hang. First of all, it is necessary to ascertain if these areas exist. If it holds true, a solution of local enlargement within the depth of the glass block masonry system from 300 mm to the full depth of the stone wall (ca 1350 mm) can be proposed.

5.2 Required Further Research

Using solid glass block masonry system in building practice is entirely new approach and there is no doubt that any kind of further study in the field of glass blocks or masonry system would have a positive impact on developing a proven methodology for the wider usage of described material. To pave the way for glass blocks in order to become commonly used building material, steps need to be taken in the production technology, since at present, the process time to create a glass block is unacceptably slow for fast-paced construction market and current demands.

Another shortcoming is the relatively high cost of the glass blocks, suitable adhesive and proposed technology of laying the masonry to fit with historical walls. Therefore, another significant key question for further research in the field is how to develop the current technology to be more cost-efficient.

Considering the case study of Toolse castle where restoration of the extensive crack in the SW tower with transparent glass block masonry system was taken as an objective, the critical steps that must follow in order to provide fully analyzed and feasible design project is:

1. detailed calculations to estimate the strength capacity of the historic natural stone wall;
2. detailed evaluation of the situation of the soils and efficiency of the current consolidation measures (tension rods);
3. building a realistic small-scale mock-up/studying existing similar small-scale masonry (that is not architectural monument) to evaluate thermal behaviour in the connection area as well as possible technology issues in the stage of intervening the historic structure, gluing, leveling and laying the glass block masonry;

The idea of the current design proposal was based on completely transparent, self-supporting glass restoration using solid glass blocks. However, if the specific case of Toolse tower is observed furthermore in terms of future restoration with glass, alternative materials can be combined to the design, such as opaque steel beams or clamps as a support or tension element to simplify the design and technology. Also, this type of approach could lead to possible saving in total cost, as for example borosilicate glass blocks could be that way replaced by soda-lime solid blocks.

SUMMARY

As a material, glass can offer exciting solutions of restoration and conservation due to its transparency and the aspect of perception. Load bearing solid glass blocks has proven to be safe choice to form a transparent masonry system, connected adhesively with UV-curing colourless acrylate. In the current thesis, the problems of connecting glass with historic stone structures were reviewed, followed by the suggestion of a feasible solution for glass restoration in the specific case of the SW tower in Toolse castle. As for results of the study, following aspects are pointed out:

1. Glass blocks can be used to restore the extensive crack in the tower in terms of the local strength and thermal movements in the connection area. For that, epoxy adhesive for horizontal connections and natural hydraulic lime to fill the cavities between glass and stone are proven to be effective in terms of strength and durability. MS polymer based adhesive, also considered strong enough to bear stresses from the glass structure is not considered as suitable bonding element due to its slow curing and low age-resistance. It is critical to acknowledge that the prerequisite for proposed restoration is detailed estimation of the inner stresses in the historic stone masonry.

2. The most suitable adhesive substrate in the designed glass-stone connection is considered to be epoxy-based 2-component glue. Despite being rigid, when glass is bonded to the stone through smaller horizontal adhesion surfaces following regular pace pattern throughout the length of the observed crack, the occurring stresses from self-weight of the glass masonry even in the most critical contact surface area will not exceed the stress capacity value of the connection itself, derived from the analysis of the conducted shear test results and by rough estimation of the local compressive strength of the stone.

3. Proposed restoration of filling the crack with fully transparent glass block masonry is considered to be technologically complex handiwork that requires skillful assembling of the predefined glass blocks in terms of glass type (borosilicate or soda-lime) and precise dimensions. In the current case study, the crack is proposed to be laid mostly out of borosilicate blocks with some exceptions in lower third of the tower where granite is used in the historic masonry – in this case, soda-lime blocks are likely to be used. However, each row is unique and must be observed separately after more detailed analysis of the crack width and the composition of the stone masonry.

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APPENDIXES

Appendix 1. Characteristics of Heat-treated Glass

Table 8. Characteristics of heat-treated glass [76]

	Wind-loading strength	**Thermal stress breakage resistance (edge-strength)**	**Impact resistance***	**Break pattern upon impact**	**Penetration resistance (afterbreakage)**
Monolithic Annealed	Basic Glass Strength (1x)	Low resistance to high thermal stresses	Moderate	Many cracks forming large, long and narrow shards	Limited after breakage
Heat-strengthened	Two times basic glass strength of the same thickness (2x)	Resists high thermal stresses	Stronger than annealed	Simple, few cracks and larger pieces	Limited after breakage
Fully Tempered	Four times basic glass strength of the same thickness (4x)	Resists high thermal stresses	Stronger than heat-strengthened. Can qualify as "Safety Glazing"	Entire sheet breaks into small, irregular shaped fragments	None after breakage
Laminated Annealed	75% – 100% as strong as monolithic annealed of the same thickness	Low resistance to high thermal resistance	Moderate. Can qualify as "Safety Glazing"	Starburst pattern from impact point, one or both sheets may break	Good penetration resistance (proportional to interlayer thickness)
Laminated Heat-strengthened	Almost twice as strong as laminated annealed of the same thickness (1,5x – 1,8x)	Resists high thermal stresses	Stronger than annealed. Can qualify as "Safety Glazing"	Simple, few cracks and larger pieces, one or both sheets may break	Good penetration resistance (proportional to interlayer thickness)
Laminated Fully Tempered	Almost four times as strong as laminated annealed of the same thickness (3,0x– 3,6x)	Resists high thermal stresses	Stronger than heat-strengthened. Can qualify as "Safety Glazing"	One or both sheets may break into small, irregular shaped fragments	Good penetration resistance (proportional to interlayer thickness)

* Impact resistance and break pattern after breakage are dependent upon the size, weight and type of impactor and the speed at which it impacts the glass.

Appendix 2. Embodied Energies of the Materials

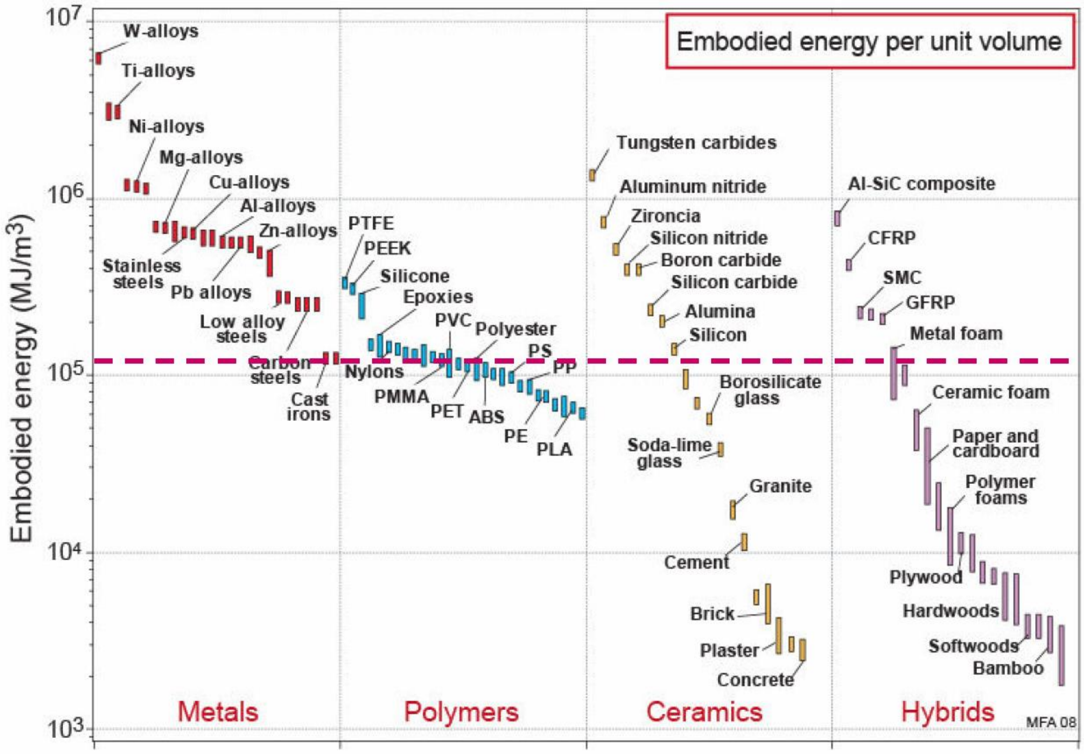


Figure 49. Embodied energy per unit volume according to M. Ashby [31]

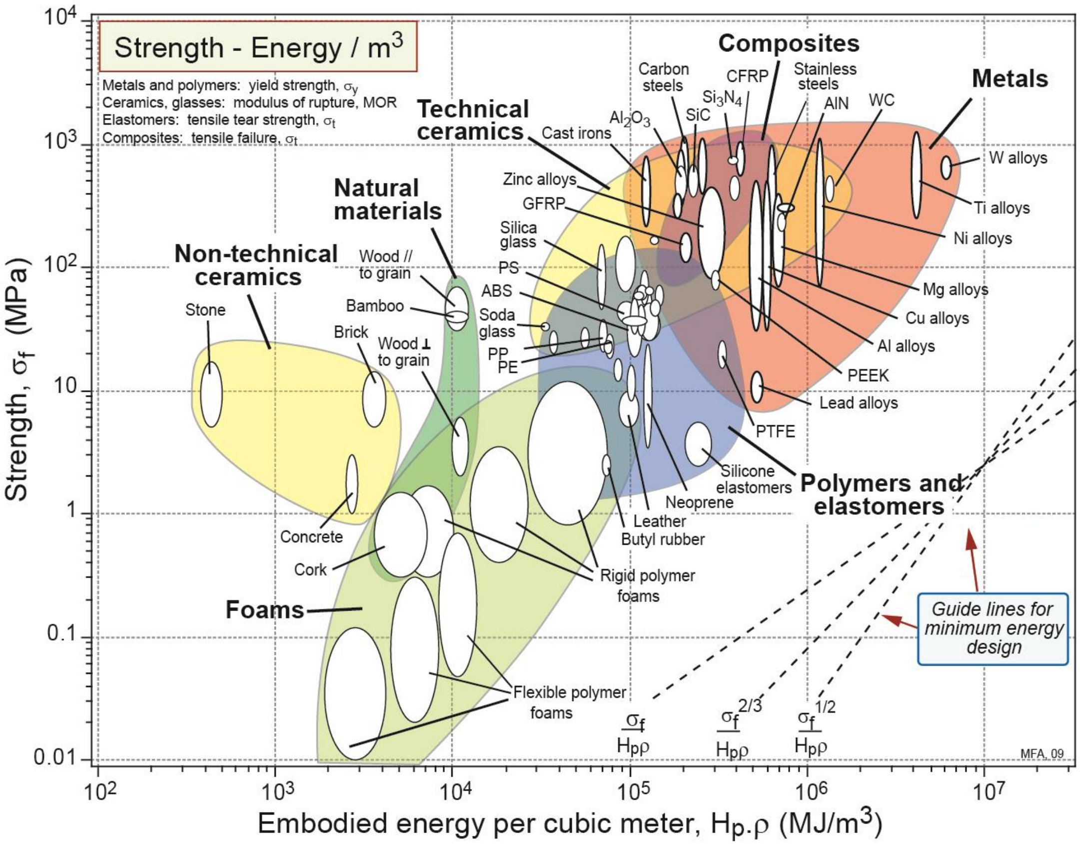


Figure 50. Embodied energy per unit cubic meter according to M. Ashby [31]

Appendix 3. Existing Examples of Glass Blocks in Architecture

Maastricht Academy of Arts & Architecture [77]

Architects: Wiel Arets Architects | Project Year: 1993
Location: Maastricht, The Netherlands | Photographs: Jan Bitter

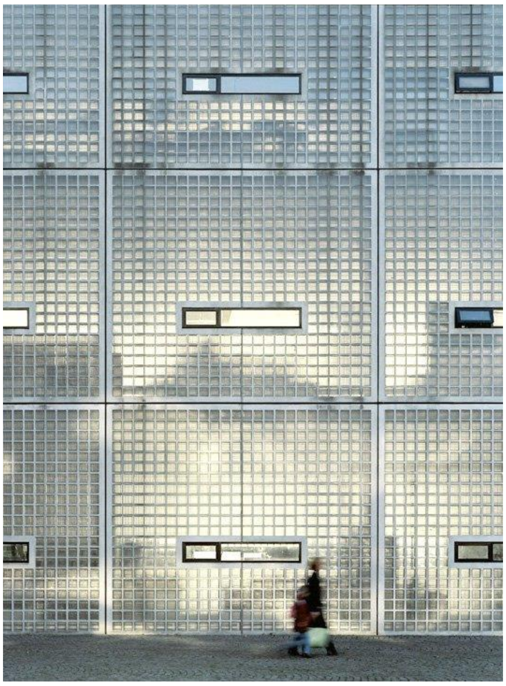


Figure 51. The glass block façade from the street

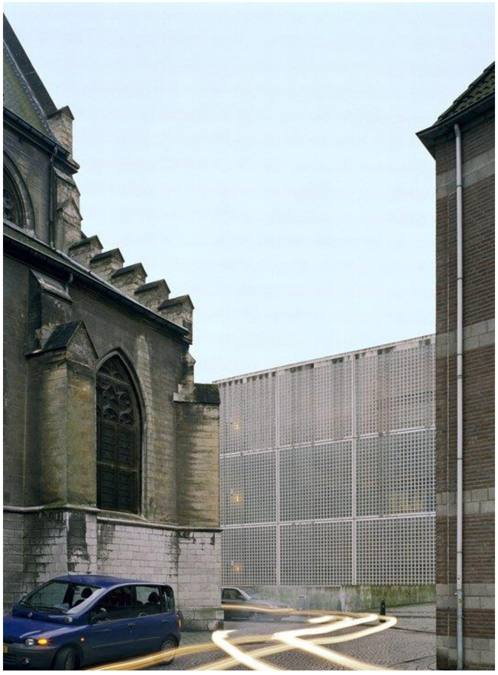


Figure 52. Convergence of the glass block house and historic buildings

Maison Hermes [78]

Architects: Renzo Piano BW | Project Year: 1998 – 2006
Location: Tokyo, Japan | Photographs: F.Lariviere/M. Denance

Figure 53. Impressions of the Maison Hermes at night

Optical Glass House [53]

Architects: Hiroshi Nakamura & NAP Location: Hiroshima, Japan

Project Year: 2012 Photographs: Koji Fujii/Nacasa&Partners

Figure 54. Street-side façade

Figure 55. Glass block texture from the exterior

Atocha Monument [79]

Architects: Estudio FAM Location: Madrid, Spain

Project Year: 2007 Source: www.worldarchitecturefestival.com (copyright from source)

Figure 56. Glass masonry of Atocha

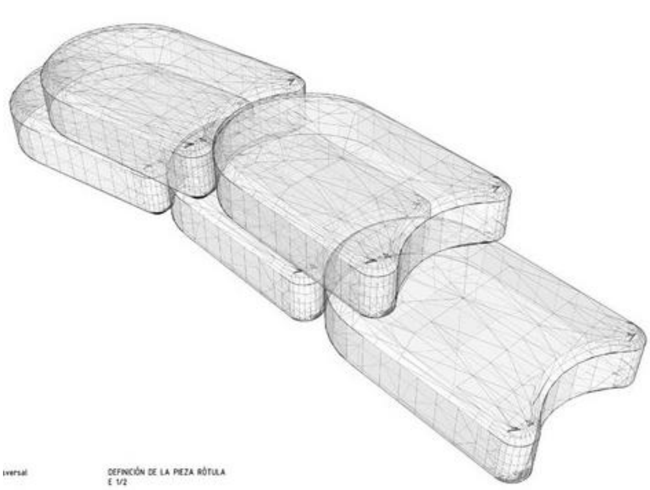


Figure 57. Technology and shape of borosilicate glass blocks

Appendix 4. 3D Impressions of the Glass Block Façade for the Crystal House in Amsterdam by Ashendene-Leeuwenstein BV

Figure 58. Impressions of the façade in daylight

Figure 59. Impressions of the façade at nigh

Appendix 5. Location of Toolse Order Castle

Figure 60. Toolse on the map of Estonia [80]

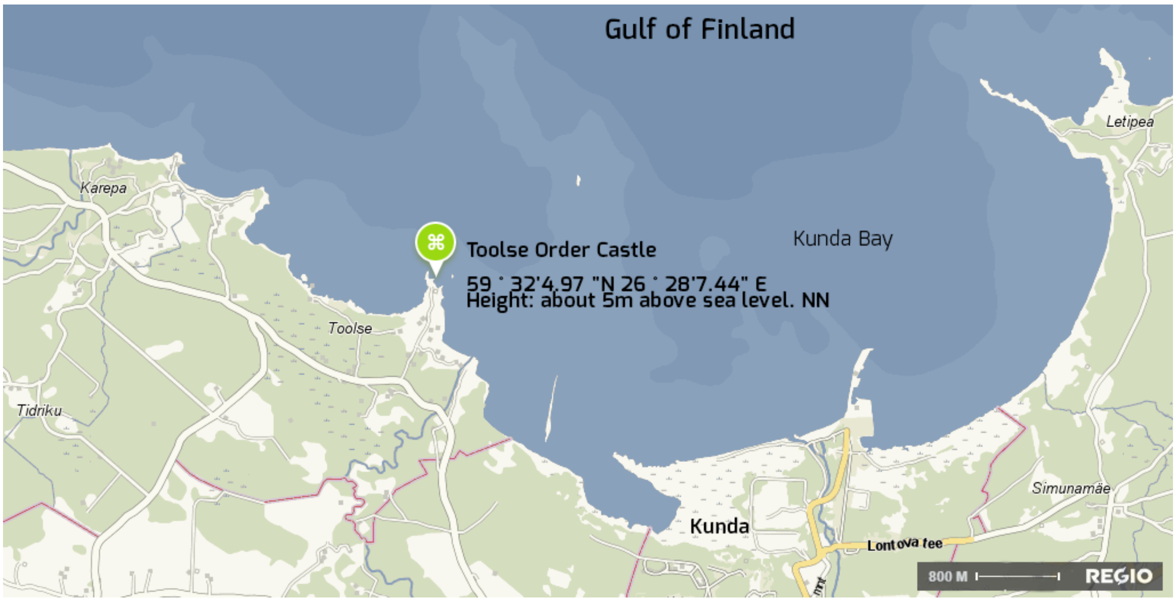


Figure 61. Detailed location data of Toolse castle [80]

Appendix 6. Data of Shear Tests for Glass-stone Connection Specimens

Specimen preparation:

- Brick and glass specimens cut into matching sizes with disk saw;
- Brick specimens dried in the oven for 3 hours in +21°C in order to glue to dry surfaces;
- Glass surfaces cleaned with propanol, brick surfaces with pressure air and steel brush;
- Adhesives applied in room temperature conditions (+21°C; RH 40–60%);
- Curing time: 6 days (144 hours);
- Wet specimens put into tap water 4 hours prior testing.

Specimen sizes: Small (35x50x20 mm) and large (50x50x20 mm)
Glass surface specification:

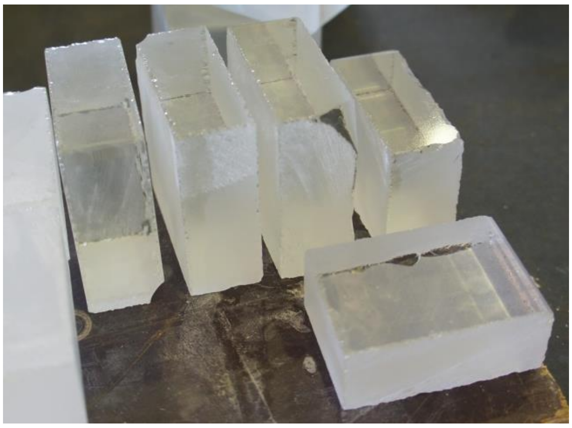


Figure 61. Glossy (transparent surface instead of matte)

Ceramic surface specification:

Figure 62. Medium rough (salt on surface)

Figure 63. Rough (loose particles on surface)

Typical failure pattern types:

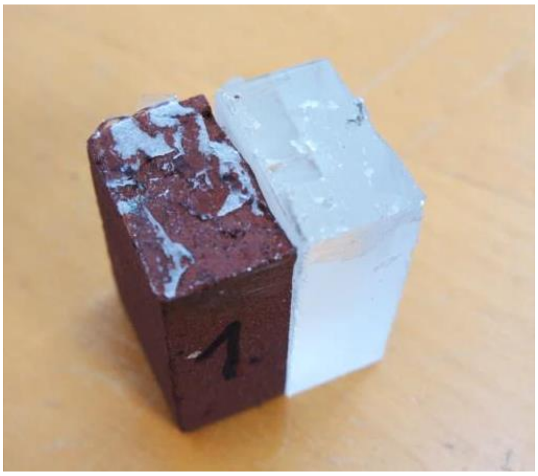


Figure 64. Glass shred sliced away (A)

Figure 65. Slicing ceramic strip (B)

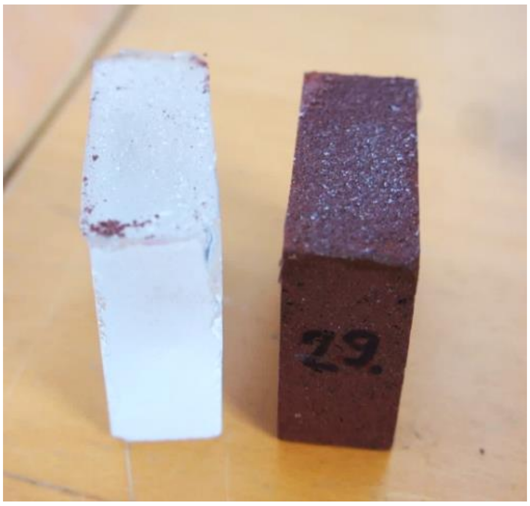


Figure 66. Complete delamination (C)

Figure 67. Fracture of the brick (D)

Figure 68. Slicing glass strip (E)

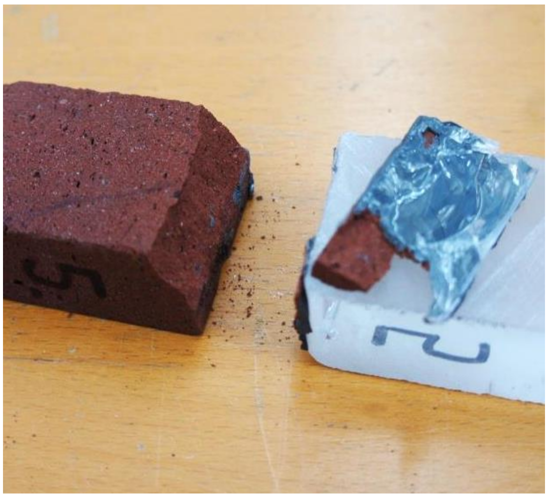


Figure 69. Disjointed adhesive layer (F)

Table 9. Test Set Number 1
Conditions: +21°C; RH 40–60%
Adhesive: MD-MS Polymer by Marston-Domsel GmbH (modified silane polymer)

Specimen number	**1**	**2**	**3**	**10**	**19**	**29**
Specimen size	Small	Small	Small	Small	Large	Large
Glass surface	Glossy	Glossy	Glossy	Glossy	Glossy	Glossy
Ceramic surface	Medium rough	Medium rough	Rough	Rough	Medium rough	Rough
Specified surface area	20 x 35 mm	20 x 34,5 mm	20 x 34,5 mm	20 x 35 mm	20 x 47 mm	20 x 50 mm
Gluing quality	Insufficient dose of glue applied	Minor air gaps between	Normal	Normal	Normal	Minor air gaps between
Moisture condition	Wet	Wet	Dry	Dry	Dry	Wet
Failure load F_{max}	310,6 N	770,4 N	976,8 N	831,2 N	1009,2 N	882,1 N
Failure pattern	A (defective specimen)	B	B	B	C	C
Shear stress σ	0,44 MPa	1,12 MPa	1,42 MPa	1,19 MPa	1,07 MPa	0,88 MPa

Table 10. Test Set Number 2
Conditions: +40°C; RH 40–60%
Adhesive: MD-MS Polymer by Marston-Domsel GmbH (modified silane polymer)

Specimen number	**9**	**11**	**17**	**18**
Specimen size	Small	Small	Large	Large
Glass surface	Glossy	Glossy	Glossy	Glossy
Ceramic surface	Rough	Rough	Medium rough	Medium rough
Specified surface area	20 x 35mm	20 x 35mm	20 x 47mm	20 x 47mm
Gluing quality	Air gaps between	Normal	Normal	Normal
Failure load F_{max}	459,7 N	882,0 N	1116,7 N	1118,0 N
Failure pattern	C (ductile; defective specimen)	C (ductile)	C (ductile)	C (ductile)
Shear stress σ	0,66 MPa	1,26 MPa	1,19 MPa	1,25 MPa

Table 11. Test Set Number 3
Conditions: +21°C; RH 40–60%
Adhesive: Araldite® 2013 by Huntsman Advanced Materials (epoxy)

Specimen number	**4**	**6**	**7**	**12**	**13**	**15**	**16**	**21**	**22**	**23**	**32**
Specimen size	Small	Small	Small	Small	Small	Small	Small	Large	Large	Large	Large
Glass surface	Glossy	Glossy	Glossy	Glossy	Glossy	Glossy	Glossy	Glossy	Glossy	Glossy	Glossy
Ceramic surface	Medium rough	Medium rough	Medium rough	Rough	Rough	Rough	Rough	Medium rough	Medium rough	Medium rough	Rough
Specified surface area, mm	20 x 30	20 x 35	20 x 35	20 x 35	20 x 35	20 x 35	20 x 35	20 x 45,5	20 x 50	20 x 50	20 x 50
Gluing quality	Insufficient dose of glue applied	Normal	Insufficient dose of glue applied	Normal	Normal	Minor air gaps between	Normal	Minor air gaps between	Normal	Normal	Normal
Failure load F_{max}, N	1956,6	2925,8	1800,4	2451,8	2694,4	1832,1	3518,3	3228,6	4536,4	3967,4	6016,8
Failure pattern	D + B	D + B	D + B	D + B	D + B	D + B	D + B	D + B	D + E	D + B	D + F
Shear stress σ, MPa	2,80	4,18	2,57	3,50	3,85	2,62	5,03	3,55	4,54	3,97	6,02

Table 12. Test Set Number 4
Conditions: +40°C; RH 40–60%
Adhesive: Araldite® 2013 by Huntsman Advanced Materials (epoxy)

Specimen number	**5**	**8**	**14**	**20**
Specimen size	Small	Small	Small	Large
Glass surface	Glossy	Glossy	Glossy	Glossy
Ceramic surface	Medium rough	Medium rough	Rough	Medium rough
Specified surface area, mm	20 x 35	20 x 35	20 x 35	20 x 48
Gluing quality	Normal	Normal	Normal	Normal
Failure load F_{max}	1486,7 N	1539,0 N	1675,2 N	2191,9 N
Failure pattern	F	B	D + B	D + B
Shear stress σ	2,12 MPa	2,20 MPa	2,39 MPa	2,28 MPa

Appendix 7. St Astier Natural Hydraulic Lime (NHL 3,5) Product Data [81]

Conforms to European Norms
EN 459 and BS 459
Strength factor: 3,5
(Moderately hydraulic)
Residue @ 0.09 mm: 6,5%
Density (volumetric weight):
typical 650 gr/litre
Available (free) lime after slaking
$Ca(OH)_2$: 25% +

Packing: 25 kg bags
Contains no additives.
Whiteness index: 72
Surface cover (cm^2 per gram): 9000
Expansion: < 1 mm
Residue of quick lime after slaking:
< 1%
Shelf life: 8-12 months kept sealed and dry

MORTARS		Compressive strength (N/mm^2)			Elastic Moduli (MPa)		
MIX RATIO	EN 459*	1:2	1:2.5	1:3	1:2	1:2.5	1:3
7 DAYS		0,75	0,57	0,53			
28 DAYS	3,5*	1,88	1,47	1,34	9010	9000	8070
6 MONTHS		7,1	5,34	3,94	15260	13501	13150
12 MONTHS		7,5	5,9	3,9	15280	13620	13150
24 MONTHS		8,63	6,00	3,97	17480	13785	13670
Consumption for $1m^3$ of mortar kg +- 10%		305	244	216			

EN 459/BS 459 (mortar ratio 1:1 by volume, with ISO 679 Sand)

Mixing: can be mixed in cement mixers
Application by spray gun: possible
Working temperatures: not below 5°C or above 30°C. Make sure that high suction materials are thoroughlydampened before application. Avoid rapid drying due to high temperatures or strong winds by curing with a light water mist several times a day if necessary.
SUITABLE FOR LATH WORK/LIME CONCRETE/INJECTION/GROUTING
Reworking: possible within 12 hours
Mortar composition: MASONRY/POINTING/ CAPPING/ BEDDING/ ASHLAR
Binder: sand ratio: from 1:1.5 to 1:3 depending on the support/background conditions, the size of the joint and the fineness of the sand. Always use well graded sands (3–4mm down to 75 microns).
RENDERING
A. Scratch coat (3–5 mm) 1 VOLUME OF NHL 3.5 : 1.5 VOLUMES OF SAND
B. Undercoat (15–20 mm) 1 VOLUME OF NHL 3.5 : 2 VOLUMES OF SAND*
C. Finishing (5–10 mm) 1 VOLUME OF NHL 3.5 : 2.5 VOLUMES OF SAND
With very fine sands possibly containing clays the binder content may have to be reduced.

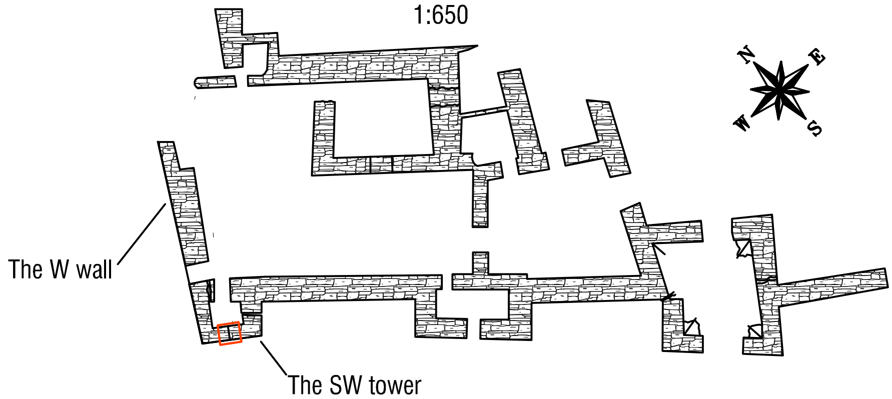
*At this dosage the consumption is approx. 0,35 kg of NHL 3,5 per m^2 for each mm thickness.

Appendix 8. Architectural Drawings

Ground plan of the ruins of Toolse order castle

Figure A Ground plan on the base of LLC Zoroaster project No 12072013/AK

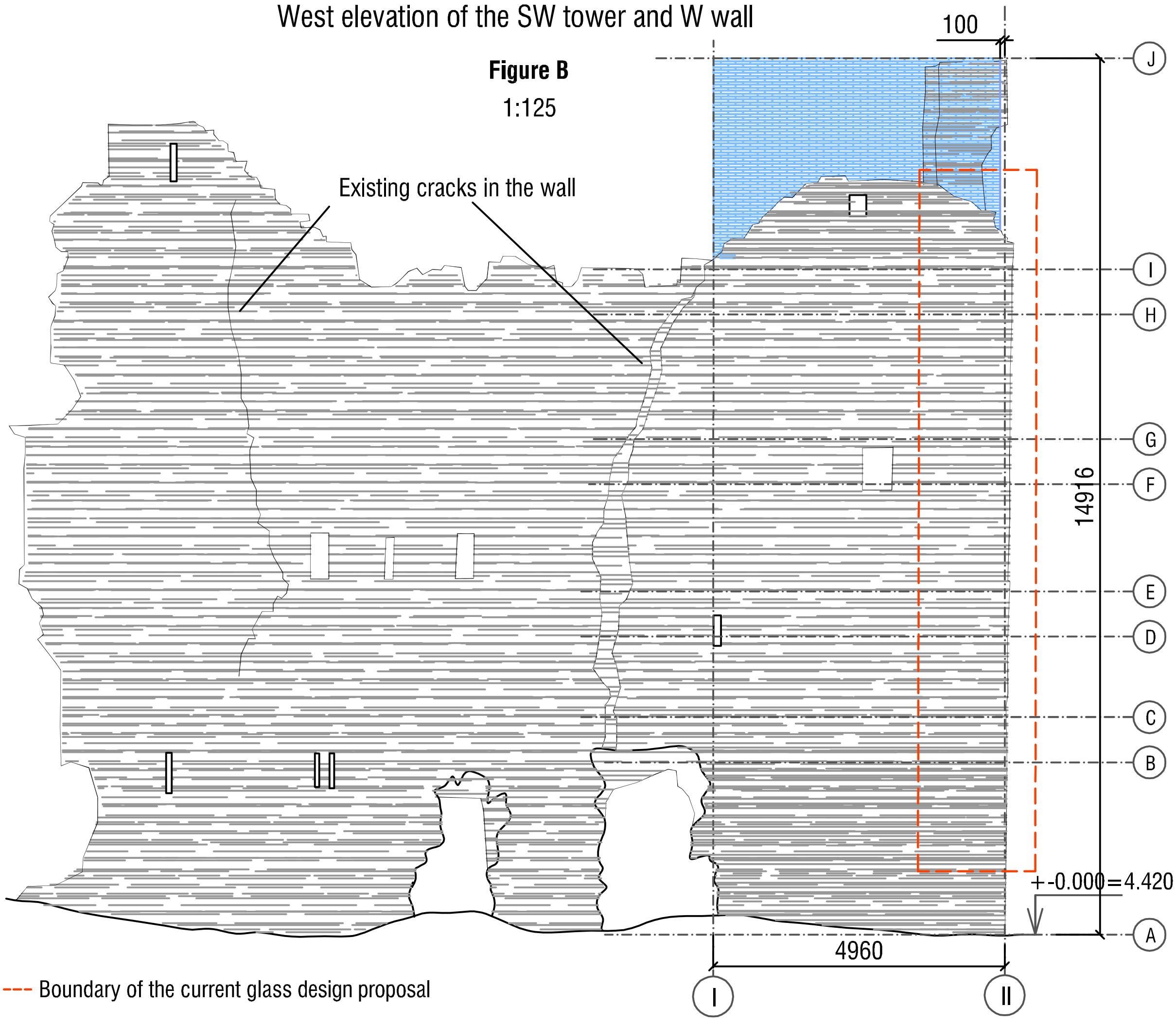
1:650



West elevation of the SW tower and W wall

Figure B

1:125



--- Boundary of the current glass design proposal

TTÜ Tartu College of Tallinn University of Technology	Master's thesis	Pages: 1/4	Scale: 1:650/1:125
Student: Kaisa Karron	Name: Drawing 1: Ground plan of the ruins of Toolse castle; West elevation of the SW tower and W wall		
Supervisor: Frederic A. Veer (TU Delft)			
Secondary supervisor: Ivar Talvik	Project name: Restoration of Architectural Monuments with Load Bearing Solid Glass Blocks. Sample Design Proposal for Glass-stone Connection		
Department of Technology			

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South elevation of the SW tower

Figure A
1:100

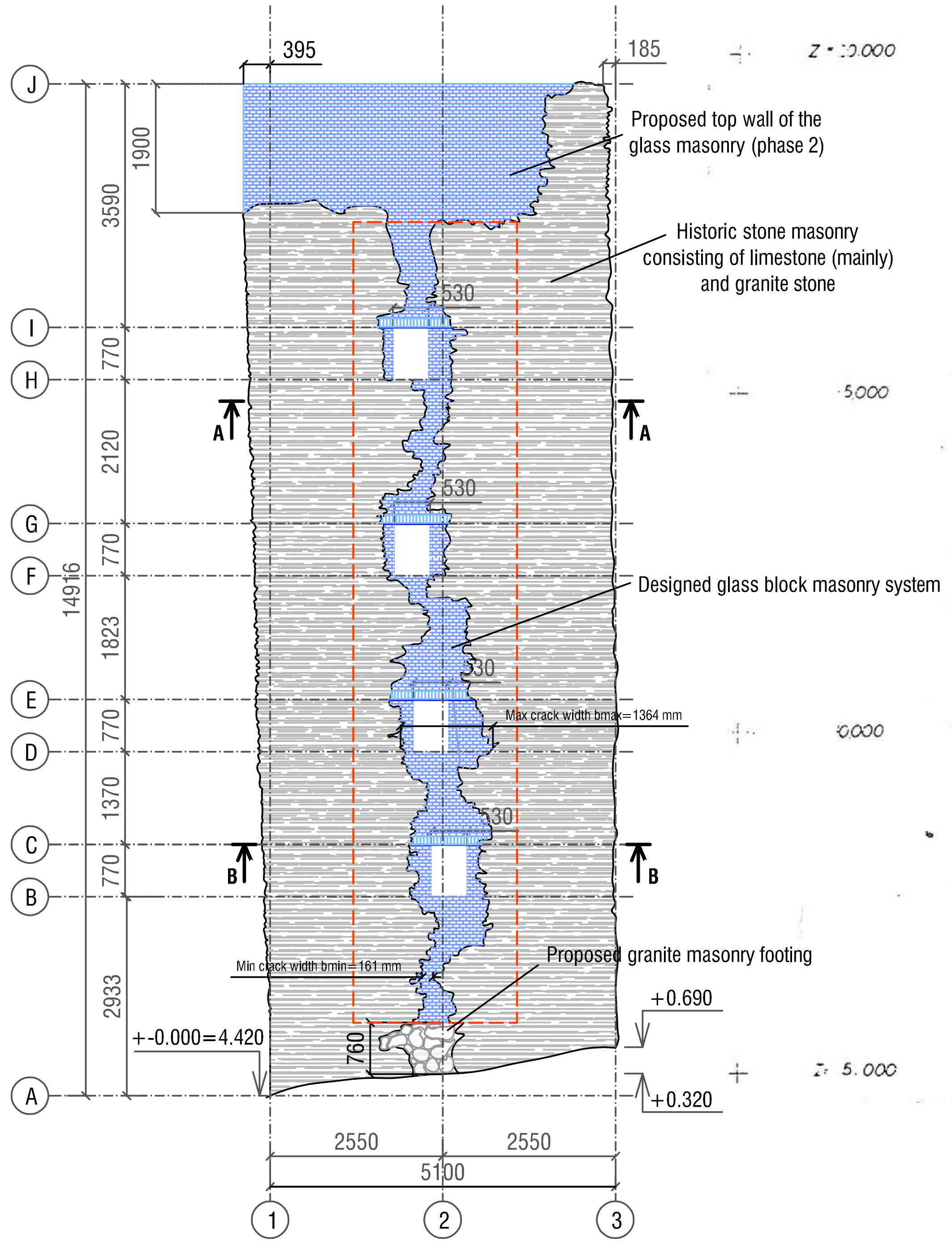


Figure B
Detailed dimensioning of the SW tower from the conservation project by H.Uuetoa from 2004

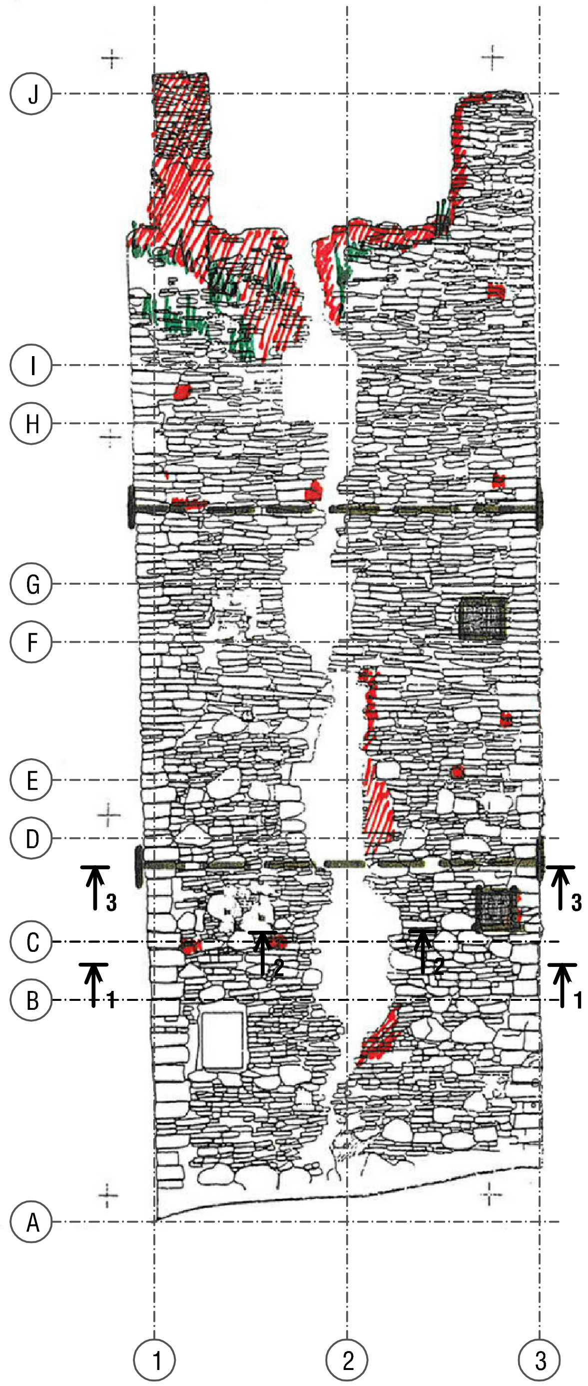
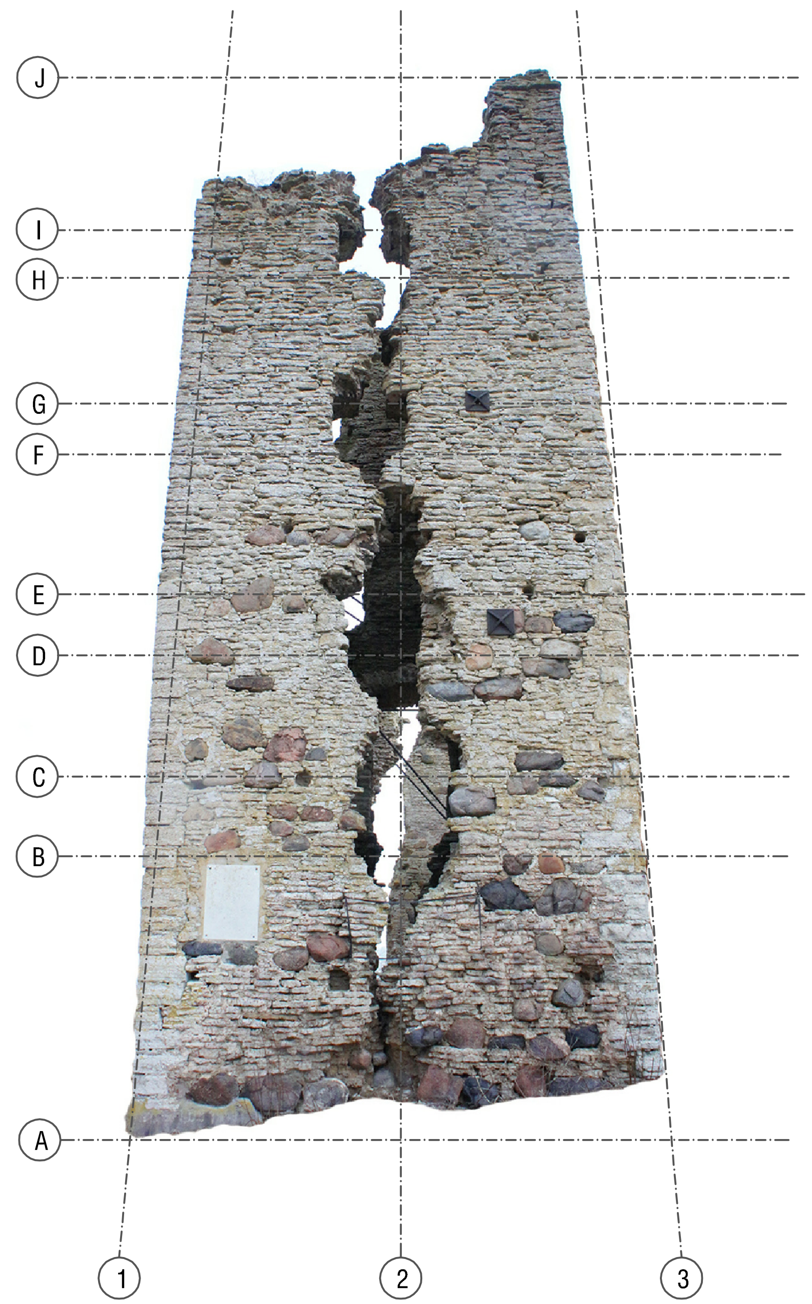


Figure C
Descriptive photograph of the SW tower and its current situation



Notes:

1. Widths of the glass blocks are illustrative.
2. In Figure B, red marks the decayed/partly decayed part of the historic masonry (by 2004).

- Boundary of the current glass design proposal
- Designed dilation joints b=20mm sealed with silicone sealant
- Location of horizontal prefabricated lintel

Tartu College of Tallinn University of Technology TTÜ	Master's thesis	Pages: 2/4	Scale: 1:250
Student: Kaisa Karron	Name: Drawing 2: South elevation of the SW tower		
Supervisor: Frederic A. Veer (TU Delft)			
Secondary supervisor: Ivar Talvik	Project name: Restoration of Architectural Monuments with Load Bearing Solid Glass Blocks. Sample Design Proposal for Glass-stone Connection		
Department of Technology			

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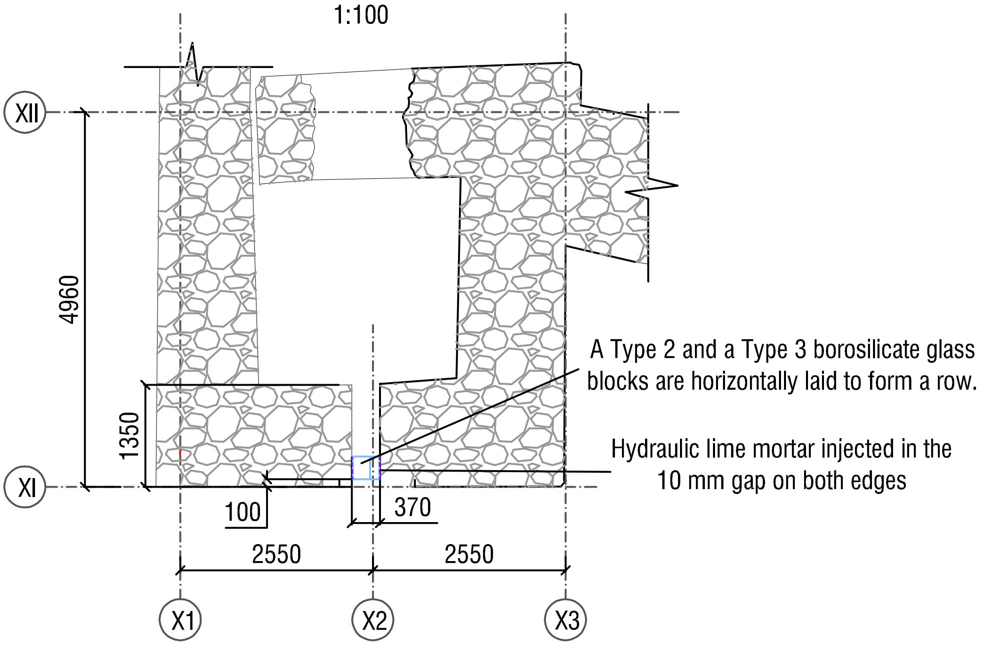
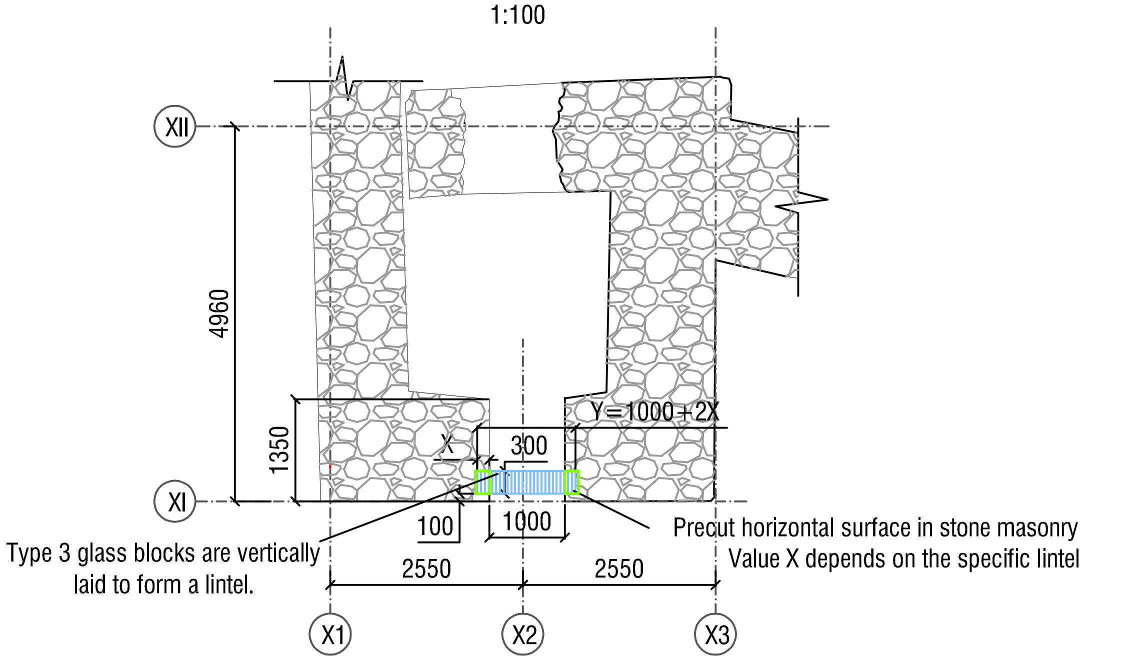
Sections A-A and B-B in the SW tower



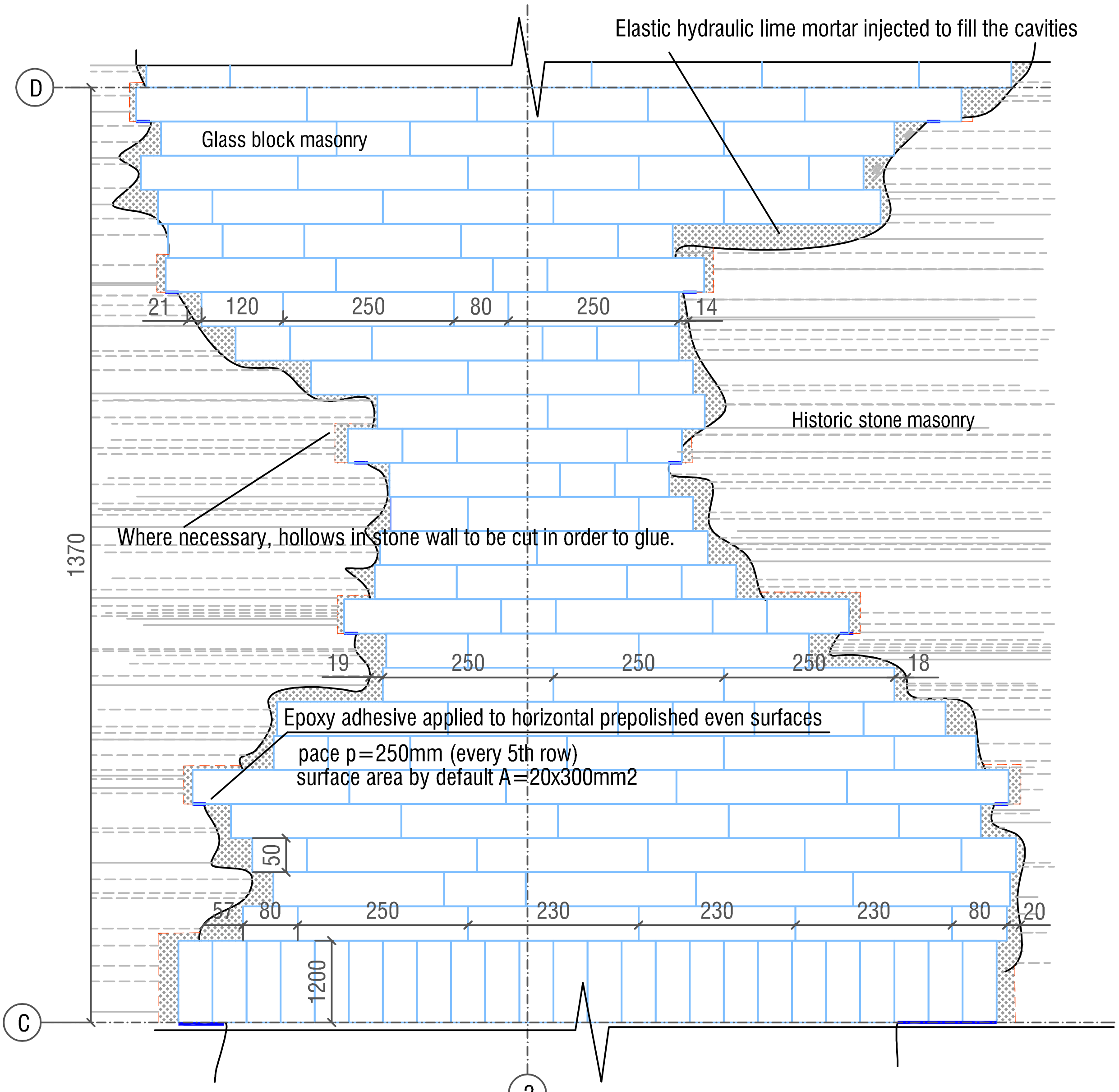


TTÜ Tartu College of Tallinn University of Technology	Master's thesis	Pages: 3/4	Scale: 1:100
Student: Kaisa Karron	Name: Drawing 3: Sections A-A and B-B in the SW Tower		
Supervisor: Frederic A. Veer (TU Delft)			
Secondary supervisor: Ivar Talvik	Project name: Restoration of Architectural Monuments with Load Bearing Solid Glass Blocks. Sample Design Proposal for Glass-stone Connection		
Department of Technology			

Glass-stone connection detail

Figure A

1:10



Notes:

1. Type 1-4 glass blocks are used to lay masonry rows.

Rigid adhesive connection (epoxy bonding)

Intervention to the stone masonry

Tartu College of Tallinn University of Technology TTÜ	Master's thesis	Pages: 4/4	Scale: 1:10
Student: Kaisa Karron	Name: Drawing 4: Glass-stone connection detail		
Supervisor: Frederic A. Veer (TU Delft)			
Secondary supervisor: Ivar Talvik	Project name: Restoration of Architectural Monuments with Load Bearing Solid Glass Blocks. Sample Design Proposal for Glass-stone Connection		
Department of Technology			

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Appendix 9.1 Data of FEM Analysis

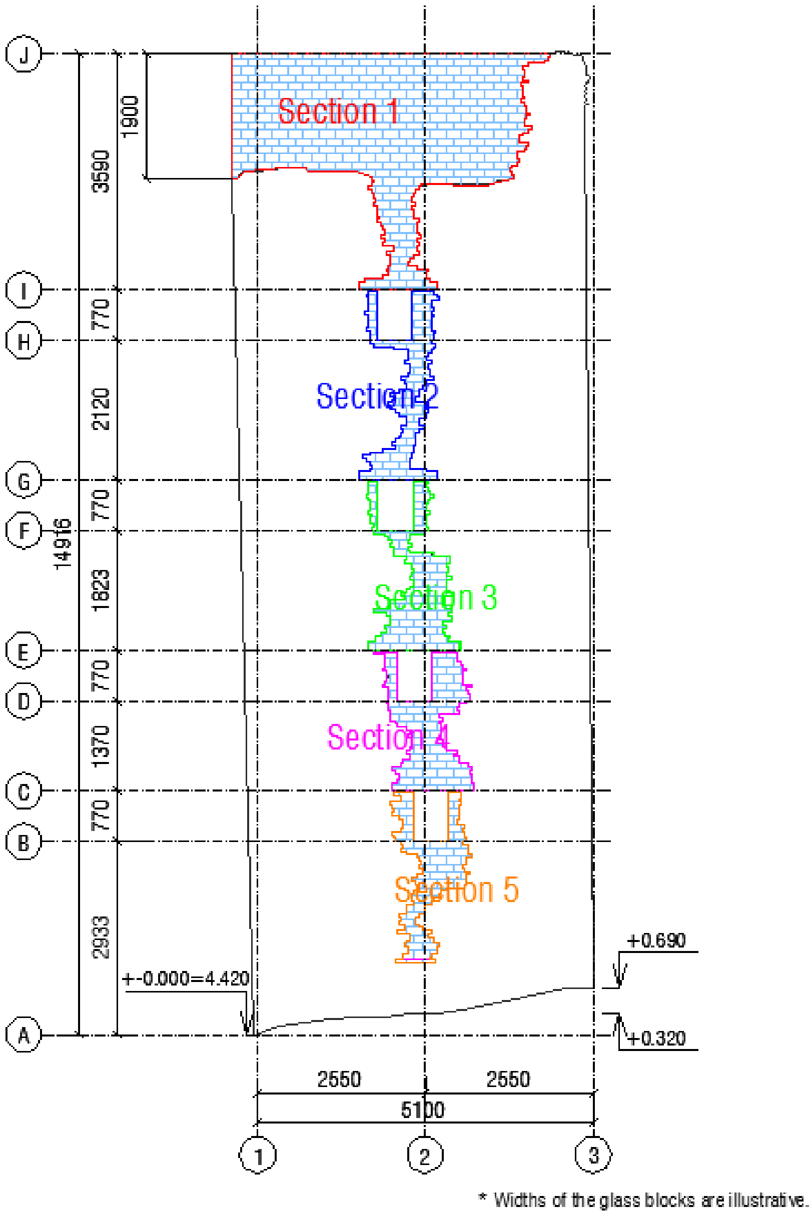


Figure 70. General drawing of the glass sections

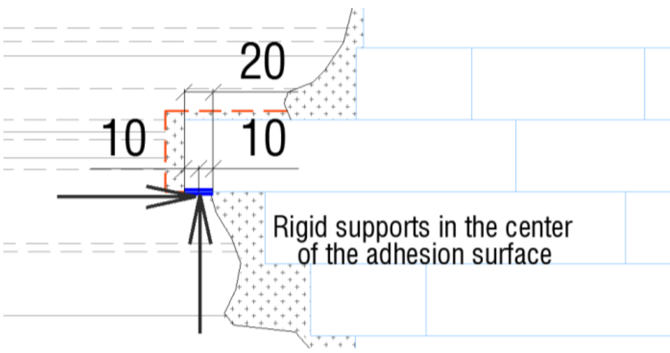


Figure 71. Schema of the designed supports

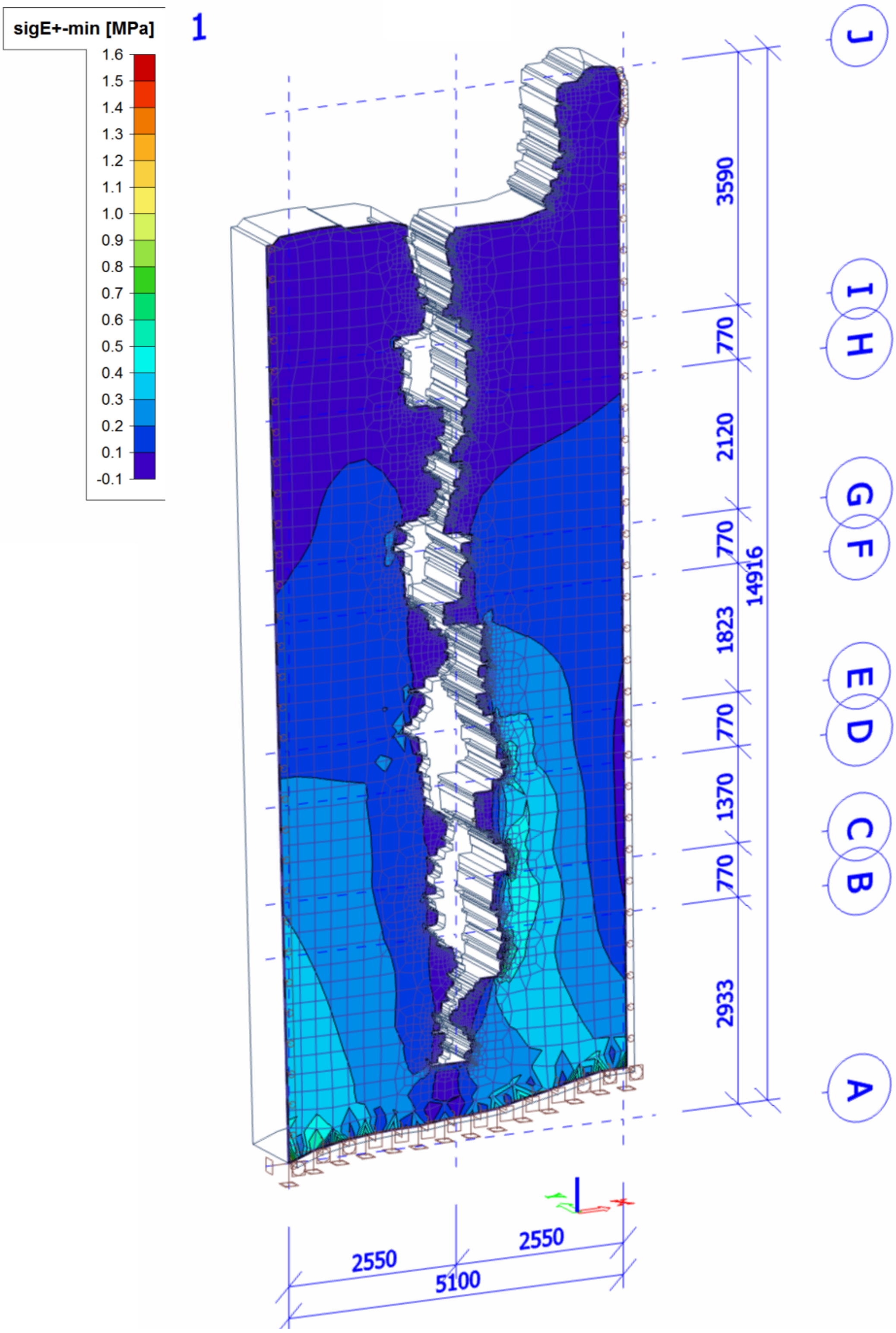


Figure 72. SW tower 2D model (screen proof from Scia Engineer 15). Informative graphical data of the equivalent (von Mises) stresses in the stone structure from the load combination 1: Self-weight (Stone Masonry) + Point Loads from Glass

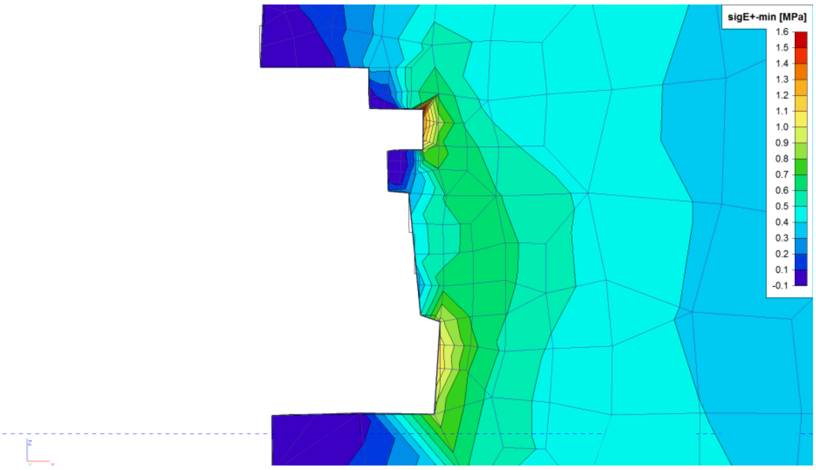


Figure 73. Close-up of the 2D model of the SW tower above axis C (screen proof from Scia Engineer 15). Inner stress magnitudes in the natural stone masonry by the load combination 1: Self-weight (Stone Masonry) + Point Loads from Glass

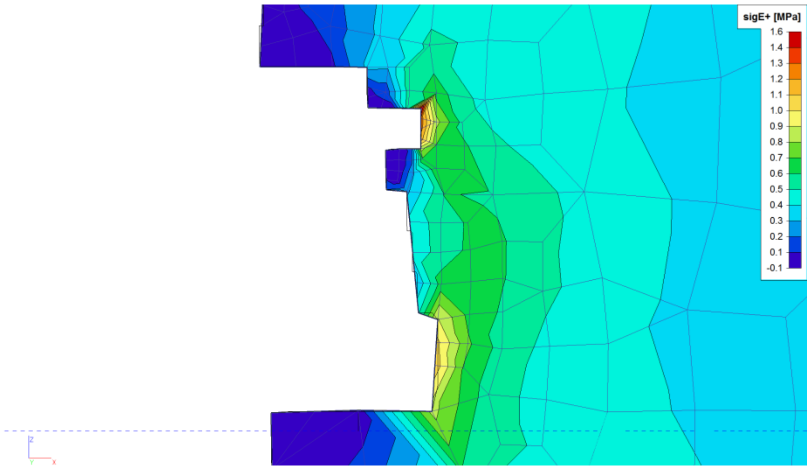


Figure 74. Close-up of the 2D model of the SW tower above axis C (screen proof from Scia Engineer 15). Inner stress magnitudes in the natural masonry from the self-weight of the structure

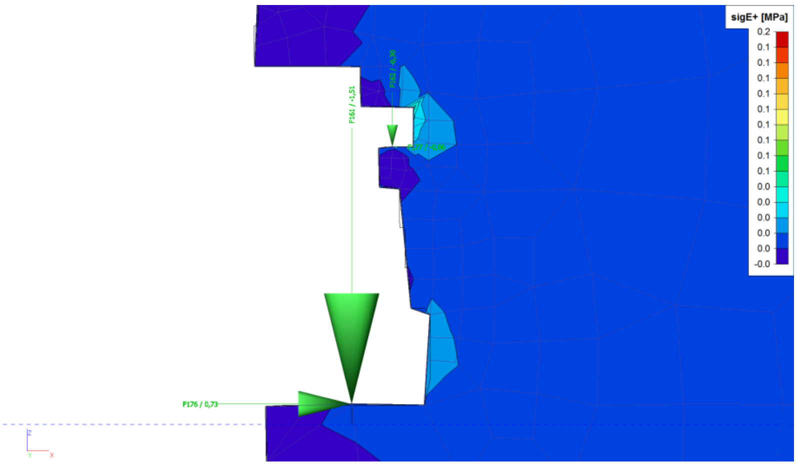
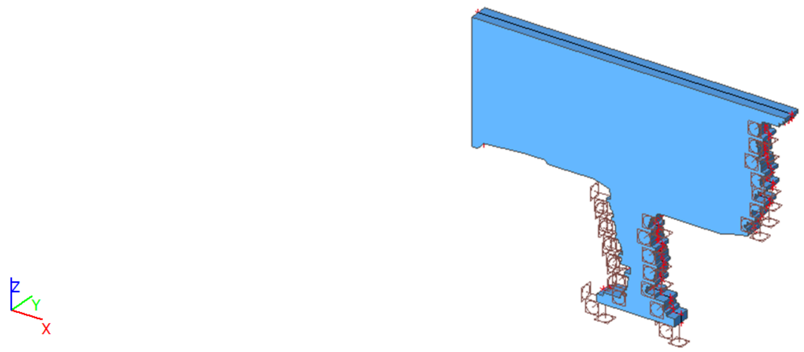


Figure 75. Close-up of the 2D model of the SW tower above axis C (screen proof from Scia Engineer 15). Inner stress magnitudes in the natural stone masonry from dead load of the connected glass structure inserted as point loads

Appendix 9.2 Support Reaction Reports of the Glass Sections

Overall project description

Isometric view: Glass Unit 1



Materials

MaterialB

Name Type	E mod [MPa] G mod [MPa]	Poisson - nu	Unit mass [kg/m³]	Log. decrement (non-uniform damping only)	Specific heat [J/gK]
Glass General material	7,0000e+04 2,8689e+04	0.22	2500,0	0.15	8,5000e+02

Load cases

Name	Description Spec	Action type Load type	LoadGroup	Direction
Self-weight		Permanent Self weight	LG1	-Z

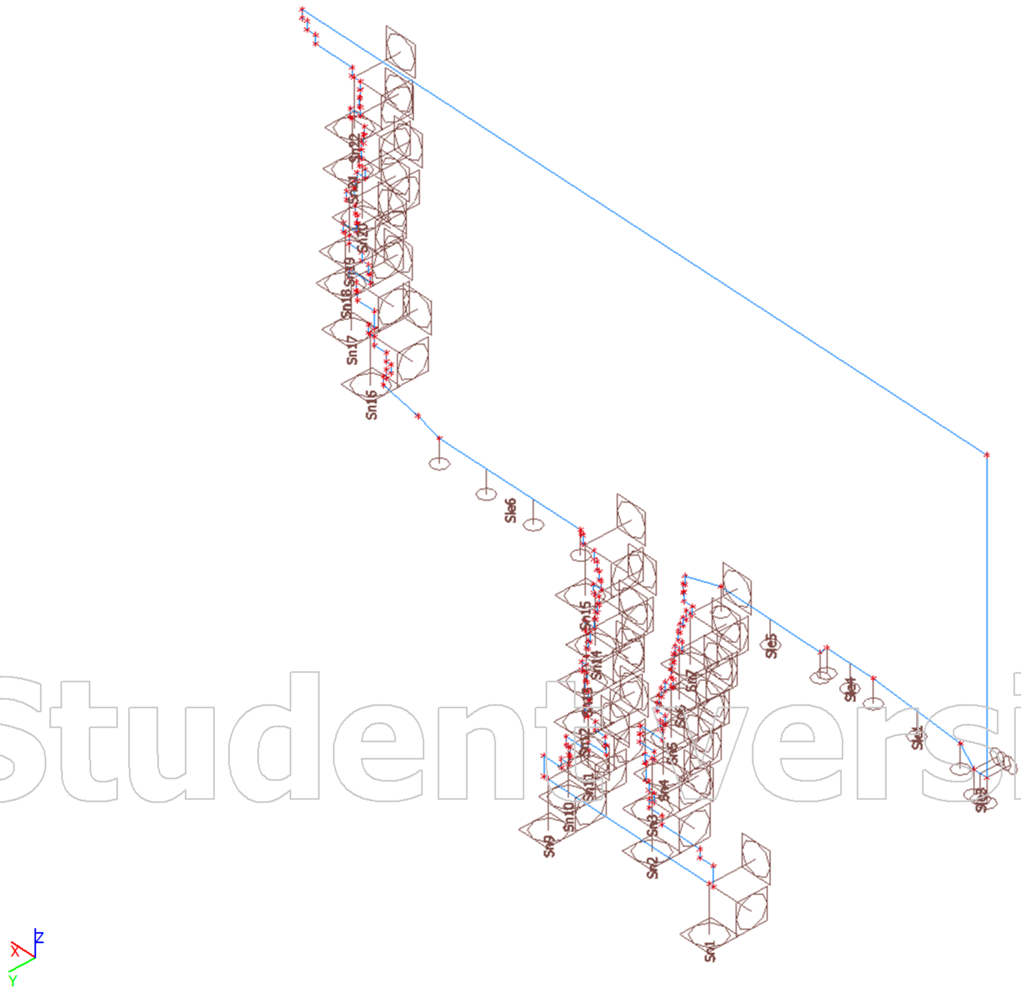
Analysis

Solver and mesh setup

Neglect shear force deformation (Ay, Az >> A)	X
Division on haunches and arbitrary members	5
Mesh refinement following the beam type	None
Bending theory of plate/shell analysis	Kirchhoff
Type of solver	Direct
Number of thicknesses of rib plate	20
Number of sections on average member	10
Warning when maximal translation is bigger than [mm]	1000,0
Warning when maximal rotation is bigger than [mrad]	100,0
Minimal distance between two points [m]	0.001
Average size of 2d element/curved element [m]	0,230
Average number of tiles of 1d element	1
Minimal length of beam element [m]	0,100
Maximal length of beam element [m]	1000,000
Average size of cables, tendons, elements on subsoil, nonlinear soil spring [m]	1,000
Generation of nodes in connections of beam elements	✓
Generation of nodes under concentrated loads on beam elements	✓
Generation of eccentric elements on members with variable height	X
To generate predefined mesh	✓
To smooth the border of predefined mesh	X
Maximal out of plane angle of a quadrilateral [mrad]	30,0
Predefined mesh ratio	1.5
Coefficient for reinforcement	1
Hanging nodes for prestressing	✓

Supports

Boundary conditions



Calculation protocol

Linear calculation

Number of 2D elements	**1904**
Number of 1D elements	**0**
Number of mesh nodes	**2070**
Number of equations	**12420**
Loadcases	Self-weight
Bending theory	Kirchhoff
Start of calculation	21.05.2015 22:28
End of calculation	21.05.2015 22:28

Sum of loads and reactions.

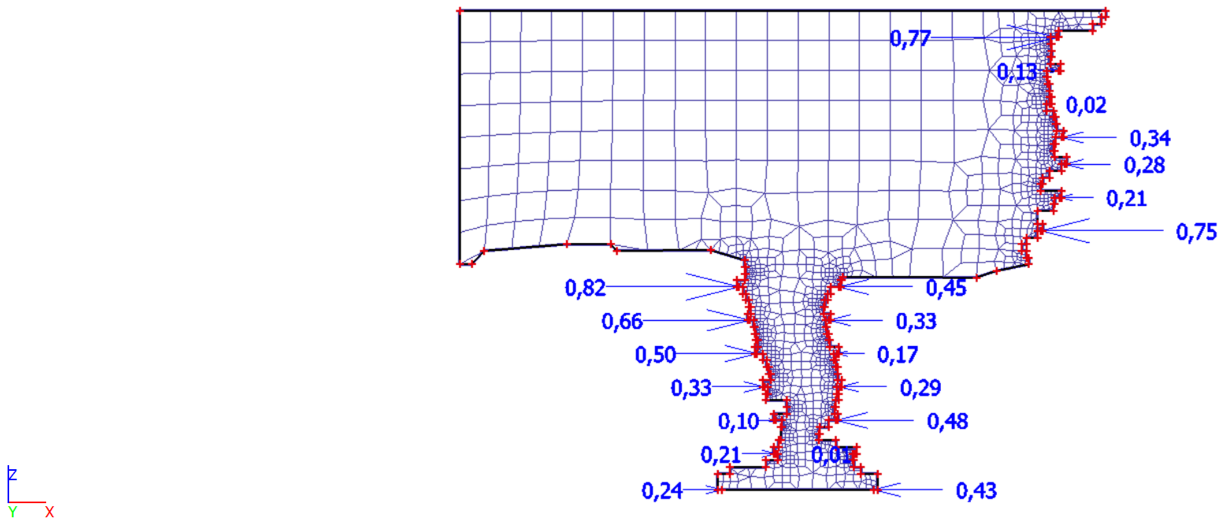
	[kN]	X	Y	Z
Loadcase Self-weight	loads	0.0	0.0	-68.8
	reactions in nodes	0.0	0.0	18.4
	reactions on lines	0.0	0.0	50.4
	contact 1D	0.0	0.0	0.0
	contact 2D	0.0	0.0	0.0

Reactions

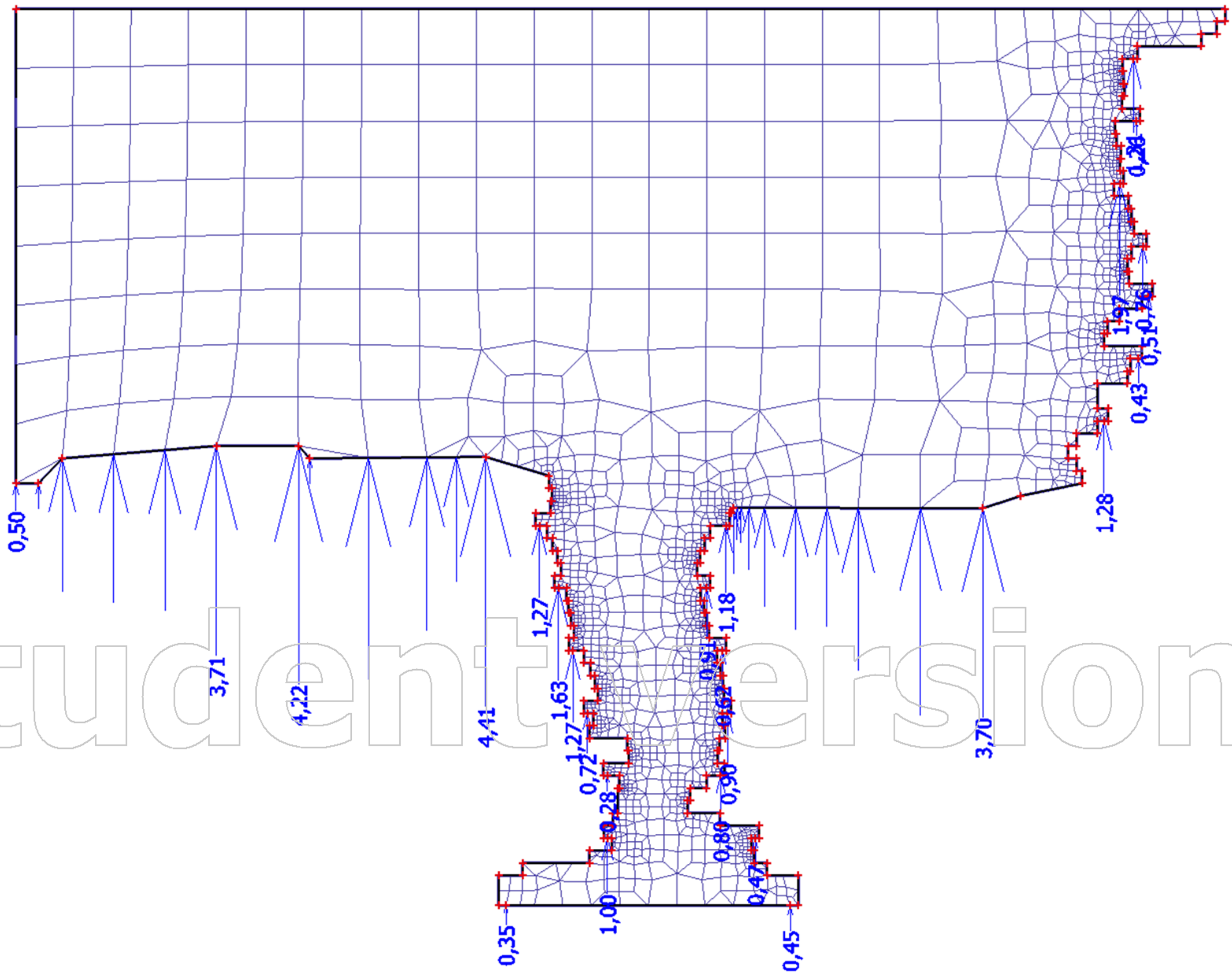
Linear calculation, Extreme : Node
Selection : All
Load cases : Self-weight

Support	Case	dx [m]	Rx [kN]	Ry [kN]	Rz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
Sn1/N154	Self-weight		**0,24**	**0,00**	**0,35**	**0,00**	**0,00**	**0,00**
Sn2/N163	Self-weight		**0,21**	**0,00**	**1,00**	**0,00**	**0,00**	**0,00**
Sn3/N172	Self-weight		**0,10**	**0,00**	**0,28**	**0,00**	**0,00**	**0,00**
Sn4/N183	Self-weight		**0,33**	**0,00**	**0,72**	**0,00**	**0,00**	**0,00**
Sn5/N194	Self-weight		**0,50**	**0,00**	**1,27**	**0,00**	**0,00**	**0,00**
Sn6/N205	Self-weight		**0,66**	**0,00**	**1,63**	**0,00**	**0,00**	**0,00**
Sn7/N216	Self-weight		**0,82**	**0,00**	**1,27**	**0,00**	**0,00**	**0,00**
Sn9/N153	Self-weight		**-0,43**	**0,00**	**0,45**	**0,00**	**0,00**	**0,00**
Sn10/N144	Self-weight		**0,01**	**0,00**	**0,47**	**0,00**	**0,00**	**0,00**
Sn11/N133	Self-weight		**-0,48**	**0,00**	**0,80**	**0,00**	**0,00**	**0,00**
Sn12/N122	Self-weight		**-0,29**	**0,00**	**0,90**	**0,00**	**0,00**	**0,00**
Sn13/N111	Self-weight		**-0,17**	**0,00**	**0,62**	**0,00**	**0,00**	**0,00**
Sn14/N100	Self-weight		**-0,33**	**0,00**	**0,91**	**0,00**	**0,00**	**0,00**
Sn15/N89	Self-weight		**-0,45**	**0,00**	**1,18**	**0,00**	**0,00**	**0,00**
Sn16/N72	Self-weight		**-0,75**	**0,00**	**1,28**	**0,00**	**0,00**	**0,00**
Sn17/N63	Self-weight		**-0,21**	**0,00**	**0,43**	**0,00**	**0,00**	**0,00**
Sn18/N52	Self-weight		**-0,28**	**0,00**	**0,51**	**0,00**	**0,00**	**0,00**
Sn19/N43	Self-weight		**-0,34**	**0,00**	**0,76**	**0,00**	**0,00**	**0,00**
Sn20/N32	Self-weight		**-0,02**	**0,00**	**1,97**	**0,00**	**0,00**	**0,00**
Sn21/N21	Self-weight		**0,13**	**0,00**	**0,26**	**0,00**	**0,00**	**0,00**
Sn22/N10	Self-weight		**0,77**	**0,00**	**1,31**	**0,00**	**0,00**	**0,00**
Sle1/S1	Self-weight	0,000	**0,00**	**0,00**	**3,71**	**0,00**	**0,00**	**0,00**
Sle1/S1	Self-weight	0,619	0,00	0,00	**2,36**	0,00	0,00	0,00
Sle3/S1	Self-weight	0,000	**0,00**	**0,00**	**0,45**	**0,00**	**0,00**	**0,00**
Sle3/S1	Self-weight	0,091	0,00	0,00	**0,50**	0,00	0,00	0,00
Sle4/S1	Self-weight	0,000	**0,00**	**0,00**	**4,22**	**0,00**	**0,00**	**0,00**
Sle4/S1	Self-weight	0,330	0,00	0,00	**3,71**	0,00	0,00	0,00
Sle5/S1	Self-weight	0,000	**0,00**	**0,00**	**4,41**	**0,00**	**0,00**	**0,00**
Sle5/S1	Self-weight	0,705	0,00	0,00	**0,45**	0,00	0,00	0,00
Sle6/S1	Self-weight	0,000	**0,00**	**0,00**	**3,70**	**0,00**	**0,00**	**0,00**
Sle6/S1	Self-weight	0,984	0,00	0,00	**0,57**	0,00	0,00	0,00

Nodal space support resultant; hor. component

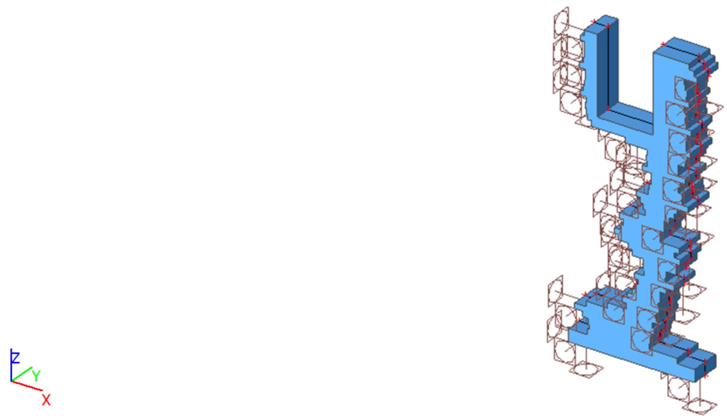


Reactions; Rz



1. Overall project description

1.1. Isometric view: Glass Unit 2



1.2. Materials

MaterialB

Name Type	E mod [MPa] G mod [MPa]	Poisson - nu	Unit mass [kg/m³]
Glass General material	7,0000e+04 2,8689e+04	0.22	2500,0

2. Load cases

Name	Description Spec	Action type Load type	LoadGroup	Direction
Self-weight		Permanent Self weight	LG1	-Z

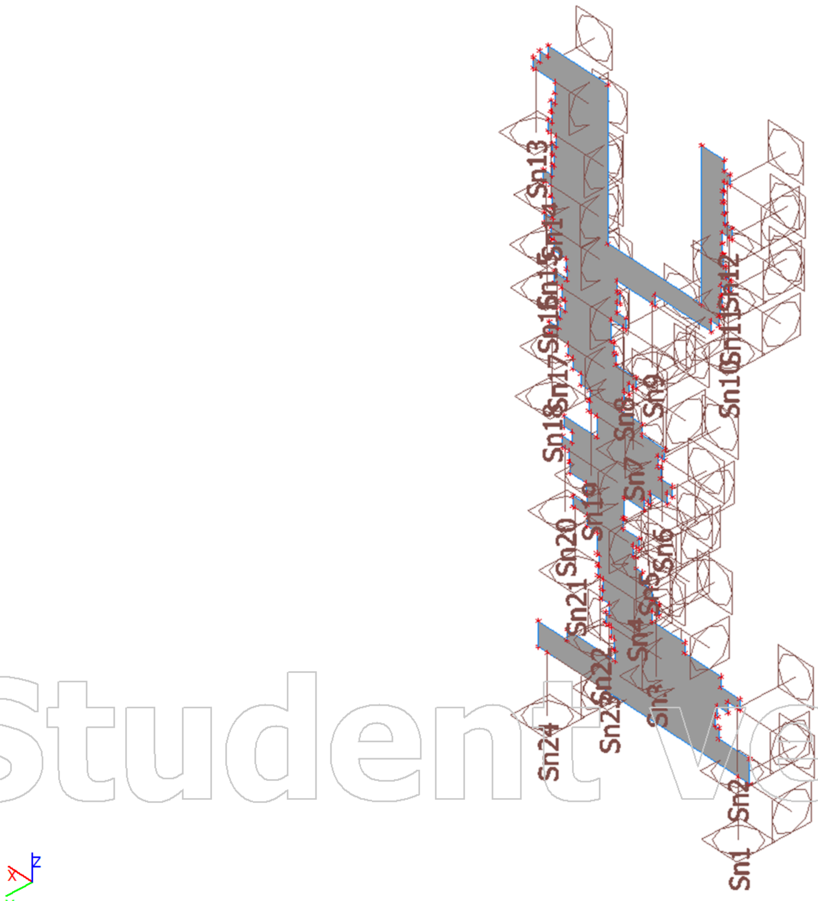
3. Analysis

3.1. Solver and mesh setup

Neglect shear force deformation (Ay, Az >> A)	X
Division on haunches and arbitrary members	5
Mesh refinement following the beam type	None
Bending theory of plate/shell analysis	Mindlin
Type of solver	Direct
Number of thicknesses of rib plate	20
Number of sections on average member	10
Warning when maximal translation is bigger than [mm]	1000,0
Warning when maximal rotation is bigger than [mrad]	100,0
Minimal distance between two points [m]	0.001
Average size of 2d element/curved element [m]	0,230
Average number of tiles of 1d element	1
Minimal length of beam element [m]	0,100
Maximal length of beam element [m]	1000,000
Average size of cables, tendons, elements on subsoil, nonlinear soil spring [m]	1,000
Generation of nodes in connections of beam elements	✓
Generation of nodes under concentrated loads on beam elements	✓
Generation of eccentric elements on members with variable height	X
To generate predefined mesh	✓
To smooth the border of predefined mesh	X
Maximal out of plane angle of a quadrilateral [mrad]	30,0
Predefined mesh ratio	1.5
Coefficient for reinforcement	1
Hanging nodes for prestressing	✓

3.2. Supports

3.2.1. Boundary conditions



4. Calculation protocol

Linear calculation

Number of 2D elements	**512**
Number of 1D elements	**0**
Number of mesh nodes	**448**
Number of equations	**2688**
Loadcases	Self-weight
Bending theory	Mindlin
Start of calculation	21.05.2015 22:32
End of calculation	21.05.2015 22:32

Sum of loads and reactions.

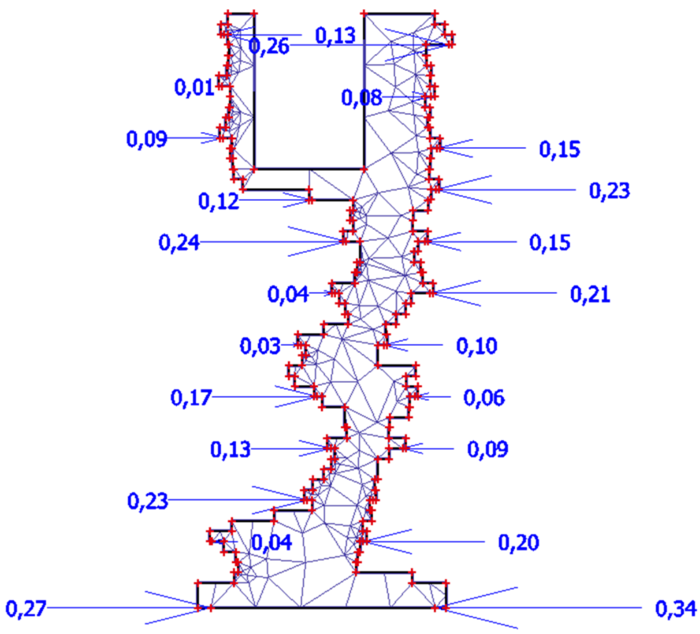
	[kN]	X	Y	Z
Loadcase Self-weight	loads	0.0	0.0	-10.0
	reactions in nodes	0.0	0.0	10.0
	reactions on lines	0.0	0.0	0.0
	contact 1D	0.0	0.0	0.0
	contact 2D	0.0	0.0	0.0

5. Reactions

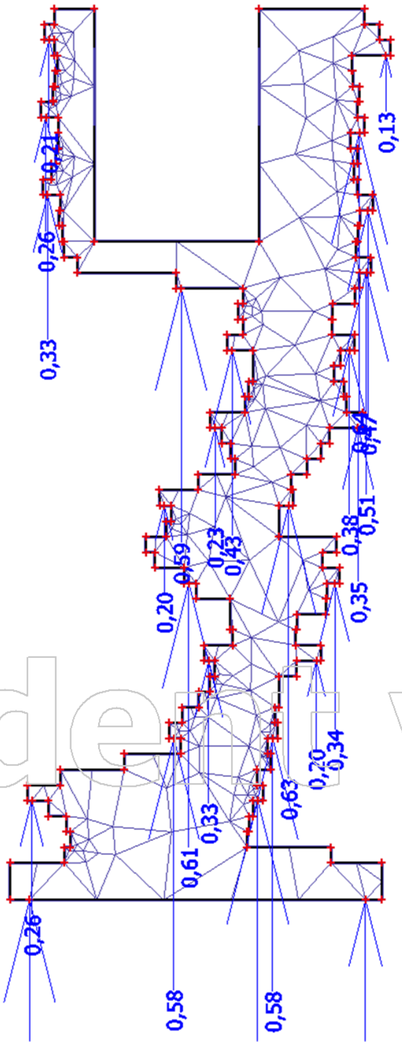
Linear calculation, Extreme : Node
Selection : All
Load cases : Self-weight

Support	Case	Rx [kN]	Ry [kN]	Rz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
Sn1/N121	Self-weight	**0,27**	**0,00**	**0,59**	**0,00**	**-0,01**	**0,00**
Sn2/N110	Self-weight	**-0,04**	**0,00**	**0,26**	**0,00**	**0,00**	**0,00**
Sn3/N101	Self-weight	**0,23**	**0,00**	**0,58**	**0,00**	**0,00**	**0,00**
Sn4/N90	Self-weight	**0,13**	**0,00**	**0,33**	**0,00**	**0,00**	**0,00**
Sn5/N81	Self-weight	**0,17**	**0,00**	**0,61**	**0,00**	**0,00**	**0,00**
Sn6/N70	Self-weight	**0,03**	**0,00**	**0,20**	**0,00**	**0,00**	**0,00**
Sn7/N59	Self-weight	**0,04**	**0,00**	**0,23**	**0,00**	**0,00**	**0,00**
Sn8/N50	Self-weight	**0,24**	**0,00**	**0,43**	**0,00**	**0,00**	**0,00**
Sn9/N41	Self-weight	**0,12**	**0,00**	**0,59**	**0,00**	**-0,01**	**0,00**
Sn10/N28	Self-weight	**0,09**	**0,00**	**0,33**	**0,00**	**0,00**	**0,00**
Sn11/N17	Self-weight	**0,01**	**0,00**	**0,26**	**0,00**	**0,00**	**0,00**
Sn12/N5	Self-weight	**-0,13**	**0,00**	**0,21**	**0,00**	**0,00**	**0,00**
Sn13/N235	Self-weight	**0,26**	**0,00**	**0,13**	**0,00**	**0,00**	**0,00**
Sn14/N224	Self-weight	**0,08**	**0,00**	**0,64**	**0,00**	**0,00**	**0,00**
Sn15/N213	Self-weight	**-0,15**	**0,00**	**0,47**	**0,00**	**0,00**	**0,00**
Sn16/N204	Self-weight	**-0,23**	**0,00**	**0,51**	**0,00**	**0,00**	**0,00**
Sn17/N193	Self-weight	**-0,15**	**0,00**	**0,38**	**0,00**	**0,00**	**0,00**
Sn18/N182	Self-weight	**-0,21**	**0,00**	**0,35**	**0,00**	**0,00**	**0,00**
Sn19/N171	Self-weight	**-0,10**	**0,00**	**0,63**	**0,00**	**0,00**	**0,00**
Sn20/N162	Self-weight	**-0,06**	**0,00**	**0,34**	**0,00**	**0,00**	**0,00**
Sn21/N151	Self-weight	**-0,09**	**0,00**	**0,20**	**0,00**	**0,00**	**0,00**
Sn22/N142	Self-weight	**0,00**	**0,00**	**0,58**	**0,00**	**0,00**	**0,00**
Sn23/N133	Self-weight	**-0,20**	**0,00**	**0,71**	**0,00**	**0,00**	**0,00**
Sn24/N122	Self-weight	**-0,34**	**0,00**	**0,38**	**0,00**	**0,01**	**0,00**

6. Nodal space support resultant; hor. component



7. Reactions; Rz



1. Overall project description

1.1. Isometric view: Glass Unit 3

1.2. Materials

MaterialB

Name Type	E mod [MPa] G mod [MPa]	Poisson - nu	Unit mass [kg/m³]	Log. decrement (non-uniform damping only)	Specific heat [J/gK]
Glass General material	7,0000e+04 2,8689e+04	0.22	2500,0	0.15	8,5000e+02

2. Load cases

Name	Description Spec	Action type Load type	LoadGroup	Direction
Self-weight		Permanent Self weight	LG1	-Z

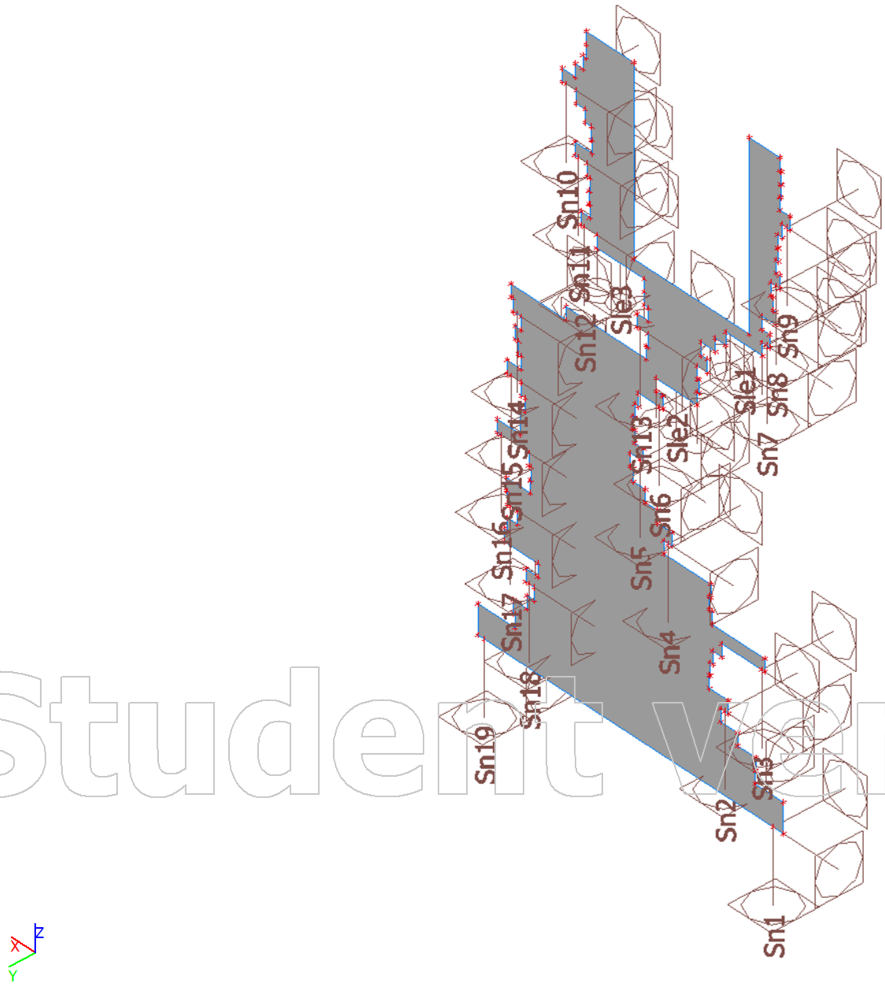
3. Analysis

3.1. Solver and mesh setup

Neglect shear force deformation (Ay, Az >> A)	X
Division on haunches and arbitrary members	5
Mesh refinement following the beam type	None
Bending theory of plate/shell analysis	Mindlin
Type of solver	Direct
Number of thicknesses of rib plate	20
Number of sections on average member	10
Warning when maximal translation is bigger than [mm]	1000,0
Warning when maximal rotation is bigger than [mrad]	100,0
Minimal distance between two points [m]	0.001
Average size of 2d element/curved element [m]	0,230
Average number of tiles of 1d element	1
Minimal length of beam element [m]	0,100
Maximal length of beam element [m]	1000,000
Average size of cables, tendons, elements on subsoil, nonlinear soil spring [m]	1,000
Generation of nodes in connections of beam elements	✓
Generation of nodes under concentrated loads on beam elements	✓
Generation of eccentric elements on members with variable height	X
To generate predefined mesh	✓
To smooth the border of predefined mesh	X
Maximal out of plane angle of a quadrilateral [mrad]	30,0
Predefined mesh ratio	1.5
Coefficient for reinforcement	1
Hanging nodes for prestressing	✓

3.2. Supports

3.2.1. Boundary conditions



4. Calculation protocol

Linear calculation

Number of 2D elements	**1484**
Number of 1D elements	**0**
Number of mesh nodes	**1365**
Number of equations	**8190**
Loadcases	Self-weight
Bending theory	Mindlin
Start of calculation	21.05.2015 22:35
End of calculation	21.05.2015 22:35

Sum of loads and reactions.

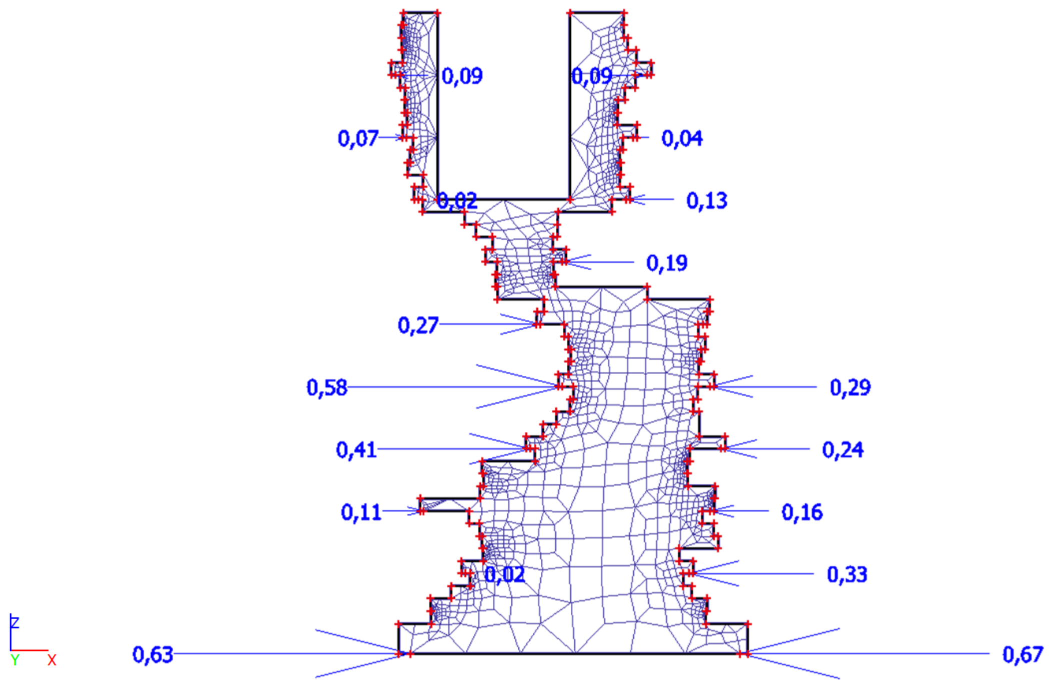
	[kN]	X	Y	Z
Loadcase Self-weight	loads	0.0	0.0	-11.7
	reactions in nodes	0.0	0.0	9.3
	reactions on lines	0.0	0.0	2.5
	contact 1D	0.0	0.0	0.0
	contact 2D	0.0	0.0	0.0

5. Reactions

Linear calculation, Extreme : Node
Selection : All
Load cases : Self-weight

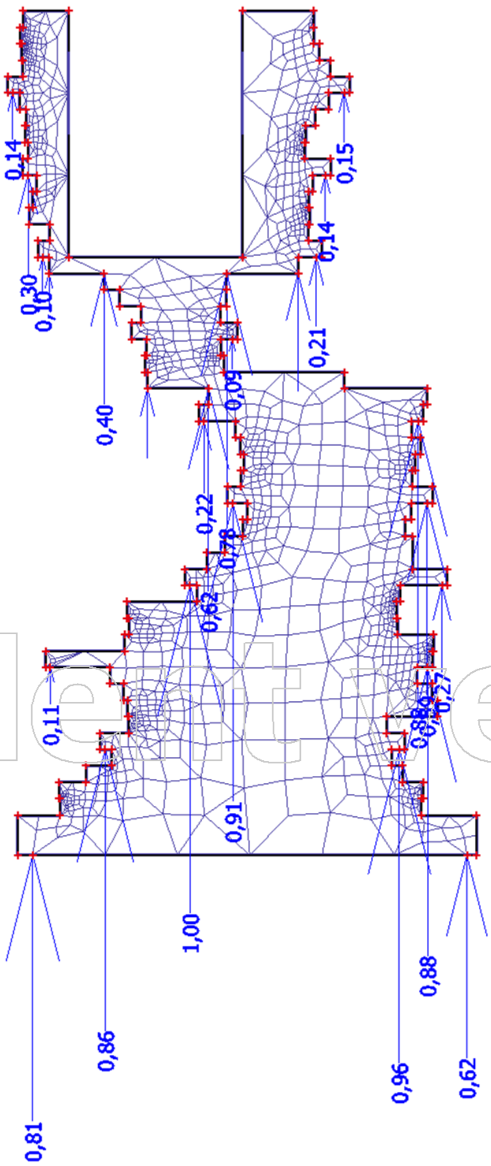
Support	Case	dx [m]	Rx [kN]	Ry [kN]	Rz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
Sn1/N111	Self-weight		**0,63**	**0,00**	**0,81**	**0,00**	**-0,01**	**0,00**
Sn2/N100	Self-weight		**-0,02**	**0,00**	**0,86**	**0,00**	**0,00**	**0,00**
Sn3/N89	Self-weight		**0,11**	**0,00**	**0,11**	**0,00**	**0,00**	**0,00**
Sn4/N78	Self-weight		**0,41**	**0,00**	**1,00**	**0,00**	**0,00**	**0,00**
Sn5/N67	Self-weight		**0,58**	**0,00**	**0,91**	**0,00**	**0,00**	**0,00**
Sn6/N56	Self-weight		**0,27**	**0,00**	**0,22**	**0,00**	**0,00**	**0,00**
Sn7/N35	Self-weight		**-0,02**	**0,00**	**0,10**	**0,00**	**0,00**	**0,00**
Sn8/N24	Self-weight		**0,07**	**0,00**	**0,30**	**0,00**	**0,00**	**0,00**
Sn9/N13	Self-weight		**-0,09**	**0,00**	**0,14**	**0,00**	**0,00**	**0,00**
Sn10/N209	Self-weight		**0,09**	**0,00**	**0,15**	**0,00**	**0,00**	**0,00**
Sn11/N198	Self-weight		**-0,04**	**0,00**	**0,14**	**0,00**	**0,00**	**0,00**
Sn12/N187	Self-weight		**-0,13**	**0,00**	**0,21**	**0,00**	**0,00**	**0,00**
Sn13/N176	Self-weight		**-0,19**	**0,00**	**0,09**	**0,00**	**0,00**	**0,00**
Sn14/N165	Self-weight		**0,00**	**0,00**	**0,88**	**0,00**	**0,00**	**0,00**
Sn15/N154	Self-weight		**-0,29**	**0,00**	**0,59**	**0,00**	**0,00**	**0,00**
Sn16/N145	Self-weight		**-0,24**	**0,00**	**0,27**	**0,00**	**0,00**	**0,00**
Sn17/N134	Self-weight		**-0,16**	**0,00**	**0,88**	**0,00**	**0,00**	**0,00**
Sn18/N123	Self-weight		**-0,33**	**0,00**	**0,96**	**0,00**	**0,00**	**0,00**
Sn19/N112	Self-weight		**-0,67**	**0,00**	**0,62**	**0,00**	**0,01**	**0,00**
Sle1/S2	Self-weight	0,000	**0,00**	**0,00**	**0,11**	**0,00**	**0,00**	**0,00**
Sle1/S2	Self-weight	0,168	0,00	0,00	**0,40**	0,00	0,00	0,00
Sle2/S2	Self-weight	0,000	**0,00**	**0,00**	**0,21**	**0,00**	**0,00**	**0,00**
Sle2/S2	Self-weight	0,186	0,00	0,00	**0,62**	0,00	0,00	0,00
Sle3/S2	Self-weight	0,000	**0,00**	**0,00**	**0,78**	**0,00**	**0,00**	**0,00**
Sle3/S2	Self-weight	0,218	0,00	0,00	**0,36**	0,00	0,00	0,00

6. Nodal space support: hor. component



Scia Engineer
Scia Engineer 15.0.115
Project Section 3
Part -
Author K.Karron
Date 21. 05. 2015

7. Reactions; Rz



1. Overall project description

1.1. Isometric view: Glass Unit 1

1.2. Materials

MaterialB

Name	E mod [MPa]	Poisson - nu	Unit mass [kg/m³]	Log. decrement (non-uniform damping only)	Specific heat [J/gK]
Type	G mod [MPa]				
Glass	7,0000e+04	0.22	2500,0	0.15	8,5000e+02
General material	2,8689e+04				

2. Load cases

Name	Description	Action type / Load type	LoadGroup	Direction
	Spec			
LC1		Permanent	LG1	-Z
		Self weight		

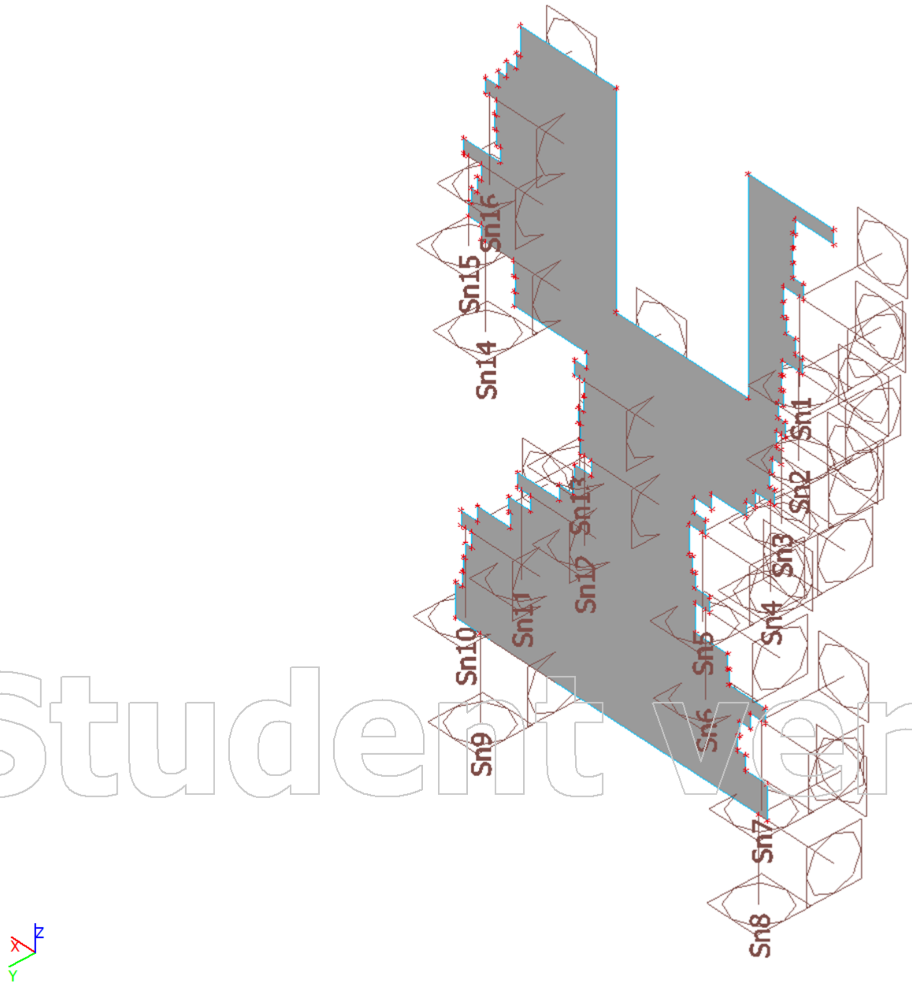
3. Analysis

3.1. Solver and mesh setup

Neglect shear force deformation (Ay, Az >> A)	x
Division on haunches and arbitrary members	5
Mesh refinement following the beam type	None
Bending theory of plate/shell analysis	Mindlin
Type of solver	Direct
Number of thicknesses of rib plate	20
Number of sections on average member	10
Warning when maximal translation is bigger than [mm]	1000,0
Warning when maximal rotation is bigger than [mrad]	100,0
Minimal distance between two points [m]	0.001
Average size of 2d element/curved element [m]	0,230
Average number of tiles of 1d element	1
Minimal length of beam element [m]	0,100
Maximal length of beam element [m]	1000,000
Average size of cables, tendons, elements on subsoil, nonlinear soil spring [m]	1,000
Generation of nodes in connections of beam elements	✓
Generation of nodes under concentrated loads on beam elements	✓
Generation of eccentric elements on members with variable height	x
To generate predefined mesh	✓
To smooth the border of predefined mesh	x
Maximal out of plane angle of a quadrilateral [mrad]	30,0
Predefined mesh ratio	1.5
Coefficient for reinforcement	1
Hanging nodes for prestressing	✓

3.2. Supports

3.2.1. Boundary conditions



4. Calculation protocol

Linear calculation

Number of 2D elements	**293**
Number of 1D elements	**0**
Number of mesh nodes	**281**
Number of equations	**1686**
Loadcases	LC1
Bending theory	Mindlin
Start of calculation	22.05.2015 23:43
End of calculation	22.05.2015 23:43

Sum of loads and reactions.

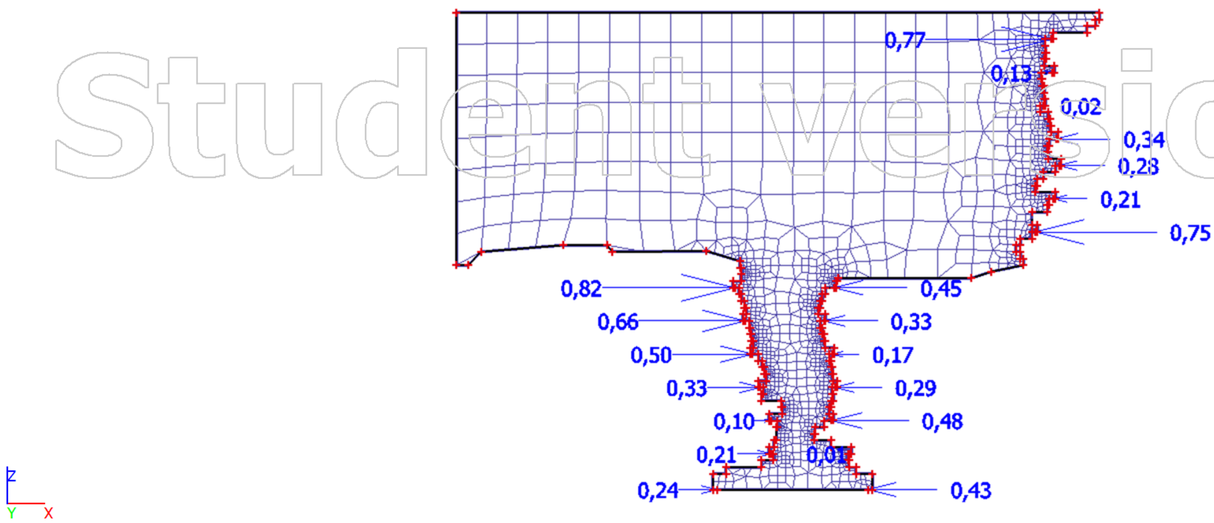
	[kN]	X	Y	Z
Loadcase LC1	loads	0.0	0.0	-12.3
	reactions in nodes	0.0	0.0	12.3
	reactions on lines	0.0	0.0	0.0
	contact 1D	0.0	0.0	0.0
	contact 2D	0.0	0.0	0.0

5. Reactions

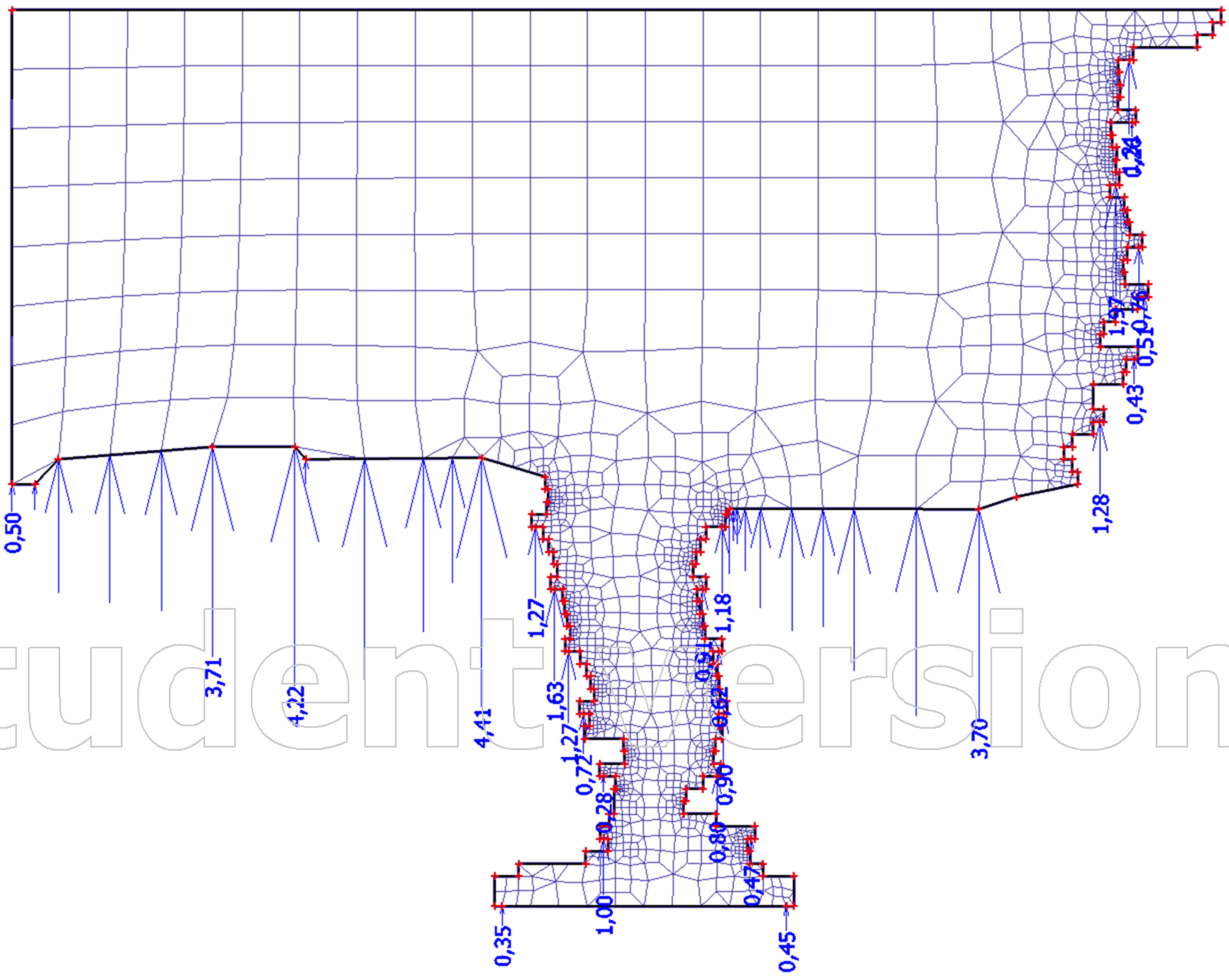
Linear calculation, Extreme : Node
Selection : All
Load cases : LC1

Support	Case	Rx [kN]	Ry [kN]	Rz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
Sn1/N14	LC1	**-0,20**	**0,00**	**0,30**	**0,00**	**0,00**	**0,00**
Sn2/N25	LC1	**-0,04**	**0,00**	**0,46**	**0,00**	**0,00**	**0,00**
Sn3/N36	LC1	**-0,11**	**0,00**	**0,58**	**0,00**	**0,00**	**0,00**
Sn4/N47	LC1	**0,34**	**0,00**	**0,78**	**0,00**	**0,00**	**0,00**
Sn5/N58	LC1	**0,37**	**0,00**	**0,94**	**0,00**	**-0,01**	**0,00**
Sn6/N67	LC1	**0,09**	**0,00**	**0,80**	**0,00**	**-0,01**	**0,00**
Sn7/N76	LC1	**-0,12**	**0,00**	**0,31**	**0,00**	**0,00**	**0,00**
Sn8/N87	LC1	**0,63**	**0,00**	**0,99**	**0,00**	**-0,02**	**0,00**
Sn9/N88	LC1	**-0,73**	**0,00**	**1,51**	**0,00**	**0,02**	**0,00**
Sn10/N99	LC1	**0,06**	**0,00**	**0,30**	**0,00**	**0,00**	**0,00**
Sn11/N110	LC1	**0,13**	**0,00**	**0,50**	**0,00**	**0,00**	**0,00**
Sn12/N121	LC1	**-0,34**	**0,00**	**1,38**	**0,00**	**0,00**	**0,00**
Sn13/N132	LC1	**-0,29**	**0,00**	**1,22**	**0,00**	**0,00**	**0,00**
Sn14/N143	LC1	**-0,59**	**0,00**	**1,54**	**0,00**	**0,01**	**0,00**
Sn15/N154	LC1	**0,19**	**0,00**	**0,15**	**0,00**	**0,00**	**0,00**
Sn16/N166	LC1	**0,61**	**0,00**	**0,56**	**0,00**	**0,01**	**0,00**

6. Nodal space support resultant; hor. component



7. Reactions; Rz



1. Overall project description

1.1. Isometric view: Glass Unit 5

1.2. Materials

MaterialB

Name Type	E mod [MPa] G mod [MPa]	Poisson - nu	Unit mass [kg/m³]	Log. decrement (non-uniform damping only)	Specific heat [J/gK]
Glass General material	7,0000e+04 2,8689e+04	0.22	2500,0	0.15	8,5000e+02

2. Load cases

Name	Description Spec	Action type Load type	LoadGroup	Direction
Self-weight		Permanent Self weight	LG1	-Z

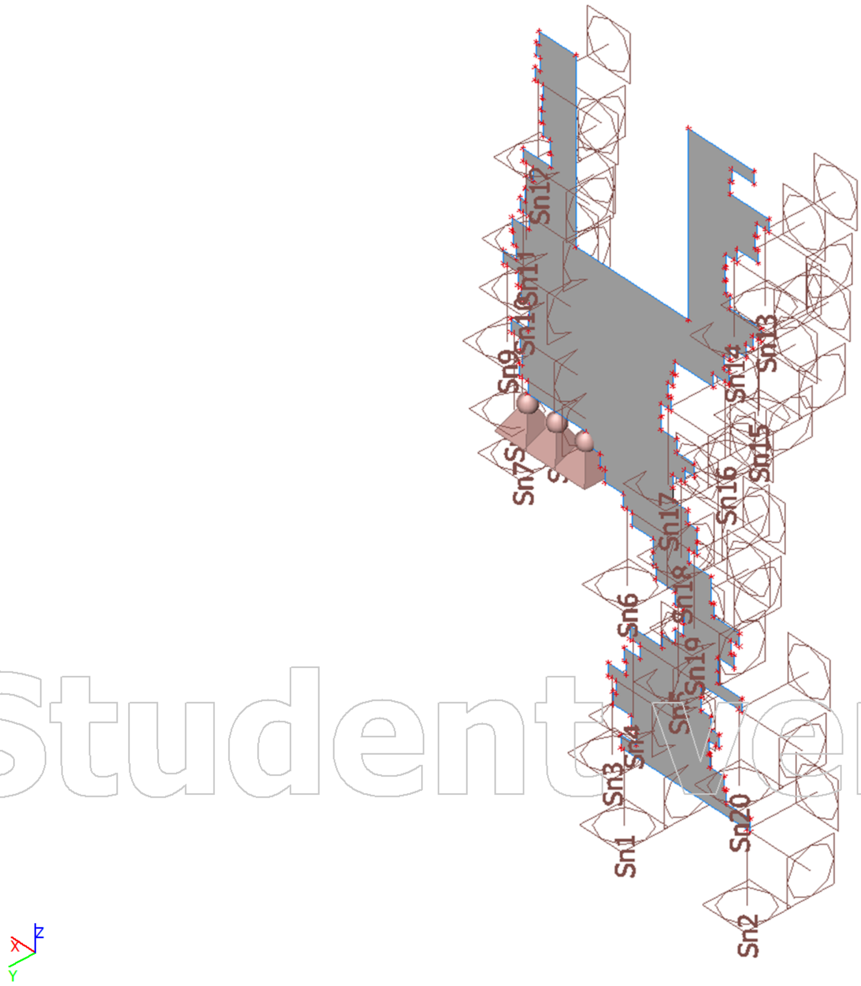
3. Analysis

3.1. Solver and mesh setup

Neglect shear force deformation (Ay, Az >> A)	x
Division on haunches and arbitrary members	5
Mesh refinement following the beam type	None
Bending theory of plate/shell analysis	Mindlin
Type of solver	Direct
Number of thicknesses of rib plate	20
Number of sections on average member	10
Warning when maximal translation is bigger than [mm]	1000,0
Warning when maximal rotation is bigger than [mrad]	100,0
Minimal distance between two points [m]	0.001
Average size of 2d element/curved element [m]	0,230
Average number of tiles of 1d element	1
Minimal length of beam element [m]	0,100
Maximal length of beam element [m]	1000,000
Average size of cables, tendons, elements on subsoil, nonlinear soil spring [m]	1,000
Generation of nodes in connections of beam elements	✓
Generation of nodes under concentrated loads on beam elements	✓
Generation of eccentric elements on members with variable height	x
To generate predefined mesh	✓
To smooth the border of predefined mesh	x
Maximal out of plane angle of a quadrilateral [mrad]	30,0
Predefined mesh ratio	1.5
Coefficient for reinforcement	1
Hanging nodes for prestressing	✓

3.2. Supports

3.2.1. Boundary conditions



4. Calculation protocol

Linear calculation

Number of 2D elements	**474**
Number of 1D elements	**0**
Number of mesh nodes	**410**
Number of equations	**2460**
Loadcases	Self-weight
Bending theory	Mindlin
Start of calculation	21.05.2015 23:42
End of calculation	21.05.2015 23:43

Sum of loads and reactions.

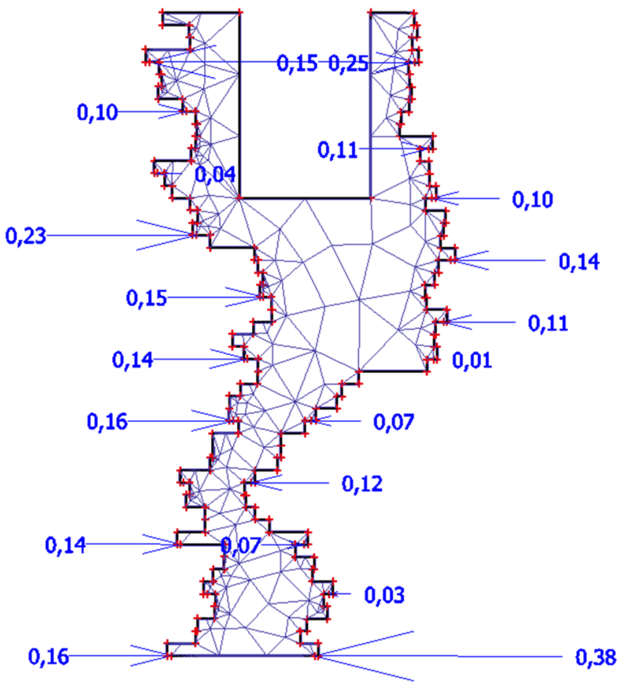
	[kN]	X	Y	Z
Loadcase Self-weight	loads	0.0	0.0	-9.6
	reactions in nodes	0.1	0.0	7.8
	reactions on lines	-0.1	0.0	1.8
	contact 1D	0.0	0.0	0.0
	contact 2D	0.0	0.0	0.0

5. Reactions

Linear calculation, Extreme : Node
Selection : All
Load cases : Self-weight

Support	Case	dx [m]	Rx [kN]	Ry [kN]	Rz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
Sn1/N115	Self-weight		**-0,38**	**0,00**	**0,49**	**0,00**	**0,01**	**0,00**
Sn2/N114	Self-weight		**0,16**	**0,00**	**0,26**	**0,00**	**-0,01**	**0,00**
Sn3/N126	Self-weight		**-0,03**	**0,00**	**0,31**	**0,00**	**0,00**	**0,00**
Sn4/N135	Self-weight		**0,07**	**0,00**	**0,29**	**0,00**	**0,00**	**0,00**
Sn5/N146	Self-weight		**-0,12**	**0,00**	**0,69**	**0,00**	**0,00**	**0,00**
Sn6/N157	Self-weight		**-0,07**	**0,00**	**0,59**	**0,00**	**0,00**	**0,00**
Sn7/N168	Self-weight		**-0,01**	**0,00**	**0,27**	**0,00**	**0,00**	**0,00**
Sn8/N175	Self-weight		**-0,11**	**0,00**	**0,16**	**0,00**	**0,00**	**0,00**
Sn9/N186	Self-weight		**-0,14**	**0,00**	**0,26**	**0,00**	**0,00**	**0,00**
Sn10/N197	Self-weight		**-0,10**	**0,00**	**0,49**	**0,00**	**0,00**	**0,00**
Sn11/N206	Self-weight		**0,11**	**0,00**	**0,22**	**0,00**	**0,00**	**0,00**
Sn12/N221	Self-weight		**0,15**	**0,00**	**0,42**	**0,00**	**0,00**	**0,00**
Sn13/N10	Self-weight		**-0,25**	**0,00**	**0,08**	**0,00**	**0,00**	**0,00**
Sn14/N19	Self-weight		**0,10**	**0,00**	**0,85**	**0,00**	**0,00**	**0,00**
Sn15/N30	Self-weight		**-0,04**	**0,00**	**0,20**	**0,00**	**0,00**	**0,00**
Sn16/N41	Self-weight		**0,23**	**0,00**	**0,56**	**0,00**	**0,00**	**0,00**
Sn17/N52	Self-weight		**0,15**	**0,00**	**0,68**	**0,00**	**0,00**	**0,00**
Sn18/N63	Self-weight		**0,14**	**0,00**	**0,43**	**0,00**	**0,00**	**0,00**
Sn19/N74	Self-weight		**0,16**	**0,00**	**0,37**	**0,00**	**0,00**	**0,00**
Sn20/N94	Self-weight		**0,14**	**0,00**	**0,21**	**0,00**	**-0,01**	**0,00**
Sle1/S1	Self-weight	0,275	**-0,23**	0,00	**0,35**	0,00	0,00	0,00
Sle1/S1	Self-weight	0,000	**0,08**	**0,00**	**1,49**	**0,00**	**0,00**	**0,00**

6. Nodal space support resultant; hor. component



7. Reactions; Rz